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REVIEW

Controlled Environment Agriculture for Effective Plant Production Systems in a Semiarid Greenhouse

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Abstract

Semiarid climate regions have great potential for productivity due to large amounts of solar radiation throughout year. However, these regions also have disadvantages, such as excessive air temperature and limited water use. Optimizing the ventilation rate and evapotranspiration during fog cooling in combination with natural ventilation will provide more favorable growing conditions for plants in a semiarid climate and allow less water use. A single-span greenhouse at The University of Arizona was used to investigate the fog cooling performance on clear days with excessively high air temperature. The environmental conditions and the natural ventilation rate were measured. The performance of fog cooling in combination with natural ventilation was compared with pad-and-fan cooling. Fog cooling and pad-and-fan cooling used 24 g m^{-2} min^{-1} and 41 g m^{-2} min^{-1} of water, respectively. The air relative humidity for fog cooling was slightly higher than that for pad-and-fan cooling, at approximately 35%. An English version of Visual VETH (ventilation-evapotranspiration-temperature-humidity) software was also developed. A cooling strategy devised for semiarid greenhouses found that the air relative humidity inside a greenhouse decreased with an increase in ventilation rate as expected from simulation based on steady-state energy balance equations, while the water use for fog cooling increased. A simple and unique control algorithm for fogging and ventilation inlet openings demonstrated the possibility of maintaining relative humidity and air temperature simultaneously within a desirable range while reducing the water use for fog cooling. The tomato plant canopy transpiration rate and the water balance relative to the natural ventilation rate in a fog-cooled greenhouse were also investigated. The transpiration rate increased linearly with an increase in vapor pressure deficit (VPD) of the air. At a lower ventilation rate made possible by reducing the ventilation inlet openings, total water use in the greenhouse decreased by 13% and relative humidity increased as was expected from the steady-state energy balance simulation. The decrease in canopy transpiration resulted from the decrease in VPD, and was at a magnitude greater than that of the fog evaporation rate under similar experimental conditions with relatively high humidity in the range of 70-94%. By optimizing the natural ventilation rate, the greenhouse could be effectively cooled with less water use. Arizona can be considered a model analogous to many other semiarid climate conditions. Due to the long history of greenhouse technology development, the application of greenhouse crop production to an area with excessive radiation and dry air remains a relatively new effort. We believe that our efforts will contribute not only to the American Southwest but also to enhancing the application of greenhouse technology for crop production in these climate regions worldwide, including Mexico, China, the Middle East and Africa.

Discipline: Agricultural Engineering / Horticulture
Additional key words: air temperature, evaporative cooling, natural ventilation, relative humidity, water use

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Introduction

Greenhouses provide an enclosed growing environment that can be controlled year-round. This allows intensive culture with annual yields as much as 10 times greater than that for field production. Greenhouse production overcomes climatic diversity and enhances the use of the sun's free energy. The use of greenhouses for crop production has been increasing worldwide, particularly in areas where cooling is an essential component of climate control. Typical and economical methods of preventing excessive rises in temperature are ventilation to exchange internal air with cooler external air, shading to reduce incoming solar radiation, and evaporative cooling.

Semiarid climate regions such as the southwestern United States and Mexico have great potential for productivity due to clear sky conditions much of the year. Arizona is the largest greenhouse vegetable producer in the USA, with 100 ha of total area (Giacomelli 2005). In the USA, greenhouses account for a total area of 8,425 ha, while Mexico has more than 11,759 ha of greenhouse area (Kacira 2011). However, both must overcome high air temperature and limited water use. Moreover, ventilation required for cooling leads to unacceptably low relative humidity inside greenhouses located in a semiarid climate. To cool the greenhouses, traditional pad-and-fan evaporative cooling systems have been widely adopted. Alternatively, fog cooling combined with natural ventilation has the potential to provide improved spatial uniformity and reduced operating costs. For more efficient utilization of fog cooling, optimum control of both the rate of water use for fog and natural ventilation is important. The natural ventilation rate, amount of injected water, and weather conditions affect both the cooling performance and water use.

Optimizing the ventilation rate and evapotranspiration during fog cooling will provide more favorable growing conditions for plants in a semiarid climate and less water use. Previous studies on fog cooling in combination with natural ventilation have been limited and concerned more with fog cooling combined with fan ventilation (Giacomelli and Roberts 1989, Arbel et al. 2003). Montero et al. (1990) compared the climates in naturally ventilated greenhouses with and without fogging. Hayashi et al. (1998) evaluated the performance of fog cooling for a three-span glasshouse with a fully open hinged ridge vent and a sliding-door type side vent. When fog was generated intermittently for 1 min every 5 min, the inside air temperature decreased 8ºC and 4ºC on average, approaching the inside wet-bulb temperature within 1 min after fogging started and then increasing after the fogging ended, resulting in a cyclic temperature change. Handarto et al. (2005) investigated the effects of fogging duration on the greenhouse climate and the evaporative cooling efficiency using a single-span greenhouse with ridge and side vents. Ishii et al. (2014) investigated the relations between the ventilation rate (as a function of inlet vent configuration) and internal/external environmental conditions in a naturally ventilated greenhouse with a high pressure fogging system. These studies were completed in temperate climate regions. In semiarid climate regions, the air temperature is higher and relative humidity lower than in temperate climates. For example, the maximum air temperature and minimum relative humidity in Tucson, Arizona reach 39ºC and 7%, respectively. Evaporative cooling will reduce the inside air temperature of semiarid greenhouses as compared with greenhouses in temperate climate regions with higher outside relative humidity.

The primary objective of this research project was to investigate the performance of fog cooling combined with natural ventilation in a semiarid climate. The overall goal was to develop an effective environmental control strategy for providing a suitable greenhouse environment for plant production and minimizing water use.

