African Journal of Biotechnology Vol. 11(80), pp. 14612-14620, 4 October, 2012
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB11.2229
ISSN 1684–5315 ©2012 Academic Journals

Full Length Research Paper

Misting cooling technique for protected culture of *Oncidium* orchids in subtropical regions

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Accepted 6 September, 2012

***Oncidium* are planted in open protected culture or under shading nets in subtropical regions. Because of the lack of cooling techniques for the inside microclimates, the production period is limited, and the quantity and quality of flowers is unstable. Without ventilating, high humidity and temperature induces severe growth problems. In this study, mechanical ventilation fans with intermittent misting were applied to modify the internal microclimate of the *Oncidium* greenhouse. Nine experimental setting of misting intervals were tested. The misting efficiency is defined and served as the performance index. The misting intervals of 3 min on to 3 min off or 5 min on to 5 min off had the higher efficiency. The cooling technique can keep the interior air temperature lower than that of outside air temperature. The temperature of plants could be maintained close to the greenhouse air temperature. The intermittent misting function with the best evaporative cooling efficiency was controlled with interval operation. This technique can be applied to other protected structures of *Oncidium* and other orchids.**

Key words: Shading nets, misting cooling, tunnel greenhouse, *Oncidium*.

INTRODUCTION

Pot orchids have become the most important flowers in the flower industry of the world. The shape of *Oncidium* flowers like a dancing girl, let to their being named "dancing orchids". The orchids have become popular in the orchids market. The adequate growth temperature for *Oncidium* ranges from 22 to 32°C. The light intensity for the growth of these orchids needs to be maintained below 300 μmol m^{-2} s^{-1}. The major production areas of *Oncidium* are in Taiwan and Malaysia. Shading nets houses are popularly used for culture of *Oncidium*. In summer, the maximum day temperature is nearly 36°C in both countries. Because of lack of air ventilation in the net houses, high inside air temperature and relative humidity retards the growth of these plants. In the rainy season, the nets do not prevent rain, and several diseases are spread because of the long-term surface wetness duration of *Oncidium*. Therefore, the unstable microclimate in the net houses reduced the flower quality and delays the time to market.

The complex structure of greenhouses with all kinds of environmental control equipments could provide an adequate microclimate for the growth and flowering of *Oncidium*. However, the production cost is too high. A high tunnel structure is an alternative type of greenhouse (Impron et al., 2007). The roof and side wall of the greenhouse is covered with plastic materials. External and internal shading nets are installed above and below the roof to reduce the solar radiation. With this effective cooling technique, this protected structure could be used

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Nomenclature: ME, Misting efficiency (decimal); **RH_{in},** relative humidity of the greenhouse (%); **RH_{out},** relative humidity of the ambient air (%); **$T_{db,a}$,** dry bulb temperature of the ambient air (°C); **T_i,** dry bulb temperature of the greenhouse (°C); **T_{leaf},** leaf temperature (°C); **T_{medium},** medium temperature (°C); **T_{out},** temperature of outside air (°C); **T_{stem},** stem temperature (°C); **$T_{wb,a}$,** wet bulb temperature of the ambient air (°C); **t_{ri},** recording interval (s); **V,** air velocity (ms^{-1}).

for *Oncidium*. This structure need not be closed with wall, so the exhausting fans could not be applied. However, the cost of unit area is only 20% that of the greenhouse because of the simple structure and cheaper equipments. In reviewing the progress of the greenhouse engineering, Critten and Bailey (2002) emphasized the importance of ventilation, Sethi and Sharma (2007) discussed four methods for the greenhouse cooling: ventilation, shading, evaporative cooling, and composite systems, Kuman et al. (2009) introduced three kinds of evaporative cooling technologies, including a fan-pad system, a fog mist system and roof evaporative cooling, Ghosal at al. (2003) developed a novel cooling method with a moving water film over an external shade cloth for evaporative cooling work.

The microclimate model is a useful tool for design of greenhouses and evaluation of the performance of controlling equipments (Chen et al., 2011; Guillermo et al., 2011; Onder, 2009; Oz et al., 2009). Abdel-Ghany and Kozai (2006) developed a microclimate model to predict heat and vapor transfer in a naturally ventilated, fog-cooling greenhouse. Perdigones et al. (2008) tested ten cooling strategies for greenhouse cooling in summer. The cooling performance of fogging was linearly related to fogging rate. As compared with the cooling effects of a fixed fogging cycle and pulse width modulation (PWM) strategy, the water consumption by the PWM method could decrease by 8 to 15% (Perdigones et al., 2008). They emphasized that as the fogging technique was applied in the greenhouse, partially, water droplets were evaporated and absorbed the sensible heat of the greenhouse, and others fell on the plant leaf surfaces or the ground. The accumulation period of the water droplets on the leaf surface is called surface wetness duration (SWD) and is important in the development of plant disease (Magarey et al., 2005). Li et al. (2006) studied the performance of a high pressure fog system and found that air temperature, humidity and leaf temperature were affected by spraying rate, vent opening of the greenhouse and outside weather. A linear regression model was established to predict the cooling ability of fogging system. Katsoulas et al. (2006) tested the effect of the fogging performance of a greenhouse with a soilless pepper crop. The air temperature in the fogging greenhouse was 3°C lower than that measured under no fog.

