Manipulating Plant Moisture Conditions Using Greenhouse High-pressure Fogging

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ADDITIONAL INDEX WORDS. air temperature, humidity, leaf temperature, leaf surface wetness, model

SUMMARY. This study investigated greenhouse and plant surface microclimate for cucumber crops (*Cucumis sativus*) under high pressure overhead fogging. Overhead fogging maintained greenhouse humidity above its set point and avoided excessively low humidity conditions on sunny days. Fogging caused minimal to moderate changes in greenhouse air temperature in the fall depending on whether or not the leaves were sunlit or shaded. The temperature of sunlit leaves decreased by 1 to 1.5 °C (1.8 to 2.7 °F) under occasional fogging in the morning and by 3 °C (5.4 °F) under extensive fogging during noon hours. The temperature of fogged shaded leaves did not significantly change (<1 °C) when compared to nonfogged shaded leaves. Leaf wetness duration (LWD) was extended when overhead fogging was used. The length of extended daytime wetness duration (LWD_{day}) from 0800 to 1700 HR in the fogged greenhouse depended primarily on global radiation at the leaf level. A simulation model was developed to predict LWD_{day} using daily integrated global radiation (R_{sum}) as the input.

Overhead misting is an important technique applied in modern greenhouses for the purpose of humidification and

cooling. This technique is widely used in ornamental greenhouses to meet the high humidity requirements of plant propagation and growth, and occasionally used in greenhouse vegetable production for cooling the air during the hot periods of the crop season. At the present time, misting is not as common as evaporative cooling pads in vegetable greenhouses because of the high cost of installation and maintenance for misting systems. Misting systems require clean water, free of any soluble salts, to prevent plugging of the misting nozzles. However, as misting becomes more cost competitive, it will become more frequently used (Jensen and Malter, 1995).

In greenhouse crops, a common reason for the failure of biological control of diseases and insect/mite pests early in the growing season, and later when outdoor conditions become hot and dry, is low humidity levels in the greenhouse (Berlinger et al., 1999). High humidity is required by many entomopathogenic fungi/nematodes, predators and parasitoids of pests (Shipp et al., 1996; Shipp and van Houten, 1997; Sivasankaran et al., 1998). Also, low humidity is related to increased incidence of diseases such as powdery mildew (*Sphaerotheca fuliginea* and *S. pannosa*) (Jarvis, 1992; Reuveni and Rotem, 1974), and the occurrence of two-spotted spider mite (*Tetranychus urticae*) outbreaks (Lindquist et al., 1987). As a result, overhead misting has been suggested as a means to control these disease and pest problems (Abiko and Kishi, 1979; Berlinger et al., 1999) and to improve the efficiency of biological control.

Overhead misting has been shown to reduce the population densities of two-spotted spider mites and western flower thrips (*Frankliniella occidentalis*) on greenhouse cucumbers (Lindquist et al., 1987; Tulisalo, 1976). However, the persistence of a water film on the plant surface can promote dispersal of fungi, such as gray mold (*Botrytis cinerea*) and downy mildew (*Peronospora parasitica*) (Jarvis, 1992) and help many fungal pathogens to complete their infection cycle (Jhorar et al., 1998; Preece, 1971; Royle and Butler, 1986). Therefore, it is critical when manipulating the greenhouse environment to make it more favorable for biological control agents and not, at the same time, promote disease and pest development.

The optimal humidity conditions provided by misting can also be used to promote crop production. Previous studies have indicated that a shortage of water during sunny days is the most limiting factor for growth of greenhouse cucumbers when adequate carbon dioxide (CO₂) is supplied. Although there may be sufficient water in the soil or growth media, the stomata will close due to the high vapor pressure deficit (VPD) between the leaves and the surrounding air (Tulisalo, 1976). Overhead misting increases air humidity while cooling greenhouse air and leaves, and subsequently facilitates the opening of the stomata which will result in increased photosynthetic rate by the leaves (Urban, 1994).