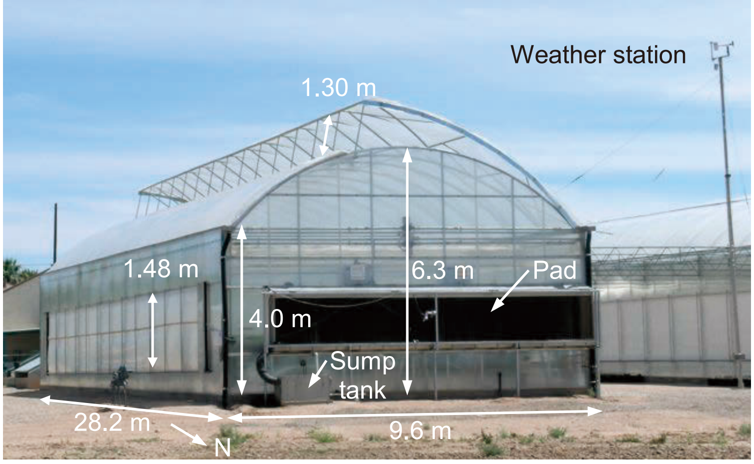
Materials and methods

1. Experimental greenhouse

The experiments were conducted in a single-span arch roof greenhouse (PolyTex Inc., USA) located at an altitude of 732 m, in The University of Arizona Controlled Environment Agriculture Center, Tucson, Arizona, USA (32.3° N, 110.9° W). The greenhouse floor area was 270 m^2 (28.2 m in length and 9.6 m in width). The height of gutters was 4.0 m and ridge height was 6.3 m. The direction of the greenhouse gutters was rotated from the north-south direction (15°). The gable end walls were covered with double-walled polycarbonate, with the sidewalls being covered with a single layer of polyethylene, and the roof with an air-inflated polyethylene double film. The roof opened at the ridge, hinging at the gutter to a maximum of 1.30 m. The sidewalls included a vent with a maximum opening of 1.48 m. The sidewall inlet openings were covered by an insect screen 0.28 mm in diameter with an opening ratio of 0.25 (Fig. 1). The roof inlet vent opening did not include an insect screen. The greenhouse floor was covered with gravel stone.

2. Pad-and-fan cooling system

The pad-and-fan system (Val-Co, USA) consisted of a 0.15-m thick cellulose pad located on the north gable end wall that was 8.5 m in width and 1.2 m in height, with the bottom edge 1.3 m above ground level. Water was pumped continuously to an overhead distribution trough, which fed water to the pad via gravity. Once the pad was saturated, all residual water that had not evaporated from the pad was returned to the sump tank. Water that evaporated from the pad was continually replenished with a makeup water



North gable end (Pad)

South gable end (Fan)

Inside greenhouse (on fog cooling)

Fig. 1. External view of the experimental greenhouse and the weather station

source that maintained a constant sump tank volume. Two exhaust fans were located at the south gable wall end of the greenhouse (Fig. 1). The belt-driven fans 1.2 m in diameter ("FSF" Model: GS48G600MGA, Val-Co, USA) were powered by a 0.746 kW electric motor. Pad-and-fan tests were completed with the roof and side vents both fully closed.

3. High pressure fog cooling system

The greenhouses were equipped with a network of high-pressure fog nozzles (Val-Co, USA), at a height of 3.1 m above the floor. There were 68 nozzles with an orifice size of 0.2 mm installed 0.30 m apart in one line at the center of the greenhouse, and extending its length. The nominal size of water droplets generated was 15 µm at an operational pressure of 10 MPa using a 3.7 kW electric motor powered pump. Measurements revealed that continuous fogging provided 25.95 g m^{-2} min^{-1} (103.3 g min^{-1} per nozzle).

4. Observation

The greenhouse environments and outside weather conditions were monitored (Fig. 2). An aspirated psychrometer using copper-constantan thermocouples (0.32 mm diameter) was installed at a height of 1.8 m in the center of the greenhouse. Pyranometers (MS-62, Eko Instruments Co., Ltd., Japan) were installed to measure downward and upward solar radiation in the greenhouse. Outside the greenhouse, a 10-m mast was equipped with a propeller-type vane anemometer (05103-L R.M. Young wind monitor, Campbell Scientific, Inc., USA), a temperature and relative humidity sensor (HMP45C-L, Campbell Scientific, Inc., USA) in a naturally aspirated radiation shield, and a LI-200 pyranometer (LI-COR, Inc., USA). The sensors were connected to two data loggers (CR21X and CR23X, Campbell Scientific, Inc., USA). All sensors sampled every 10 s and values were averaged at 60-s intervals. The sap flow rate was continuously measured using a SGA13 stem gage (Dynamax Inc., USA) in combination with a data logger (23X, Campbell Scientific, Inc., USA). Three stem gages were installed on different tomato plants, and evenly distributed in the greenhouse. The canopy transpiration rate per unit floor area was determined by multiplying the average sap flow rate by planting density, and then recording the 30-min averages.

5. Ventilation measured

The natural ventilation rate was measured continuously using the tracer gas method. The measurement system