A subtropical greenhouse with exhaust fans and pads could maintain an adequate microclimate for crop productions (Chen, 2003). Negative pressure fans were applied to support a 1.5-times ventilation rate. The wall of the greenhouse should be strong enough to resist the side pressure that is induced by these mechanical fans. The construction cost is high for this type of greenhouse. A high tunnel-type greenhouse was the other choice. This greenhouse structure is simple and inexpensive. With water for evaporation supplied by fogging or misting, the air pressure of ventilation could be supplied with natural wind or mechanical fans. The inside temperature could be reduced by evaporative cooling (Fatnassi et al., 2009). The water droplet size should be kept as small as possible to enhance the evaporative ability and to reduce the accumulation on leaf surfaces and the ground. The pressure of pumps is very high (usually > 70 kg cm^{-2}) to produce the 10 to 20 μm droplets. The cost of this pump device and nozzles is high. The water quality needs to be controlled to avoid the clogging of nozzles. An alternative is the misting cooling method. The droplet size of misting ranges from 290 to 450 μm. The required pressure of the misting pump is nearly 30 kg cm^{-2}, so the cost of this equipments and its maintenance is cheaper than that with the high pressure fogging system (Kumar et al., 2009).

The objective of this study was to evaluate the mist evaporation with mechanical fans in an *Oncidium* greenhouse. The cooling ability of misting operation with different interval times was tested. The microclimate data of this experimental greenhouse was collected and the cooling efficiencies were validated.

MATERIALS AND METHODS

Experimental greenhouse

An 11.0 × 30 × 3.5 m high, 1155 m^3 volume, plastic-glazed steel-framed structure greenhouse located at Taling, Chia-i county, Taiwan was selected. This area was the major production site of *Onicidium* in Taiwan. The weather of this area belongs to the subtropical climate regions. The transmittance was 50% for external and internal shading nets. The mechanical ventilation system consisted of 2 units of 135 cm diameter fan with 550 CMM (m^3 min^{-1}) capacity. *Oncidium* were planted in 5 inch plastic containers with regular medium and placed on fixed benches, 1.5 m height. The ratio of orchids to floor was nearly 70%. The misting droplets were produced with a 30 kg cm^{-2} pump with the fixed nozzles 2.0 m above the plants. The maximum misting rates was 3.6 kg min^{-1}.

Measuring devices

The specification of the measurement devices are listed in Table 1. The air temperature and relative humidity for greenhouse and inside air was measured by using of the Shinyei THT-B7 resistive-type transmitter (Shinyri Kaisha Company, Tokyo). The accuracy of these sensors was kept within 0.7% after calibration with saturated salt solutions. The sensors for air temperature and relative humidity measurement were placed in a radiation-shielded box including an aspiration fan. The inside solar radiation was detected by using of an E8-48 Pyranometers (Eppley Company, USA). The air velocity was measured by TSI 8450 air velocity transducer (TSI Co., St. Paul, MN USA). The measuring range of air velocity (V) was from 0 to 20 ms^{-1} and the accuracy was ± 1.5%. The plant's temperature was measured by inserting the thermocouples wires into the leaves and stems of plants and pot medium by using of the T-type thermocouples (Omega Engineering, USA). All thermocouple wires were connected to a Delta-T 2e data logger (Delta-T Company, UK). The accuracy of the temperature sensors was maintained within 0.15°C after calibration with the temperature calibrator (TC-2000, Instrutek, AS Norway). All signals of these devices were connected to a Delta-T2e data logger (Delta-T Company, UK). The recording interval (t_{ri}) was 30 s.

Table 1. Specification of the measurement sensors.

Parameter	Air temperature	Relative humidity	Solar radiation flux	Plant temperature	Air speed
Sensing element	PT-100 sensor	THP-B7J sensor	Thermopiles	Thermocouples T-type	TSI 8450 sensor
Measuring range	0-100°C	0-100 (%) RH	0-1000 Wm^{-2}	0-100°C	0-20 ms^{-1}
Accuracy	±0.15°C	±0.7%	±2%	±0.15°C	±1.5%
Manufacturer	Shinyei Kaisha company Tokyo Japan	Shinyei Kaisha company Tokyo Japan	Eppley company (Rhode Island, USA)	Omega Engineering (NL., USA)	TSI company (MN, USA)

Experimental procedure

The measuring range included the ambient temperatures and relative humidity, greenhouse air temperature and relative humidity, solar radiation, wind speed, and pot medium, leaf and stem temperature. The experimental setting of misting intervals were: 2 min on to 3 min off, 2 min on to 6 min off, 3 min on to 3 min off, 3 min on to 6 min off, 5 min on to 5 min off, 5 min on to 10 min off, 6 min on to 6 min off, 6 min on to 12 min off and continuous misting.

The misting efficiency

The misting efficiency (ME) is defined as follows (Katsoulas et al., 2006):

$$ME = \frac{T_{db,a} - T_i}{T_{db,a} - T_{wb,a}} \times 100\%$$

where, $T_{db,a}$ is the dry bulb temperature of the ambient air, T_i is the dry bulb temperature of the greenhouse temperature and $T_{wb,a}$ is the wet bulb temperature of the ambient air (all in °C).