To avoid leaf surface wetness when misting, high pressure [4000 to 7000 kPa (580 to 1015 lb/inch²)] misting systems with 10 µm (0.00039 inch) diameter nozzles and a sonic misting system that requires compressed air to create 10-µm-diameter water droplets have been developed. When properly used, these systems create a fog that gradually disperses as the water droplets evaporate in the air (Berlinger et al., 1999). To identify high pressure misting from other misting systems, these systems are called fogging systems.

Incorrect operation of a fogging system, however, can promote conditions leading to salt accumulation on the foliage, wetting of the foliage and subsequent disease outbreaks and leaf scalding (Arbel et al., 1999). A better understanding of leaf surface microclimate conditions under fogging is important for the optimal use and the further development of this system for greenhouse vegetable production. The objectives of this study were to investigate air and leaf surface microenvironments during greenhouse fogging application, and to develop a descriptive model to predict leaf wetness duration (LWD) when using overhead fogging. The results from this study can be used to evaluate the potential use of fogging to improve management practices for greenhouse crop production and disease/pest control.

MATERIALS AND METHODS

A multicompartment greenhouse trial was conducted in two adjacent high-gutter greenhouse compartments [9.1 × 7.3 m (30.0 × 24.0 ft), gutter

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height 4.5 m (14.6 ft)], located at the Greenhouse and Processing Crops Research Centre, Harrow, Ont., Canada. The greenhouse compartments were covered with double-polyethylene for the roof and double-polycarbonate for the walls. Both compartments were equipped with a high pressure [6900 kPa (1000 lb/inch²); 0.089 L·min⁻¹ (0.024 gal/min)] Ultra Cool fogging system (Zwart Systems, Grimsby, Ont., Canada) with 12 overhead nozzles (10- μ m orifice) per row. The fogging nozzles were located 0.6 m (2.1 ft) above crop canopy and the heating pipes were located at the bottom of the canopy (Fig. 1). The fogging system in the treatment greenhouse was controlled automatically by an Argus greenhouse management system (Argus Control System Ltd., White Rock, B.C., Canada) and in the control greenhouse no fogging was applied. The air temperature (T_a) and relative humidity (RH) set points for heating, ventilation, and fogging were 20/18 °C (68.0/64.4 °F), 24/22 °C (75.2/71.6 °F) and 80%/75% for day/night (D/N) respectively. Minimum on and off times for the fogging were 30 and 20 s, respectively.

Previous observations showed that climatic conditions in a horizontal direction are relatively uniform throughout the greenhouse compared to vertical variations (T.J. Jewett, unpublished data). Thus, two sensors for each climatic parameter were placed one at each of two heights near the center of each greenhouse. T_a and RH above and within canopy (middle of the stand) were measured using Argus wet and dry bulb thermistors in a vented box and a temperature-humidity probe (accuracy $\pm 2\%$ RH) (model IH-3602-C; Hycal Co., El Monte, Calif.) respectively (Fig. 1). The probe was outfitted with a radiation shield comprised of two concentric, white polyvinyl chloride pipes. The pipes were connected to an aspirating fan so air was drawn through the center pipe of each radiation shield to aspirate the temperature-humidity probes at the rate of 0.3 m³·min⁻¹ (12.0 ft³/min). Solar radiation above the canopy was measured using a pyranometer (model 200 SB; LI-COR Inc., Lincoln, Nebr.). The surface temperatures (T_l) of a sunlit leaf at the top of the canopy and of a shaded leaf in the middle of the canopy located near the center of the greenhouses were measured with in-

frared (noncontact) temperature sensors (field of view 25°) (model 3000.2; Everest Interscience Inc., Tucson, Ariz.). Leaf wetness (LW) sensors (model 237; Campbell Scientific Inc., Logan, Utah) were used to measure the wetness of the sunlit and shaded leaves at the same heights as the infrared sensors. The LW sensor is an electrical impedance grid with readings in the range of 0 to 6999 ohms (where 6999 ohms is the maximum resistance measured by the data logger, although resistance values from the LW sensors may be greater). A high resistance reading indicates that the leaf is dry and a low reading indicates that the leaf is wet (Gillespie and Kidd, 1978). Above-canopy temperature and humidity conditions, and equipment operating status were recorded by the Argus greenhouse management system. A datalogger (model CR21X; Campbell Scientific) was installed in each greenhouse to scan the sensors for in-canopy climatic measurements. The data loggers were programmed to scan every 20 s and output 15-min average values.

