Simulated Effects of Various Environmental Management Practices on Water Consumption in Open and Confined Greenhouse Systems

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Abstract

The objective of this study was to evaluate the effects of relative humidity, light management, minimum ventilation rates, CO_2 enrichment and canopy size on water consumption in three different greenhouse systems (conventional, open heat pump, and confined heat pump) in winter, spring, and summer months. Using different relative humidity set points resulted in almost the same relative humidity regimes within the confined greenhouse system, resulting in similar transpiration rates. No difference was observed in transpiration rates in the open system in winter either, because the inside relative humidity levels never reached the 70% and 80% set points. Some differences were observed in spring and summer. Up to a 5.1% reduction was observed in transpiration rates by going from a 70% set point to an 80%. Maintaining an average solar radiation level of 250 W/m^2 instead of 350 W/m^2 inside the greenhouse reduced the transpiration rate approximately 12.5% at both relative humidity set points. Using a minimum ventilation rate of 0.005 m^3/s.m^2 instead of 0.01 m^3/s.m^2 reduced the transpiration rates about 16%, 11%, and 3% in winter, spring, and summer, respectively. The higher decrease in winter was caused by the increase in inside relative humidity when lower ventilation rate was used. Using a CO_2 enrichment level of 1000 ppm compared to an enrichment level of 350 ppm resulted in transpiration rates that were predicted to be slightly lower in all the three greenhouse systems used. This decrease was 14% in the confined system, and by about 5% in both the conventional and open heat pump systems. The partial canopy stands (0.4 m) had approximately 7%, 5%, and 6% higher transpiration rates than the full canopy stands (2.0 m) in the conventional, open heat pump, and confined heat pump systems, respectively.

INTRODUCTION

To provide economically optimal micro-environments for plant growth, producers can use or control the number of glazing layers, insulation curtains or screens to reduce long-wave radiation losses at night, reduced ventilation rates, evaporative coolers, and shading devices to control incoming solar radiation. In addition, a Rankine power cycle heat pump that was developed by Yildiz et al. (1993) holds promise for reducing water consumption, winter heating requirements and warm weather cooling loads. These systems involve complex tradeoffs between initial and operating costs for plant responses to various environmental factors and the strategies used to regulate temperature, humidity and CO_2 levels in the crop canopy. Special attention must also be given to the operational strategies associated with the use of heat pumps, especially in maintaining acceptable relative humidity levels within greenhouses.

A dynamic simulation model was developed and validated to provide an accurate prediction of greenhouse energy and moisture exchanges as a function of dynamic environmental factors (Yildiz and Stombaugh, 2006). This model was used to predict transpiration rates and water consumption, and to evaluate the operational strategies associated with heating and cooling using the proposed heat pump and a conventional system. The heat pump was evaluated for both open and confined greenhouse systems, and these were compared to a conventionally ventilated and heated greenhouse. The specific objective of this study was to evaluate the effects of canopy size, relative humidity, light management levels, CO_2 enrichment and minimum ventilation rates on water consumption in three different greenhouse systems (conventional, open heat pump, and confined heat pump) in winter, spring, and summer.

PROCEDURES

Weather File

January, April, and July weather files for Delaware (latitude 40^o 17' N, longitude 83^o 05' W), Ohio, U.S.A. were used to represent winter, spring, and summer in the simulations. Simulations were performed starting at the beginning of the fifth day and ended at the end of 29th day of the month providing a 25-day simulation.