RESULTS AND DISCUSSION

Characteristics of the microclimate in the *Oncidium* greenhouse

A typical microclimate of the *Oncidium* greenhouse for July 14, 2010 is presented in Figures 1 and 2. The maximal solar radiation in the greenhouse was nearly 355 Wm^{-2}. The sky was partly cloudy. The relative humidity of the ambient ranged from 50 to 80% RH. At the noon (12:00 to 14:00), the ambient relative humidity was nearly 50%. However, the internal relative humidity ranged from 65 to 85% because of the evaporation of the medium or soils. The ventilation was induced by natural wind, and the air exchange rate was nearly 0.15 h^{-1}. Temperature distributions are shown in Figure 2. Because of the accumulation of heat in the greenhouse, the greenhouse air temperature ranged from 30 to 40.5°C. The medium temperature was the lowest temperature because of the shading effect of *Oncidium* leaves. The temperatures of leaves and stems were 1.5°C lower on average than that of greenhouse air temperature. The higher temperatures of leaves and stems of *Oncidium* indicated that these plants were under the heat stress because of the lower ventilation rate of the greenhouse. In this case, the ventilation rate was low, no misting was supplied, and the solar radiation was the dominant energy source.

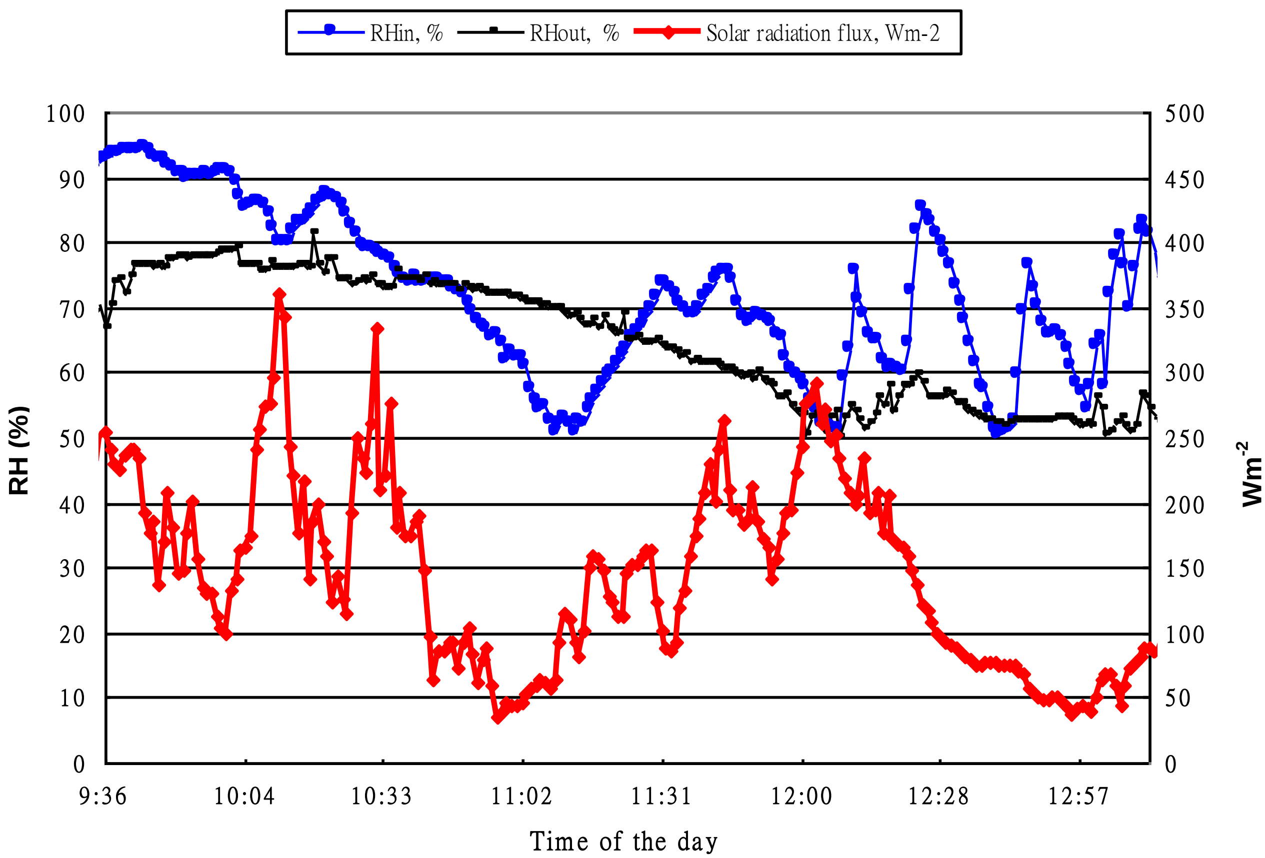
Effect of interval misting times on cooling performance

The results of the interval misting times on the cooling performance are presented in Figures 3 and 4. The interval time was 6 min on, 6 min off. The relative humidity of the inside air was increased with a 2 min delay. The delay in evaporation by misting could be explained by the lower evaporation efficiency. The size of misting droplets was from 200 to 250 μm. The time lag may be explained by the dynamical response of the water evaporation. The delay of the cooling effect was also reported by Abdel-Ghany and Kozai (2006). The temperature distribution of the misting cooling at the 6 min on-6 min off intervals is shown in Figure 4. The air exchange rate with the exhaust fans was 1.35 min^{-1}. Before the misting operation, the leaf and inside air temperature was 3°C higher than that of outside air. As the misting began, the leaf and inside air temperature reduced from 35 to 31.4°C; and as misting was inactive, the leaf and inside air temperature still decreased. Water droplets were partially evaporated and then absorbed the sensible heat of the inside air. Some water droplets fell on the leaf surfaces and ground. With misting off, the residual droplets began to evaporate and had a cooling effect on the inside air and plants.