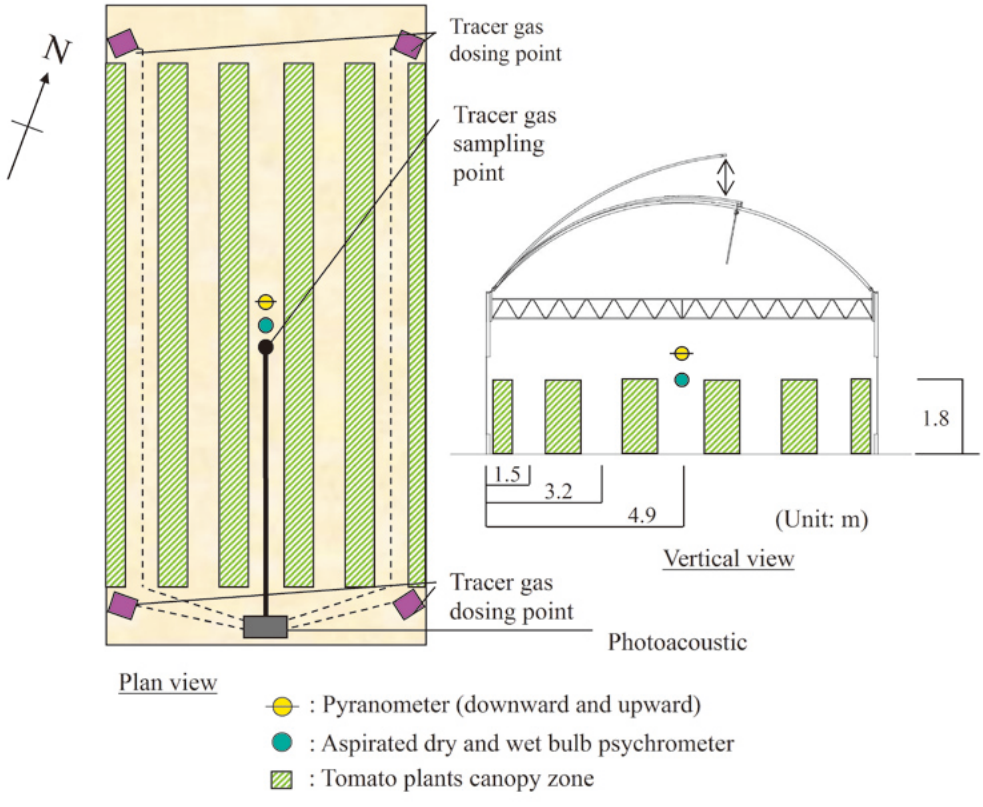


Fig. 2. Objective greenhouse and measuring points

consisted of a 1312 Photoacoustic Multi-gas Monitor (Innova AirTech Instruments A/S, Denmark), 1303 Multipoint Sampler and Doser (Innova AirTech Instruments A/S, Denmark), 7620 Application Software of the Tracer-gas Monitoring System (Innova AirTech Instruments A/S, Denmark), and a personal computer. The measurement of ventilation rate was based on the constant concentration method. A tracer gas (sulfur hexafluoride, SF_6) was supplied at four corners of the greenhouse and sampled in the center of the greenhouse (Fig. 2). The advantage of using SF_6 gas is that it does not affect plants and humans. Gas injection was regulated to maintain concentration at a constant level of 5 ppm. The ventilation rate was calculated from the amount of gas supplied and recorded at approximately 50-s intervals, according to the method described by Ikeguchi et al. (2005).

The ventilation rate (expressed as internal air volume changes per second) was calculated from data measured during a period, to obtain a more accurate value (Innova 1998) using the following equation:

$$V_s = \frac{(G_t / H_v + (\overline{C}_{k\text{-}p} - \overline{C}_k)) / T_a}{\overline{C}_{avg} - C_b} \tag{1}$$

where V_s denotes the ventilation rate, s^{-1}; H_v the volume of the greenhouse, m^3; T_a the averaging period, s; G_t the total dose of tracer gas delivered in the period T_a, mg; $\overline{C}_{k\text{-}p}$ the Kalman-filtered concentration measured at the start of the averaging period, mg m^{-3}; $\overline{C}_k$ the Kalman-filtered concentration measured at the end of the averaging period, mg m^{-3}; $\overline{C}_{avg}$ the average Kalman-filtered concentration in the averaging period, mg m^{-3}; and C_b the background concentration of tracer gas at the measurement location, mg m^{-3}.

The ventilation rate (expressed as internal air volume changes per hour) was calculated from V_s as follows:

$$V_h = V_s \cdot 3600 \tag{2}$$

where, V_h denotes the ventilation rate, h^{-1}.

The ventilation rate (expressed as internal air changes per minute of floor area) was calculated from V_s as follows:

$$V_{mf} = \frac{V_s H_v}{A_f} 60 \tag{3}$$

where, V_{mf} donates the ventilation rate, m^3 m^{-2} min^{-1}; and A_f the floor area of the greenhouse, m^2.

6. Visual ventilation-evapotranspiration-temperature-humidity (VETH) chart software

The concept of the VETH (Ventilation-Evapotranspiration-Temperature-Humidity) chart was introduced (Mihara 1980) to better understand and effectively present the relations between greenhouse evaporative cooling, ventilation, evapotranspiration, air temperature and relative humidity. Based on this concept, interactive Visual VETH software was first developed in a Japanese Windows environment (Fukuda and Hayashi 2004), and later Kubota et al. (2006) developed an enhanced English version to make the software available for greenhouse engineers, teachers, and students in controlled environment agriculture worldwide. This software can create VETH charts automatically based on the input data of environmental conditions inside and outside the greenhouse, and the physical properties of the greenhouse, based on a greenhouse steady state energy balance. Use of the VETH chart was particularly helpful for greenhouse design with a cooling system, especially when introducing fog cooling systems, for which available information and design standards are limited. VETH charts can also be used to assist in the design of more conventional pad-and-fan cooling systems through estimation of the resulting air temperature and relative humidity of air exhausted by mechanical fans providing the selected ventilation rates.

Results and discussion

1. Comparison between pad-and-fan and high pressure fog cooling systems

Sase et al. (2005) compared pad-and-fan and high pressure fog cooling greenhouses in a semiarid climate region. Without plants growing inside the greenhouses, the evaporative cooling performance and water use were investigated in October 2004. The outside weather conditions and inside environments were monitored. Pad-and-fan tests were completed with both the roof and side vents fully closed, and with two exhaust fans operating. During the fog cooling tests, the roof and side inlet vents were fully open and the fogging system was continuously operated. The inside air temperature under fog cooling was similar to that under pad-and-fan cooling (Table 1).

The water use for fog cooling was 24 g m^{-2} min^{-1} and significantly less than 41 g m^{-2} min^{-1} required for pad-and-fan cooling. The relative humidity with fog cooling was slightly higher than that with pad-and-fan cooling, but still approximately 35%. This suggested that a lower ventilation rate could improve the humidity condition for plants at a constant target temperature.