Crop canopy consisted of two double rows of 'Flamingo' cucumber plants with a spacing of 0.6 m (2.0 ft) between single rows, 1.2 m (4.0 ft)

between the double rows, and a within row spacing of 0.7 m (2.3 ft) between plants. The two outside single rows near the walls were guard rows. Cucumber seedlings were transplanted into the greenhouse on 30 Aug. 1999 and a full canopy had developed by the end of September 1999.

Climatic data for the full canopy were collected from 4 to 28 Oct. 1999. Observations for each day were considered as independent values. These observations covered different outside weather conditions and corresponding heat and ventilation requirements during the experimental period. For the outside weather conditions, the daily mean air T_a and RH varied between 6.4 and 20.1 °C (43.5 and 68.2 °F) and 51.9 and 86.5%, respectively.

A regression model was developed for cumulative LWD_{day} for sunlit leaves as a function of integrated global radiation for the period (R_{sum} , 0800

Fig. 1. Locations of sensors for climate measurements in the fogged and nonfogged greenhouses. Diagram does not depict full canopy because a full canopy would clutter the figure and not show all the sensors. T = temperature, RH = relative humidity, LW = leaf wetness, IR = infrared, 1.0 m = 3.28 ft.

to 1700 HR) in the greenhouse. The model was validated using data collected in a fogged glass greenhouse at the Greenhouse and Processing Crops Research Centre [15.6 × 9.6 m (51.2 × 31.5 ft), gutter height 2.6 m (8.5 ft)], in Summer 1997 (30 May to 2 July 1997). The glass greenhouse was equipped with a high-pressure [4.800 kPa (700 lb/inch²)] fogging system (Microcool; Climate Control Systems Inc., Leamington, Ont., Canada) with 10-μm overhead nozzles. In this greenhouse, the temperature and humidity set points for fogging were 24.0/22.0 °C and 70%/80% RH (D/N). Maximum, minimum, and pause time periods for the system were 5.0, 2.0, and 5.0 min, respectively. Mean bias difference (MBD) and root mean square difference (RMSD) between measured and simulated LWD_{day} were calculated as follows:

$$\text{MBD} = \frac{1}{n} \sum_{i=1}^n (\text{measured}_i - \text{simulated}_i)$$

$$\text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\text{measured}_i - \text{simulated}_i)^2}$$

RESULTS AND DISCUSSION

EFFECT OF FOGGING ON GREENHOUSE MICROCLIMATE CONDITIONS. The overall range for humidity levels for top-canopy air in the fogged compartment was essentially maintained at or above setpoint (70.8% to 97.8% RH), while humidity in the nonfogged greenhouse compartment varied between 53.0% and 94.6% RH depending on weather conditions. On 11 Oct. 1999, for example, RH was as low as 55.5% (Fig. 2) during the day. The lowest humidity was mostly observed during noon hours and it was during this time period that overhead fogging was mostly required.

Daytime humidity can have an important influence on plant photosynthesis activity because of the controlling effect by humidity on stomata conductance. To reach the fogging setpoint of RH = 80% during day [air vapor pressure deficit (VPD) = 0.6 kPa (0.08 lb/inch²) at Ta of 23.0 °C (73.4 °F)], humidity in the fogged house was increased by as much as 25 to 30% RH compared to RH in the nonfogged greenhouse, where RH was as low as 53% [VPD = 1.6 kPa (0.2 lb/inch²) at Ta of 23.0 °C] at noon hours. This decrease in VPD from 1.6 to 0.6 kPa (0.2 to 0.08 lb/inch²) by fogging,

according to Bakker (1991) and van de Sanden and Veen (1992), can cause a 65% to 79% increase in stomatal conductance of cucumber, tomato (*Lycopersium esculentum*), sweet pepper (*Capsium annuum*) and eggplant (*Solanum melogana*). Because well-watered plants grown under high humidities lacked any closing response to increasing ambient CO₂ (Raschke, 1986), the use of overhead high pressure fogging can potentially increase the effectiveness of CO₂ enrichment for vegetable production.