The effect of different misting interval times on the relative humility is presented in Figure 5. With misting, the relative humidity was increased. The humidity still increased when misting stopped.

Table 2. The ME values of different experimental settings.

Experimental setting	Minimum (%)	Maximum (%)	Average (%)
2 min on to 3 min off	17.6	44.2	34.5
2 min on to 6 min off	23.8	47.1	34.6
3 min on to 3 min off	31.1	55.1	47.1
3 min on to 6 min off	32.5	53.1	41.1
5 min on to 5 min off	28.7	62.1	46.6
5 min on to 10 min off	28.1	64.2	40.5
6 min on to 6 min off	30.6	65.2	43.2
6 min on to 12 min off	31.9	57.2	40.1



Figures 1. A typical microclimate of the *Oncidium* greenhouse for 14 July, 2010.

The time lag of the evaporation of water droplets could be easily observed with changes in air relative humidity. The temperature distribution of the different misting interval times is shown in Figure 6. By the evaporative cooling function, the inside air temperature and the leaf temperature were lower by 2 to 4°C than that of the outside air temperature. The temperature range of leaves could be maintained under adequate conditions. However, the stem temperature showed serious fluctuation perhaps because of the shape of the *Oncidium* organs. The leaves are similar to a small bent stripe and could keep more water droplets on the surface. These droplets were evaporated and absorbed the heat of leaves. The stems of *Oncidium* are ellipse shapes and smooth surfaces, so droplets cannot easily stay on the stem surface. The lack of droplets on the plant's surface induced a fluctuation in temperature. The evaporative cooling efficiencies of the different interval times are listed in Table 2. The lower mean efficiencies were 32.5% for 2 min on to 3 min off, and 34.6% for 2 min on to 6 min off.

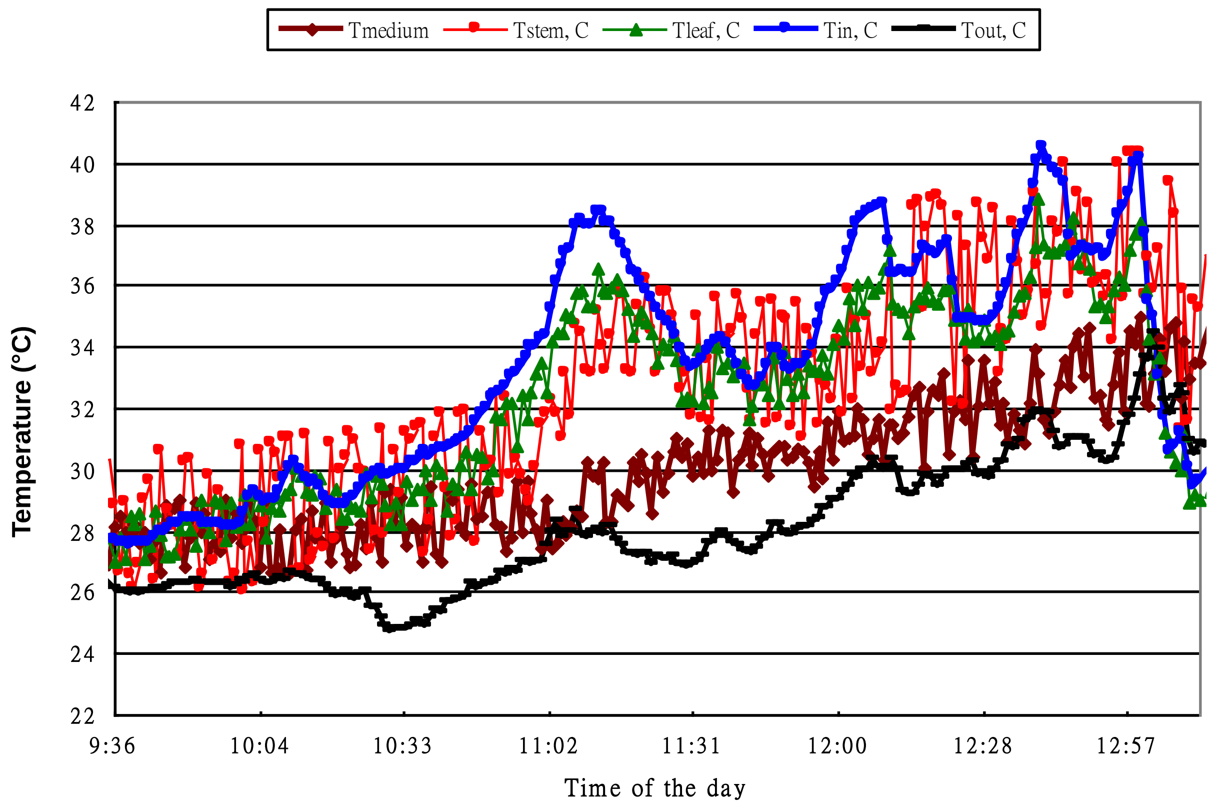


Figure 2. The distribution of temperatures of the *Oncidium* greenhouse for July 14, 2010.