When cyclic fogging for 45 s every 120 s at an average injection rate of 8.9 g m^{-2} min^{-1}, the ventilation rate was independent of wind velocities below 2 m s^{-1}, while slightly dependent on wind direction. The ventilation rate increased when wind blew into the roof vent opening, and decreased when wind blew parallel to the greenhouse gutters.

In Figure 3, (a) shows the effect of ventilation rate on the difference between inside and outside air temperature from 12:00 to 13:00 on a clear day with an outside solar radiation peak of 818 W m^{-2}, and with only the roof vent of the greenhouse being fully open. The temperature difference was negatively correlated with the ventilation rate, as was expected from the energy balance of the greenhouse. The inside relative humidity had a similar relation (Fig. 3 (b)). For example, the temperature difference and relative humidity increased from 2.6ºC and 18% up to 4.6ºC and 47%, respectively, when the ventilation rate was decreased from 20 to 5 h^{-1}.

The average temperature difference, relative humidity, ventilation rate and outside wind velocity during the 12:00 to 13:00 time period were 4.1ºC, 40%, 8.4 h^{-1}, and 1.1 m s^{-1}, respectively. In contrast, when both the roof and side vents were fully open under almost similar solar radiation from 11:00 to 12:00 on the same day, those same values were 3.2ºC, 33%, 9.7 h^{-1}, and 1.2 m s^{-1}, respectively.

From these results it was concluded that by optimizing the natural ventilation rate, we could effectively cool the greenhouse with less water using fog evaporative cooling.

2. VETH application example of a semiarid greenhouse

In order to demonstrate the application of an English version of Visual VETH chart software, Kubota et al. (2006) discussed a cooling strategy for semiarid greenhouses where water use for evaporative cooling is considered significant. In semiarid greenhouses, the water use for cooling is not negligible, as evaporative cooling is necessary to grow plants inside a greenhouse during a significant period of time (from late spring to early fall), in order to maintain nearly optimum air temperature for plant growth.

Figure 4 shows the main menu and VETH Chart Drawer windows. Although this software expects users to have a certain level of familiarity with the greenhouse energy balance and terminology, such as the overall heat transfer coefficient specific to glazing, the users' manual assists users in selecting values for the parameters.

Figure 5 shows the effect of ventilation rate on the evapotranspiration rate needed for cooling a single-span glass greenhouse to 25°C air temperature and the resulting relative humidity inside the greenhouse (plotted with output

Table 1. Preliminary comparison between fog cooling and pad-and-fan cooling (Sase et al. 2005)

	Continuous fogging with fully-opened side and roof vents	Pad-and-fan cooling
Air temperature (ºC)	31.7	31.5
Relative humidity (%)	34.8	28.2
Water use (g m^{-2} min^{-1})	24	41
Inside solar radiation (W m^{-2})	360	495

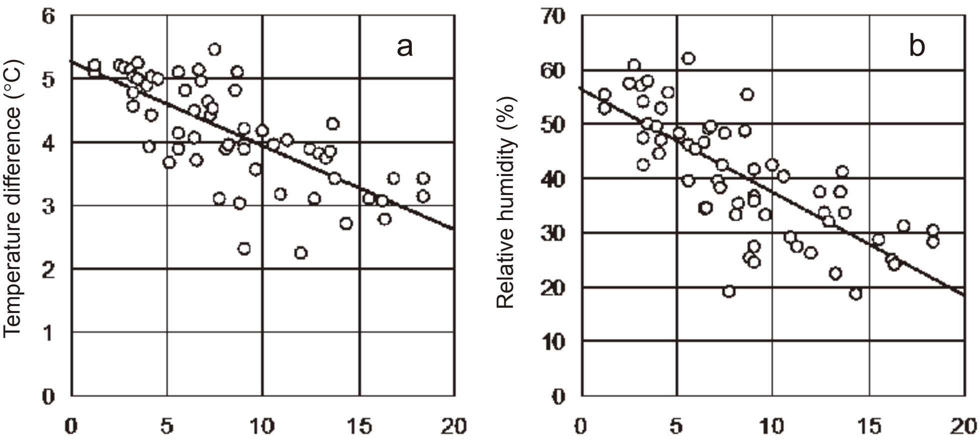
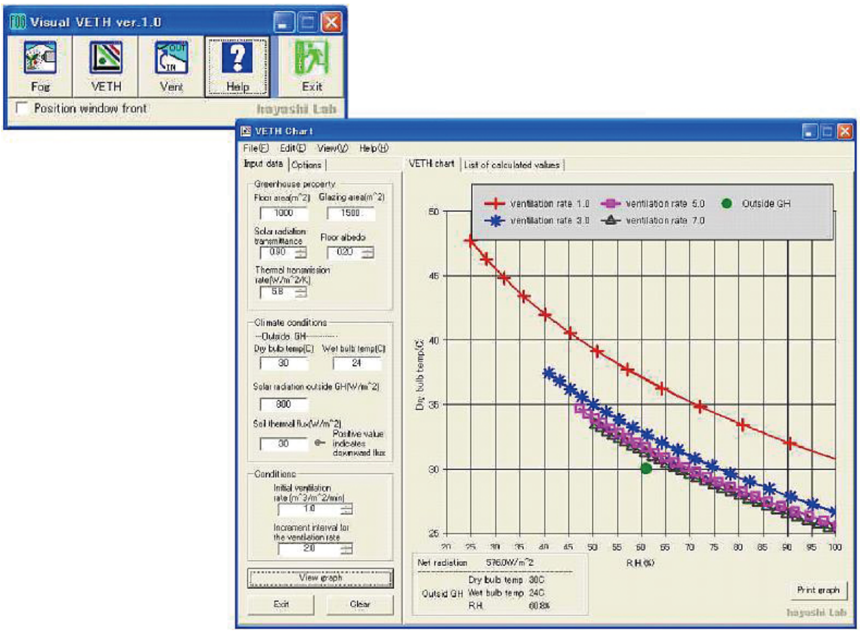