To present a more generic view, the diurnal courses of RH and Ta averaged over the entire experimental period are presented in Fig. 3. Mean RHs in the fogged greenhouse were kept above the setpoints (80%/75%, D/N) for both top and in-canopy air, while the mean in-canopy RHs in the nonfogged greenhouse decreased lower than set point from noon to late afternoon. For both greenhouses, mean RHs within the canopy was 5% to 8% lower than top canopy air due to the following possible reasons: 1) air closer to the heating pipe was warmer resulting in lower RH, 2) water from overhead fogging may not have completely reached the deep canopy, and 3) transpiration of younger leaves at top canopy was more vigorous than for deep canopy leaves. The standard deviation (SD) bars in the figure showed the variations among the different experimental days. Humidity in the fogged greenhouse was more consistent (SD varied in the range of 0.9% to

7.5% RH) compared to the nonfogged greenhouse (SD varied in the range of 2.6% to 9.2% RH), which is more dependent on the outside climate.

There was no difference in the temperature of top canopy air in the two compartments except for morning when fogging caused a slight decrease in temperature. In the fogged greenhouse, Ta within the crop canopy was often 1.0 °C higher than that in the nonfogged greenhouse. This difference, depending on the time of the day, might be the result of increased heating requirement in the fogged greenhouse at night (2% more on average mixing valve opening) and due to modified long wave radiation exchange caused by fogging during the day (Oke, 1987).

Therefore, overhead high pressure fogging can be used to avoid excessive low humidity conditions during sunny days without causing large changes in air temperature.

EFFECT OF FOGGING ON LEAF SURFACE MICROCLIMATE CONDITIONS.

Leaf surface microclimate conditions were described by T_l and LW in this study. The effect of fogging on T_l varied depending on the time of fogging application (Figs. 2 and 4). Intermediate fogging did not cause a large

Fig. 2. Relative humidity (RH) in two greenhouses with and without fogging and the corresponding fogging time periods (vertical bars) in the fogged house on a sunny day 11 to 12 Oct. 1999.

difference in T_l for both sunlit and shaded leaves, whereas under extensive fogging, the T_l of the fogged sunlit leaf was decreased by 2.0 to 3.0 °C (3.6 to 5.4 °F) (Figs. 2 and 4A) due to evaporative cooling of the intercepted water on the surface. For shaded leaves, the difference caused by fogging was negligible (Fig. 4B).

The effect of overhead misting on T_l was also observed in other studies. A reduction of 3.6 °C (6.5 °F) in T_l of cyclamen [*Cyclamen persicum* 'Finlandia' (F₁ hybrid)] was observed when misting was applied during August and October (Montero et al., 1990). Montero et al. (1990) proposed that transpiration was not one of the main terms in the daily energy budget, which could be interpreted as evaporation from a wet leaf surface is more effective for cooling than is transpiration. Our results on exposed leaves supported their results and suggested that the effect of misting on T_l is wetness and climate dependent.

According to Katsoulas et al. (2001), as VPD decreased under misting, the transpiration rate was not significantly changed due to the compensatory effect between VPD and bulk stomatal resistance. When the leaf was partially wetted by misting, the evaporative cooling of water droplet caused the leaf temperature to decrease. For plants growing in summer, however, our observations showed that T_l was not significantly modified (unpublished data). This is because in summer, the misting droplet may be evaporated before intercepted by leaves under the high light conditions. Therefore, to determine the surface temperature of misted leaves, evaporative cooling of the intercepted water from misting has to be included in the energy budget.