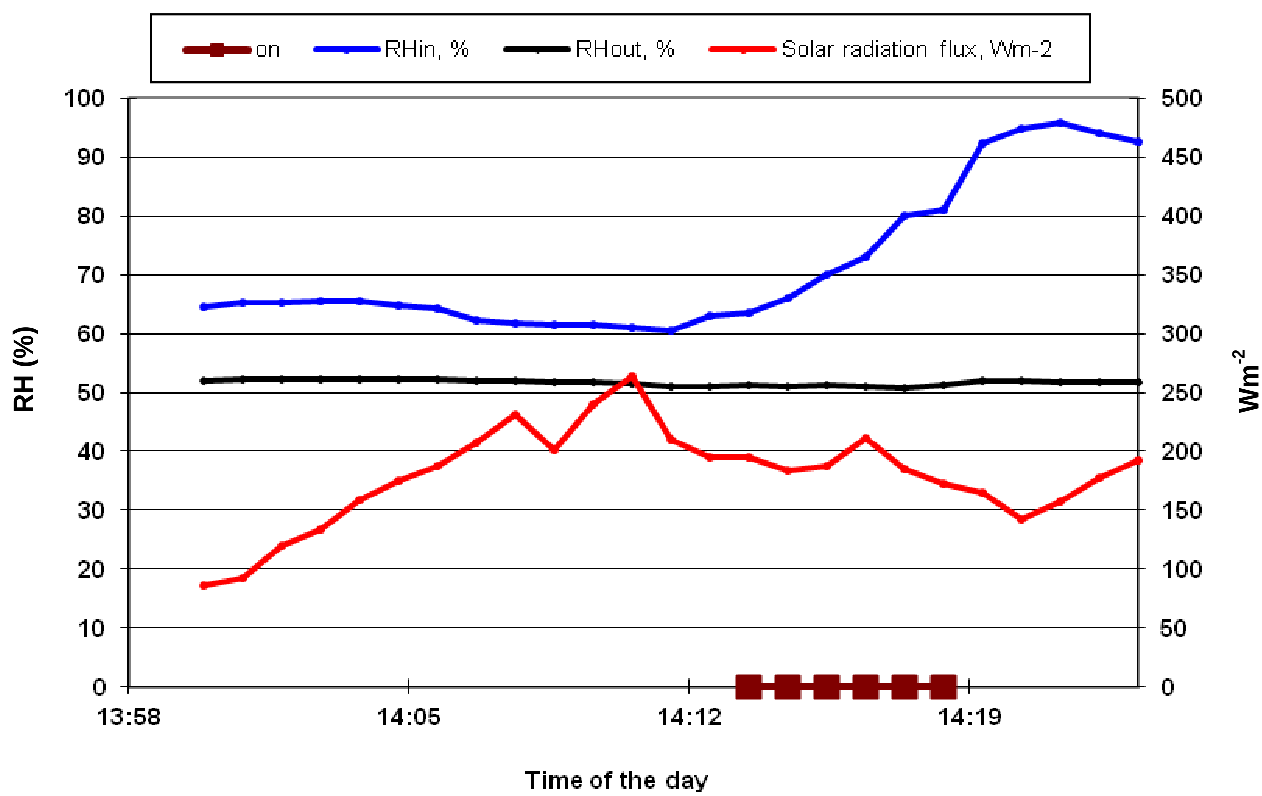


Figure 3. The solar radiation flux and relative humidity distribution with misting cooling of the 6 min on to 6 min off intervals.