Fig. 3. Effect of ventilation rate on the difference between inside and outside air temperature (a) and inside relative humidity (b) under cyclic fogging with only the roof vent fully open (Sase et al. 2005)



Greenhouse property
Floor area(m^2) 1000
Glazing area(m^2) 1500
Solar radiation transmittance 0.90
Floor albedo 0.20
Thermal transmission rate(W/m^2/K) 5.8

Climate conditions
Outside GH
Dry bulb temp(C) 30
Wet bulb temp(C) 24
Solar radiation outside GH(W/m^2) 800
Soil thermal flux(W/m^2) 30
Positive value indicates downward flux

Conditions
Initial ventilation rate (m^3/m^2/min) 1.0
Increment interval for the ventilation rate 2.0

Net radiation 576.0W/m^2
Outsid GH Dry bulb temp 30C
Wet bulb temp 24C
R.H. 60.8%

Fig. 4. Visual VETH main menu window and VETH Chart Drawer window, presenting four sets of VETH charts (curves of coordinates of air temperature and relative humidity at four ventilation rates ($m^3\ m^{-2}\ min^{-1}$)) under the given set of greenhouse and outside climate conditions. Each symbol in the chart denotes a coordinate of dry bulb temperature and relative humidity outside the greenhouse at a given evapotranspiration rate (ET) occurring inside the greenhouse. The initial plotted value (left most) on each curve is the coordinate of temperature and relative humidity at ET = 1 g $m^{-2}\ min^{-1}$. ET increases by 1 g $m^{-2}\ min^{-1}$ for each additional plotted value (toward the right) on the same curve, showing that increasing ET lowers the air temperature and increases relative humidity. For further information, refer to the Visual VETH Users Manual (available for download from the Worldwide Greenhouse Education Website: http://www.uvm.edu/wge) (Kubota et al. 2006)

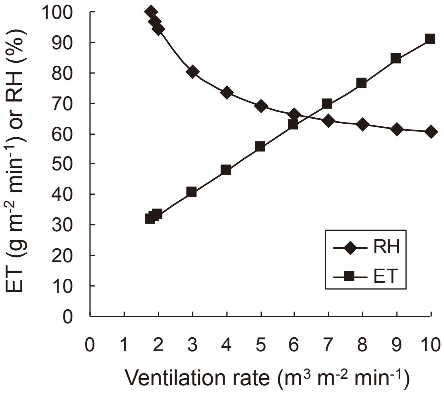


Fig. 5. Effect of ventilation rate on the evapotranspiration rate (ET) needed for cooling a single span, glasshouse to 25°C air temperature and resulting inside relative humidity (RH) in the greenhouse (plotted with output values estimated by Visual VETH) (Kubota et al. 2006)

values estimated by Visual VETH). The outside conditions used for the calculation were 40°C, 10% relative humidity, and 1000 W m^{-2} solar radiation. Some greenhouse characteristic parameters include 596 m^2 glazing and 269 m^2 floor area, 70% solar radiation transmittance of glazing, 15% albedo inside surfaces, 0 W m^{-2} ground heat flux, and 5.8 W m^{-2} K^{-1} overall heat transmission coefficients. At a ventilation rate of 1 $m^3\ m^{-2}\ min^{-1}$, relative humidity reached the saturation point and prevented air temperature from reaching the set point (25°C). However, the amount of water needed for cooling varies considerably under different outside air temperature and radiation conditions. The ventilation rate of the greenhouse should be manipulated to reduce the water consumption for evaporative cooling, as the amount of water required for the evapotranspiration rate (ET) increases with increasing ventilation rate. Evapotranspiration is the total amount of water evaporated through plant transpiration and from the evaporative cooling system; therefore, if the greenhouse is empty or the plants are very small, the evaporative cooling system should account for most of the evapotranspiration.

The wet-bulb temperature outside a greenhouse is the lowest theoretical temperature that could be achieved inside the greenhouse when using evaporative cooling; therefore, under humid conditions (or when wet-bulb temperature outside the greenhouse is close to the target air temperature inside), enhancing the ventilation rate and air circulation is the most common strategy employed to increase evaporation and cooling efficiency. Compared with such conventional greenhouse situations in humid and temperate climate regions, the air temperature inside semiarid greenhouses can be reduced relatively easily to the set point due to relatively low wet-bulb temperature.

Figure 6 shows an example of the VETH chart software. In this example, potential mid-day air temperature and relative humidity inside a single polyethylene (PE) greenhouse located in dry highlands in Guadalajara, Mexico, were computed using the VETH software. Mid-day air temperature and relative humidity inside a single-span polyethylene greenhouse were simulated varied ventilation rates with tomato plants or without plants inside the greenhouse (outside midday conditions: 33°C air temperature, 11% relative humidity, and 1200 W m^{-2} solar radiation). The evapotranspiration rate from the plants is assumed to be constant at 18 g m^{-2} min^{-1}. This estimation assisted growers in understanding the influence of plants in greenhouse temperature control and the necessity of a humidification system when air is likely to be too dry for plant growth.

3. New strategy of controlling ventilation in semiarid regions to save water use

Sase et al. (2006) proposed a unique control algorithm that incorporates the adjustment of vent openings. Observations were completed in the greenhouse without plants growing early in June 2005. Fogging was operated cyclically by on-off control with an air temperature set point of 24.5°C, and with lower and upper limits of 24°C and 25°C, respectively. The minimum duration for continuous fogging was 20 s due to mechanical limitations of the fogging system. The fog generated was collected from three nozzles and measured at 15-min intervals. Plastic petri dishes were placed on the greenhouse floor to evaluate non-evaporated water droplets. In some cases, the vent position was manually maintained at a constant opening.

The following new control algorithm was proposed and tested:

– Rule 1: Use fogging (on-off control) to control air temperature.
– Rule 2: Adjust vent openings (proportional control) to control relative humidity.