LWD was extended by the use of fogging. Measured LW conditions are presented in Figs. 4 and 5. Fogged sunlit leaves remained wet continuously day and night, while nonfogged sunlit leaves were wet only during early morning, late afternoon and sometimes during the night period (Fig. 4A). For shaded leaves, the onset time of wetness on fogged leaves occurred 15 min earlier and finished 15 min later for each wetness period compared to the nonfogged leaves (Fig. 4B).

To provide an overview of the entire experimental period, all measured LW values for nonfogged leaves

were plotted on the x-axis and simultaneously measured LW values for fogged leaves were plotted on the y-axis in Fig. 5. This figure showed that almost all readings were located in the (wet, wet) and (dry, wet) area for sunlit leaves (Fig. 5A), where the first and second values in the bracket represent the LW readings in the nonfogged and fogged houses, respectively. This distribution means that, under the same weather and inside temperature conditions, fogged sunlit leaves were consistently more wet when compared to the corresponding nonfogged leaves. For shaded leaves, the distribution was more divergent in the four areas with the majority of values located in (wet, wet), (dry, wet) and (dry, dry) areas (Fig. 5B), indicating that fogging above crop canopy did not affect the wetness of shaded leaves as greatly and as uniformly as compared to sunlit leaves.

The surface wetness conditions of sunlit leaves exposed to overhead fogging were found to be highly correlated to incident global radiation (R) in the greenhouse. When incident R was $>130 \text{ W}\cdot\text{m}^{-2}$ (41.2 British thermal units (Btu)/ft²/h), fogging did not wet the leaf, and when R was lower than $80 \text{ W}\cdot\text{m}^{-2}$ (25.4 Btu/ft²/h), the leaves remained wet due to dew or fogging, or both (data not presented).

Solar radiation values of between 80 and $130 \text{ W}\cdot\text{m}^{-2}$ were related to either wet or dry surfaces. This light level was usually measured in early morning and on cloudy days. Therefore, the uncertainty of wetness under these light levels is because the leaves might be wet in the early morning if dew was extended by fogging, while on cloudy days fogging was not normally required and the leaves may remain essentially dry.

Greenhouse fogging is not supposed to affect LW, since droplets $\leq 10 \mu\text{m}$ stay suspended in the air while they are evaporating (Breuer and Knies, 1995). Our results indicated that this is true only when light intensity in the greenhouse is $>130 \text{ W}\cdot\text{m}^{-2}$. The dependence of LW on irradiation levels results from the effect of net radiation on the evaporation rate of fine water droplets (Monteith and Unsworth, 1990). When irradiation is high, water droplets suspended in the air surrounding the leaf will evaporate quickly resulting in little or no water deposit on

Fig. 3. Daily courses for air temperature (°C) and relative humidity (%) in two greenhouses with and without fogging, averaged over 4 to 25 Oct. 1999; °F = (9/5 °C) + 32. Vertical bar is the standard deviation from the mean (n = 2016).

Fig. 4. Leaf temperature (T_l) and leaf wetness (LW) in two greenhouses with and without fogging on 11 to 12 Oct. 1999 for (A) sunlit leaves and (B) shaded leaves. Sensor reads 6999 ohms when it is dry and a value of 3000 ohms was determined for visible wetness on the leaf surface; $^{\circ}\text{F} = (9/5 ^{\circ}\text{C}) + 32$.

the leaf surface. Otherwise, the size of the droplet increases due to accumulated fogging until the droplet can no longer stay suspended in the air. When heating in the greenhouse is necessary, our data showed that the air around shaded leaves was drier due to the fact that the heating pipes were near the bottom of the canopy and that some of

the fogged water was intercepted by the top leaves. Thus, LWD was subsequently shorter on shaded compared to sunlit leaves.

In conclusion, the use of overhead fogging greatly extended LWD and may slightly lower the temperature of sunlit leaves. To avoid the daytime LW, the fogging is recommended to be used only when global radiation is $>130 \text{ W}\cdot\text{m}^{-2}$.