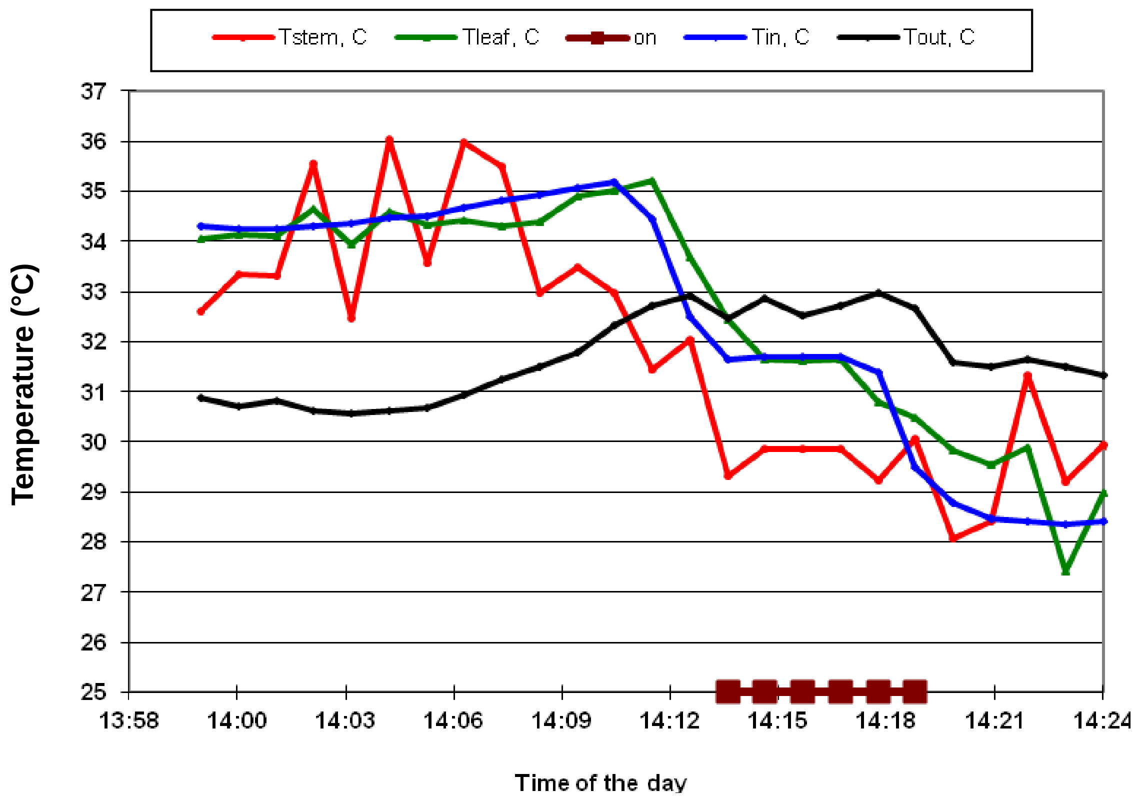


Figure 4. The temperature distribution with misting cooling at the 6 min on to 6 min off intervals.

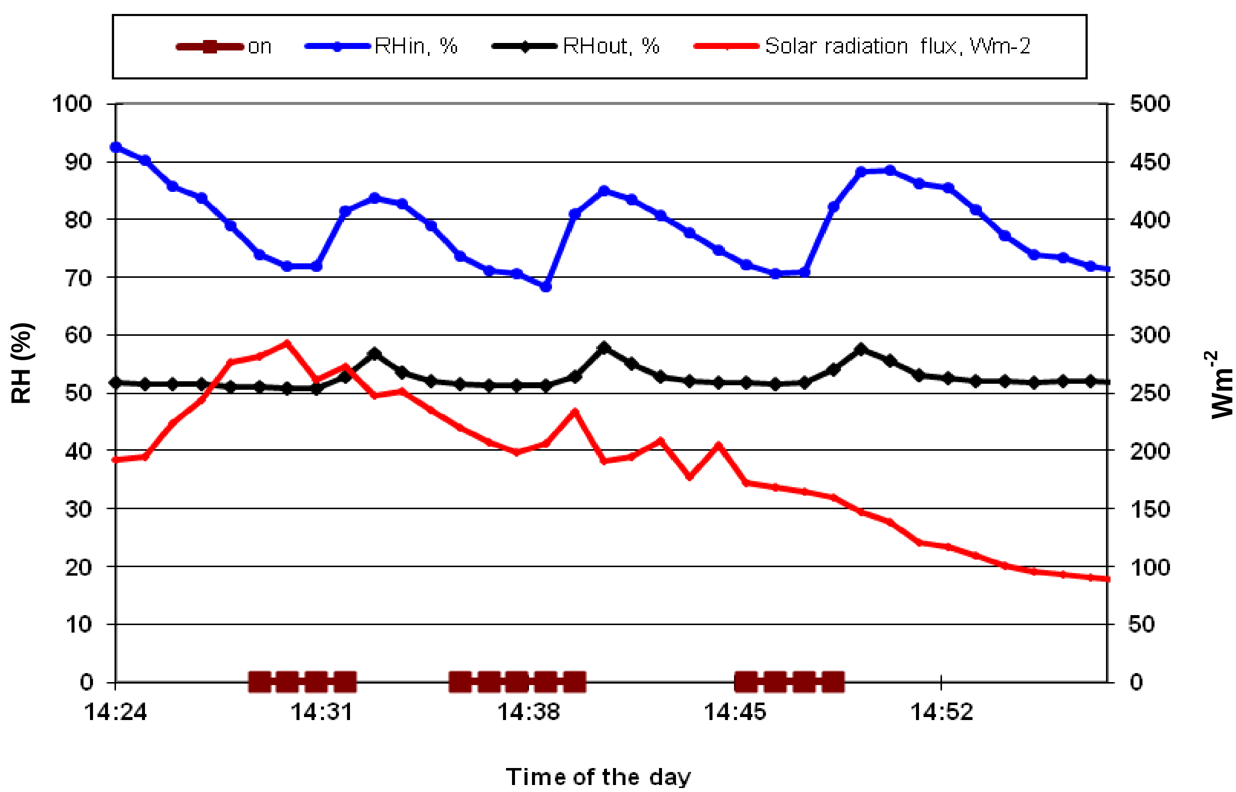


Figure 5. The solar radiation flux and relative humidity distribution with misting cooling at several misting interval times.