Figure 7 shows an example of preliminary results of the control algorithm on a clear day with target ranges of 24-25°C and 65-75% set for air temperature and relative humidity, respectively. The side openings were controlled by the algorithm (Rule #2), while the roof vent was kept at a fully open position. The proportional gain was determined experimentally by try-and-error method. For the side vents with insect screens, the gain (adjustment of opening) was 25% to a difference of 5% between the observed range and target range in relative humidity. The control action was made at 15-min intervals.

As shown in Fig. 7, the side openings were initially set at 50% and then were shortly closed by 25% due to the observed low relative humidity. When the relative humidity increased to the upper limit of the target range before noon due to variations in the outside conditions, the side openings were opened by 50%. As a result, both relative humidity and air temperature were maintained nearly within the target ranges, even though the side openings were not frequently adjusted. The data for fixed side openings of 100% are also showed in Fig. 7 as a control. The relative humidity was lower than the target range, when the side openings were kept at 100%. The average water use in Fig. 7 for fog cooling under the control algorithm was 14.0 g m^{-2} min^{-1} and 21% less than 17.7 g m^{-2} min^{-1} for the control with fixed side openings at 100%.

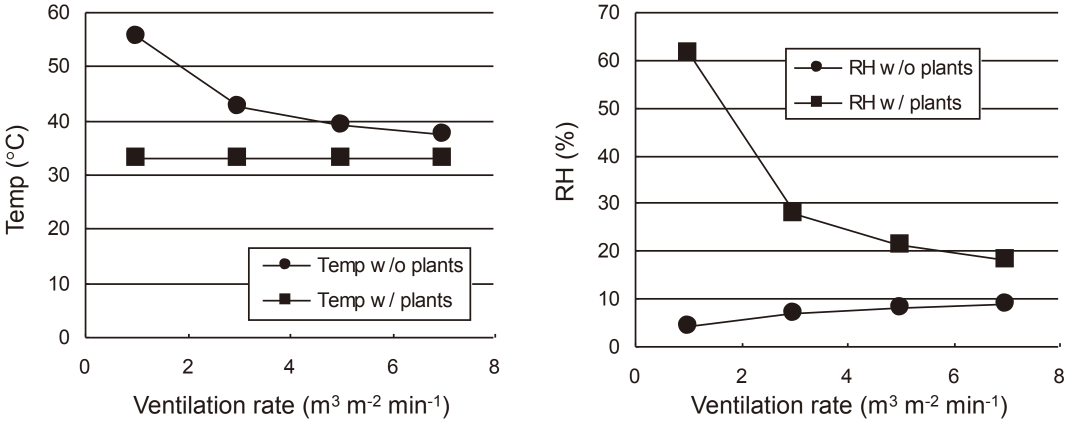


Fig. 6. Simulated mid-day inside air temperature (Temp) and relative humidity (RH) in a single span polyethylene greenhouse located in Guadalajara, Mexico, at varied ventilation rates with tomato plants (w/plants) or without plants (w/o plants) inside the greenhouse (Kubota et al. 2006)

These results demonstrated the possibility of maintaining relative humidity and air temperature simultaneously within a desirable range while reducing the water use for fog cooling.

4. Effective environmental control strategy to cool plant production greenhouses and minimize water use in a semiarid climate

Sase et al. (2007) and Ishii et al. (2006) investigated the effect of the natural ventilation rate on humidity and water use for fog cooling, with the side vent openings was manually adjusted from 0% to 100% at 45-min intervals, and with the roof vent fully open in May 2005 (in Tucson, Arizona). Tomato plants (cv. Durinta) were grown hydroponically (rockwool) using a high-wire system at a density of 2.8 plants m^{-2} in the greenhouse (with seeding on March 20, transplanting on April 22, and with the plants reaching a height of approximately 1.8 m).

Figure 8 shows the time courses of measured solar radiation, wind velocity, fog generation rate, canopy transpiration rate, inside air temperature, and relative humidity; Table 2 summarizes the 2-h averages. The duration of fogging-off ranged from 25 to 37 s with constant fogging-on of 20 s for an on-off cycle. The cycle was repeated and the actual instantaneous changes in air temperature and relative humidity were greater than the 15-min averages shown