MODELING DAYTIME WETNESS DURATION ON THE LEAF SURFACE DUE TO FOGGING. Daytime LW is very important, because this time period is usually accompanied by higher temperatures and may result in greater sporulation of pathogens if wetness

persists. To determine the effect of light levels in the greenhouse on LWD_{day} on fogged crops, cumulative daytime LWD from 0800 to 1700 HR (LWD_{day}) on sunlit leaves was plotted against corresponding integrated daily R from 0800 to 1700 HR (R_{sum}) that was measured above the crop canopy. LWD_{day} was found to be inversely proportional to R_{sum} values with the longest wetness durations observed at $R_{\text{sum}} \leq 1.4 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($123.3 \text{ Btu}/\text{ft}^2/\text{d}$) (Fig. 6). To use this relationship for any R_{sum} conditions, a regression line was fitted to the data (SigmaStat 3.0). The model simulated LWD_{day} (h) due to fogging as a linear function of R_{sum} ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$):

$$\text{LWD}_{\text{day}} = (-1.42 \pm 0.17) R_{\text{sum}} + (11.07 \pm 0.31) \\ (R_{\text{sum}} \leq 7.8 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}, R^2 = 0.90, n = 19)$$

From this response line, the relationships between LWD_{day} and the corresponding irradiance conditions are clearly illustrated. Because this model was developed from data in the fall, it is only applicable to those days with a daily integrated global radiation $R_{\text{sum}} \leq 7.8 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ($687.2 \text{ Btu}/\text{ft}^2/\text{d}$). However, according to our observations, light conditions in the greenhouses of North America are within this range for most of the days of the cropping seasons (spring, winter, and fall). The good agreement between the measured values and the regression line indicates that solar radiation was a prime determining factor.

This model was validated using data collected in Summer 1997 in a fogged glass greenhouse at the Greenhouse and Processing Crops Research Centre. Results for 18 d with LWD_{day} were presented in Fig. 7. MBD and RMSD between measured and simulated values were 0.02 and 1.3 h. For 78% of the days, the maximum differences between measured and simulated LWD_{day} were within 2 h, of which 57% were within 0.5 h. The deviations between measured and simulated values may be due to factors that were not included in the model, such as the difference in the settings for the fogging humidity threshold and the operational procedures for the two fogging systems (e.g., on-off or maximum, minimum, and pause time periods).

Fogging systems have been characterized and modelled in terms of efficiency and water supply in previous studies (Arbel et al., 1999). However, the resulting wetness on the plant sur-

Fig. 5. Leaf wetness (LW) for misted leaves versus LW for nonmisted leaves for sunlit and shaded leaves in Fall 1999 (4 to 25 Oct. 1999) for 15-min averages (n = 2016). Sensor reads 6999 ohms when it is dry and a value of 3000 ohms was set for visible wetness on the surface.

face from fogging applications has never been quantified. Our LWD_{day} model provides a simple way to quantify this important parameter. Greenhouse vegetable producers using high pressure fogging can use this model to predict LWD_{day} with integrated global radia-

tion measurements. Predicting wetness durations are useful for optimizing fogging control in the greenhouse to avoid disease and pest problems. Further studies are needed to evaluate the potential use of high pressure fogging as a means to improve greenhouse pest and crop management practices.

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Fig. 6. Plot of cumulative daytime leaf surface wetness duration (LWD_{day}) (h) on sunlit leaves (0800 to 1700 HR) versus the corresponding integrated global radiation in the greenhouse for the same time period (R_{sum} , $MJ \cdot m^{-2} \cdot d^{-1}$) during Fall 1999 (4 to 25 Oct. 1999). The model: $LWD_{day} = (-1.42 \pm 0.17) R_{sum} + (11.07 \pm 0.31)$, $n = 19$, $R^2 = 0.90$; $1 MJ \cdot m^{-2} \cdot d^{-1} = 88.1$ British thermal units/ft²/d.

Fig. 7. Measured and modeled cumulative daytime leaf surface wetness duration (LWD_{day}) (h) for fogged cucumber crop in Summer 1997 (30 May to 2 July 1997). Mean bias difference (MBD) = 0.02 h and root mean square difference (RMSD) = 1.3 h.

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