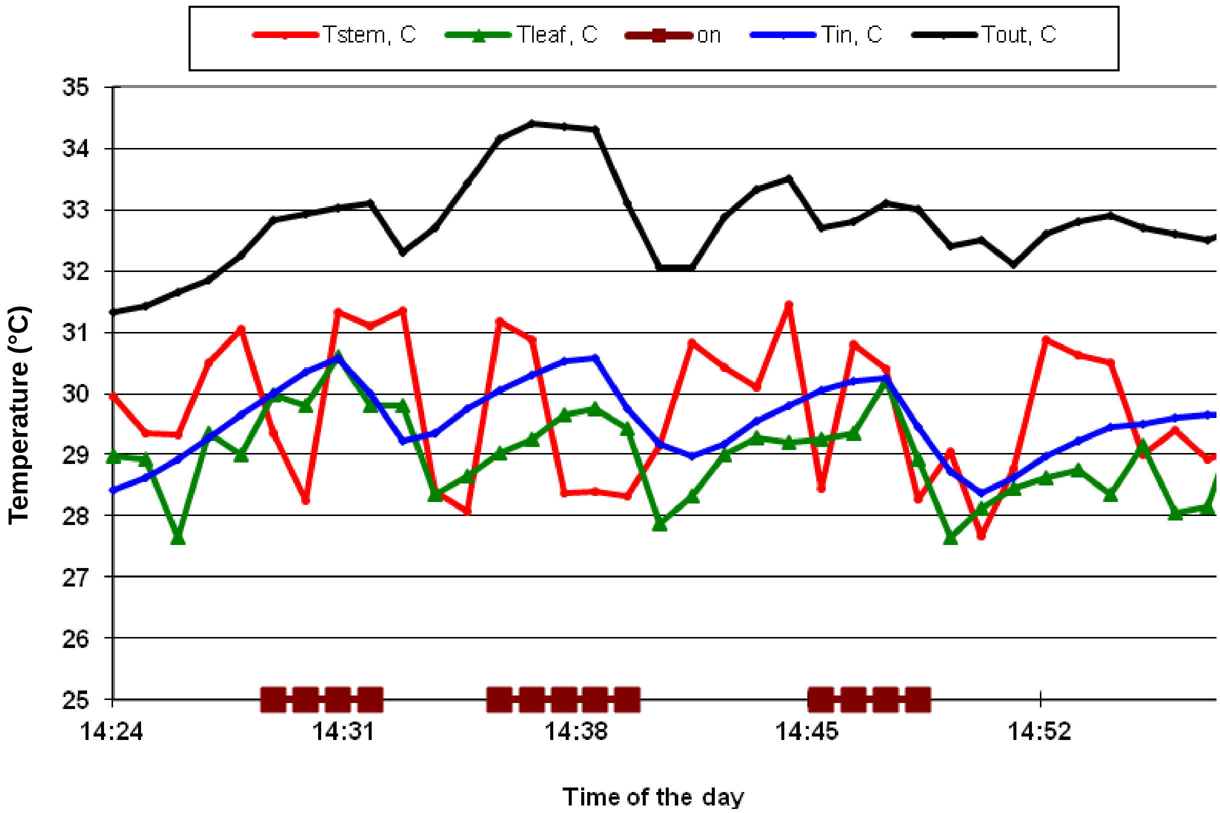


Figure 6. The temperature distributions with misting cooling at several misting interval times.

The higher mean efficiency was 47.1% for 3 min on to 3 min off, and 46.6% for 5 min on to 5 min off. With a higher time of active misting, 5 or 6 min, the longer inactive time of misting would decrease the mean efficiency. The results were found at the longer inactive time (for example, 5 min on to 10 min off, 6 min on to 12 min off). If the inactive time was too long, all water droplets were evaporated, for no water droplets is available to adsorb the sensible heat of the entering air, and the greenhouse air and leaf temperature were increased because of the heat accumulation in the greenhouse.

Continuous misting

In this test, the water feed rate was maintained at 2.4 kg min^{-1}, with misting operated from 13:10 to 16:00. The typical distribution of relative humidity of the ambient air and inside greenhouse is presented in Figure 7. The air relative humidity at this misting period was nearly 55%. The relative humidity of the inside greenhouse was higher than 75% RH. Sometimes, the relative humidity reached the saturated state. The typical temperature distribution with this test is shown in Figure 8. The air and leaf temperature was 4°C lower than that of the outside temperature. The leaf temperature could be maintained below 32°C. The stem temperature fluctuated. The mean evaporative efficiency was 62.5% with continuous misting, thus, continuous misting with less water feed rate was a promising way for cooling performance of the *Oncidium* greenhouse.