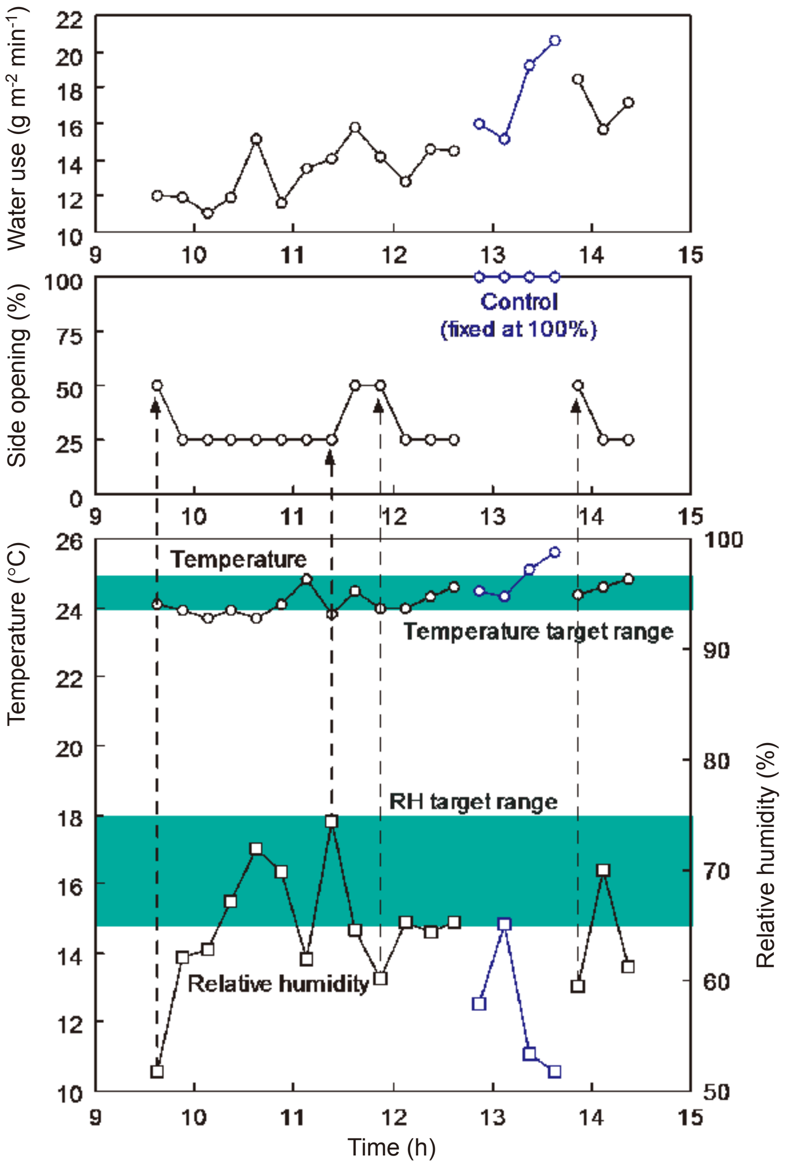


Fig. 7. Preliminary results of the control algorithm on a clear day. Arrows show the control actions of side openings based on measured relative humidity. The roof vent was kept at a fully open position. The plots for the fixed side openings of 100% during a mid-day hour of 12:45-13:45 are given as a control (Sase et al. 2006)

in Fig. 8. The inside air temperature in the afternoon was approximately 1ºC higher than that in the morning. This was primarily due to higher outside air temperature in the afternoon. Although the inside relative humidity during the experiment was relatively high, relative humidity in the afternoon decreased to 70% as expected from simulation based on the steady-state energy balance using Visual VETH software. The canopy transpiration rate in the morning was 27% less than in the afternoon, while the fog generation rate in the morning was almost the same as that in the afternoon. As a result, total water use in the morning decreased by 13% as compared with that in the afternoon. The relation between the air vapor pressure deficit (VPD) and the canopy transpiration rate showed that canopy transpiration increased linearly with an increase in VPD (Fig. 9). Medrano et al. (2003) demonstrated similar linear relations between the leaf transpiration rate and VPD for tomato plants grown in a Mediterranean climate, although the range of VPD was wider and up to 4 kPa. The decrease in canopy transpiration rate was driven by the decrease in VPD, and was at a greater magnitude than that of the fog evaporation rate under the present experimental conditions

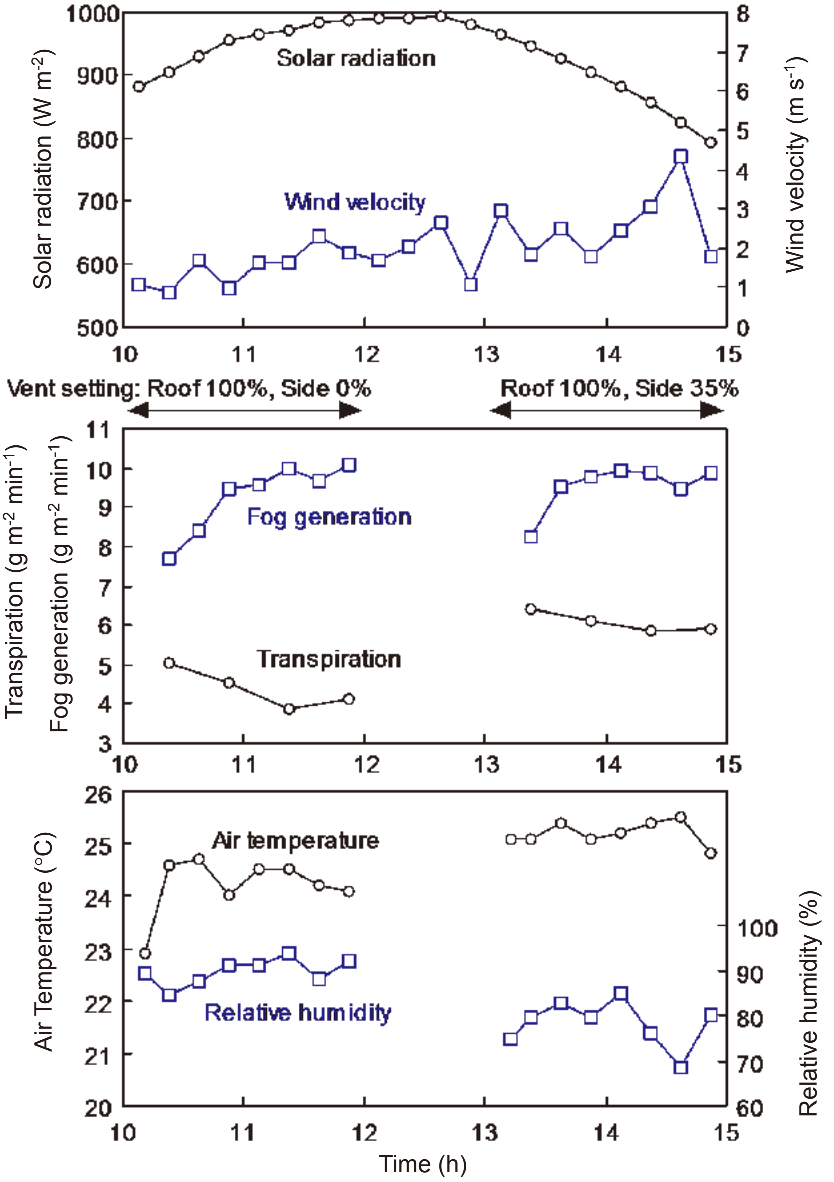


Fig. 8. Time courses of measured solar radiation, wind velocity, fog generation rate, canopy transpiration rate, inside air temperature, and relative humidity. 30-min averages for canopy transpiration and 15-min averages for other are plotted (Sase et al. 2007)