Conclusion

As a result of the simple structure and cheaper equipments, constructing a greenhouse with a misting system is cheaper than that with a pad-and-fan system for *Oncidium.* Such orchids can endure longer surface wetting, so the orchids greenhouse is suitable for the misting cooling system. In this study, the different interval times of misting were tested. The cooling performance of the leaves and stems for *Oncidium* was validated. The evaporative efficiency was affected by the misting interval time. If the misting time was too short or the misting inactive period was too long, the efficiency was decreased. Nine experimental setting of misting intervals were tested. The misting efficiency is defined and served as the performance index. The misting intervals of 3 min on to 3 min off or 5 min on to 5 min off had the higher efficiency. Continuous misting and lower water feed rate could appropriately modify the microclimates of the

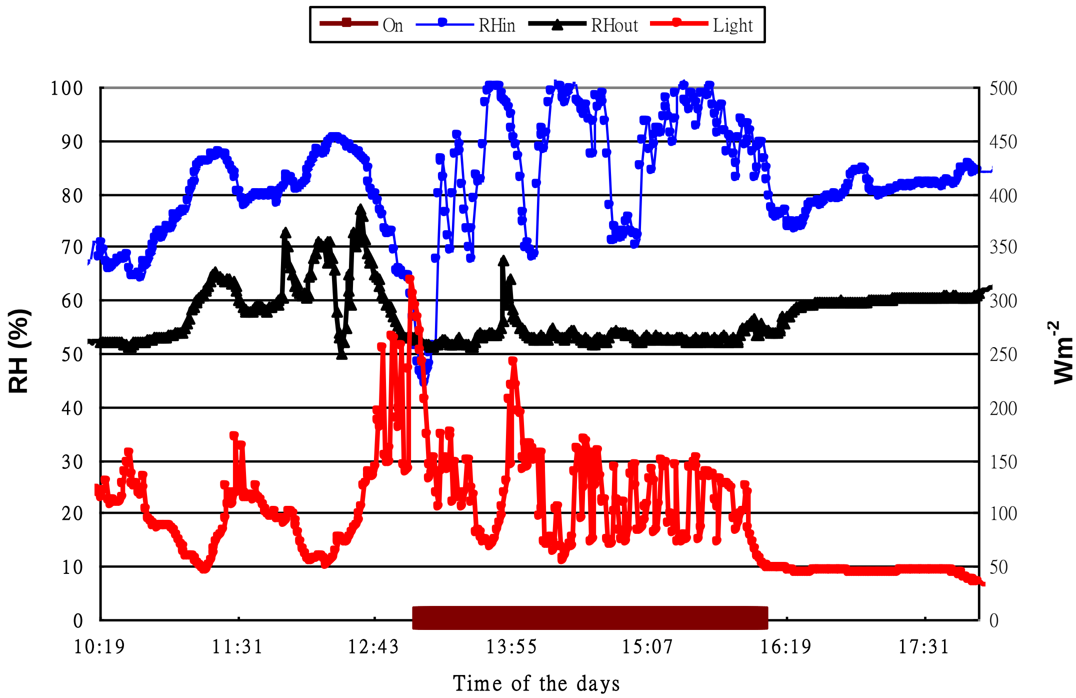


Figure 7. The solar radiation and relative humidity distribution with continuous misting cooling.

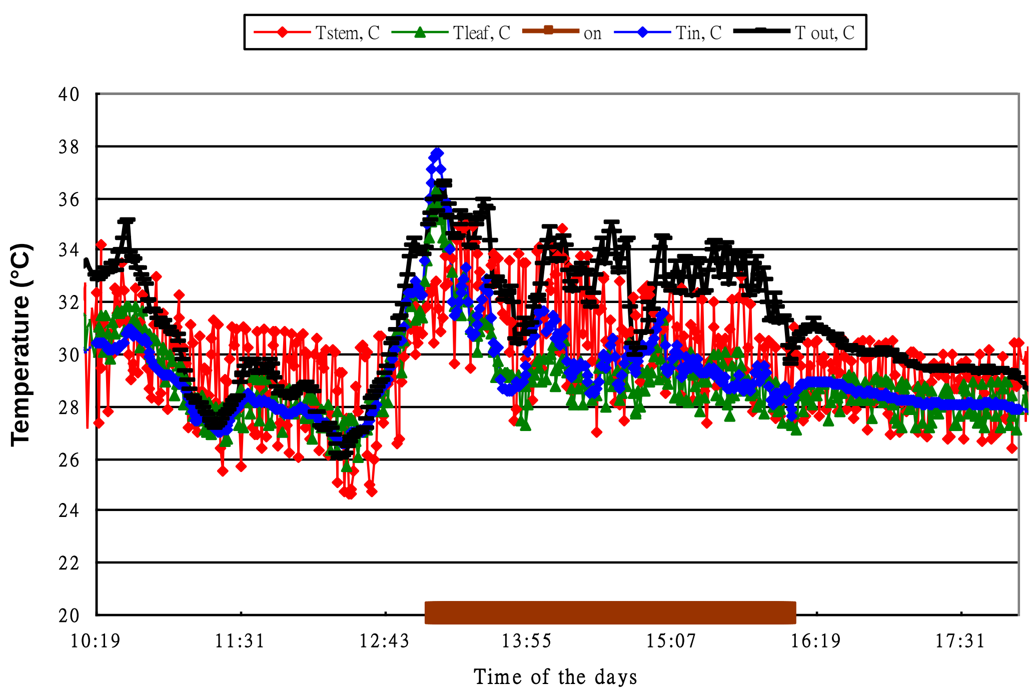


Figure 8. The temperature distribution with continuous misting cooling.

greenhouse for *Oncidium* culture. It provides a simple way to apply the misting technique. Future studies will focus on the long-term stability of the misting system, the effect of the quantity and quality of flowers, and the possibility of disease development. This technique can be applied to other protected structures of *Oncidium* and other orchids.

ACKNOWLEDGEMENT

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No NSC-95-2313-B-005-019.

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