Table 2. Comparison of 2-h averages between vent configurations (Sase et al. 2007)

Vent settings	Wind velocity (m s^{-1})	Ventilation rate (m^3 m^{-2} min^{-1})	Relative humidity (%) or VPD (kPa)	Water injection by fog (g m^{-2} min^{-1})	Canopy transpiration (g m^{-2} min^{-1})	Total water use (g m^{-2} min^{-1})
Roof 100% Side 0%	1.5	1.3	90 (0.29)	11.1	4.4	14.4
Roof 100% Side 35%	2.6	2.2	78 (0.67)	11.5	6.1	16.6

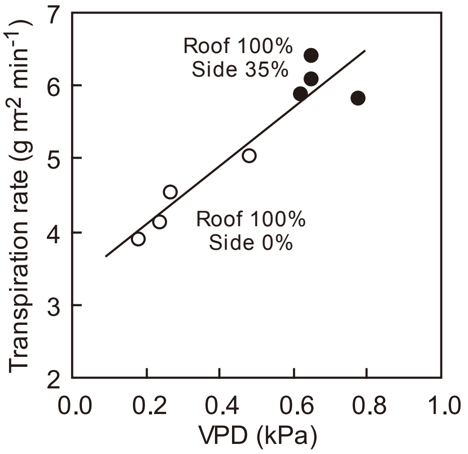


Fig. 9. Relation between the 30-min average VPD and canopy transpiration rate (Sase et al. 2007)

with inside relatively high humidity ranging from 70 to 94%.

The ventilation rate increased with the side vents open. Outside wind velocity and direction also affected the ventilation rate. However, the inside airflow velocity measured at the greenhouse center was low and ranged from 0.13 to 0.20 m s^{-1} at a wind velocity range of 0.9 to 4.3 m s^{-1}. Although not evaluated, it was presumed that the fine mesh insect screen on the sidewall inlet vent openings and the existence of plants were likely to restrict natural ventilation and airflow in the greenhouse.

Figure 10 shows a comparison of the measured 30-min averages and the values predicted by Visual VETH for the ventilation rate and water use. The predicted ventilation rates were found to be underestimated. However, the predicted evapotranspiration was slightly overestimated as compared with the measured water use, when a large amount of fog was generated under a high ventilation rate. Moreover, some non-evaporated fog droplets were observed to be exhausted outside. This could partially explain the cause of inaccurate predictions in ventilation rate and water use.

Conclusions

Semiarid climate regions have great potential for productivity due to a large amount of solar radiation throughout the year. Greenhouse cooling is essential, yet water use needs to be limited. The primary objective of this international research project was to investigate the performance of fog cooling in combination with natural ventilation in a semiarid climate. The main conclusions determined from our studies can be summarized as follows:

1. The performance of fog cooling combined with natural ventilation was compared with pad-and-fan cooling. The water use for fog cooling was 24 g m^{-2} min^{-1} and less than 41 g m^{-2} min^{-1} for pad-and-fan cooling. The inside relative humidity with fog cooling was 35% and only slightly higher than that for pad-and-fan cooling. By optimizing the ventilation rate, we could effectively cool a greenhouse with less water and electric energy use in a semiarid climate region.
2. The VETH chart was used to develop a cooling strategy for semiarid greenhouses where water use for evaporative cooling was estimated, and determined that: 1) controlling the ventilation rate is critical for saving water in semiarid greenhouses, 2) higher relative humidity may reduce the evaporation efficiency of water, and 3) manipulating the ventilation rate for humidity control could be combined with operating the evaporative cooling system for temperature control.
3. A simple and unique control algorithm for fogging and inlet vent openings was proposed. It was possible to maintain inside relative humidity and air temperature simultaneously within the desirable ranges, while reducing the water use for fog cooling.
4. Under two combinations of roof and side inlet vent openings of a semiarid greenhouse, air temperature, relative humidity, ventilation rate and water use indicated that the canopy transpiration rate increased linearly with an increase in air VPD. When the ventilation rate was decreased by closing the side vents with the roof vent fully open, the total water use decreased by 13% and

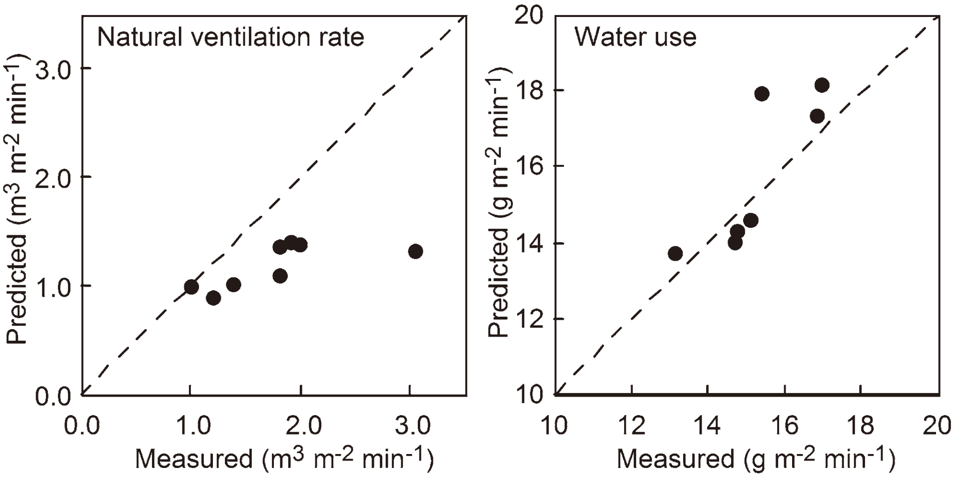


Fig. 10. **Comparison between the measured 30-min averages and the values predicted by Visual VETH for the natural ventilation rate (left) and water use (right) (Sase et al. 2007)**

inside relative humidity increased. By optimizing the natural ventilation rate, we could effectively control the inside air temperature and humidity with fog cooling, while reducing water use.

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