Greenhouse Features, Heating, Cooling, Ventilation, Shading, and CO_2 Dosing

A dynamic computer simulation model to determine greenhouse microclimates was developed and validated. Table 1 shows the greenhouse and crop characteristics used in this study. Yildiz and Stombaugh (2006) reported the theoretical approach, model validation, and all the other greenhouse and crop characteristics. The proposed heat pump system evaluated for both open (OHP) and confined (CHP) greenhouse systems was a 10,548 W (3 ton, 36,000 Btu/hr, based on system heat removal capacity) unit consisting of a Rankine power cycle and a vapor compression cycle which uses a novel hydraulically connected rolling diaphragm piston cylinder device as motor, compressor and pump (Yildiz, 1993; Yildiz et al., 1993). And to provide multiposition proportional control it was assumed that three heat pump units were used in each greenhouse. In this system, the power generated by the power cycle replaces the electric power used to drive the compressor. Natural gas was used as the energy source, which supplied heat to the evaporator of the power cycle. A fixed burner rate of 12,306 W (42,000 Btu/hr) and a burner efficiency of 0.9 were used. The vapor compression cycle removed the energy from the heat source through an evaporator attached to a hydronic cycle. R123 (dichlorotrifluoroethane) and R22 (chlorodifluoromethane) refrigerants were used for the power and refrigeration cycles, respectively. For the conventional greenhouse (CON) simulations, it was assumed that the conventional gas-fired furnace provided 24,612 W of heat input each. A furnace efficiency of 0.7 was assumed for the conventional heating system (Badger and Pole, 1979). No heat storage facility was used in this study. An overhead plastic tube was used for the hot and the cold air distribution in both heating and cooling modes. One of the heat pump units in the confined greenhouse system was used as a dehumidifier while operating as a heater. The only difference from the original heating unit was circulating the inside greenhouse air through the outdoor coil instead of the outside air. This prevented moisture build up in the confined greenhouse system. During the winter season, 0.943 m^3/s of inside air passed through the condensers, and 2.829 m^3/s of inside air was passed through the outside evaporator, which provided the dehumidification. An evaporative cooler was employed for cooling the conventional greenhouse. In the open and confined greenhouse systems, however, the heat pump units provided the cooling requirements in the greenhouse. Outdoor air was used in the evaporative cooling system, and it was assumed that the air at the evaporative cooler outlet was fully saturated. In the heat pump systems, indoor air was recirculated and introduced back to the inside at a lower temperature.

Two shading clothes with transmissivities of 0.75 and 0.50 were used to reduce the cooling loads. The use of these shading clothes provided shading levels of 25%, 50% and 62.5% by using them individually or together. An aluminized (both sides) night curtain was used at night to reduce the heat loss due to long-wave radiation exchanges between the inside greenhouse components and the sky. In the open systems (CON and OHP), ventilation was provided by two fans, one with a fixed flow rate to provide a minimum level of air exchange at all times, and the other one with a variable flow rate.

CO_2 enrichment was provided in all three-greenhouse systems. Liquid CO_2 tanks were employed and the enrichment was provided through a CO_2 injector. 350 ppm and 1000 ppm CO_2 enrichment levels were evaluated.

Operational and Control Strategies

The day or nighttime greenhouse temperature set points were based on the solar position. Based on the indoor air temperature, the control system operated in either the heating or cooling mode. If the system was in heating mode and if heating was required, the ventilation rate was first set to the minimum rate. The control system turned on other heating units based on the difference between the indoor and set point temperatures, providing a multi-position proportional control. If no heating was required in this mode no heating unit operated; but the system remained in the heating mode until it was switched to the cooling mode.

The cooling mode operated in two steps. The first step was to reduce the cooling load using a variable shading system and to cool the inside air by increasing ventilation rates. Two shading cloths provided the variable shading with transmissivities of 0.75 and 0.50 used individually or together. The minimum and maximum ventilation rates were 0.01 $m^3/s.m^2$ (or half this rate) and 0.08 $m^3/s.m^2$, respectively. If the first step in cooling could not handle the cooling load, then the second step was activated, in which the heat pump units (OHP) or evaporative cooling (CON) provided the cooling. In the conventional system, introducing an outside airflow rate of 0.08 $m^3/s.m^2$ when the second step was activated in the cooling mode provided evaporative cooling. Relative humidity levels in the conventional system were controlled indirectly by the temperature control. In the open heat pump system, however, additional relative humidity control was provided. When the inside relative humidity levels exceeded relative humidity set points (70% or 80%), additional ventilation was introduced to decrease inside relative humidity. In the confined system, the same criterion was used to prompt the heating mode. However, the cooling mode was activated at lower inside temperatures than those used in the other two systems. The operation of the heating system was the same as in the other two systems. However, the minimum ventilation rate was used in the open system while no ventilation was used in the confined system. In the cooling mode of the confined system, there was only one step unlike the conventional and open heat pump systems, which had two-step cooling systems. Here, no cooling was provided by ventilation; instead, the cooling was provided by the three heat pump units providing a multiposition proportional control, after reducing the cooling load using the variable shading system. The operation of the shading system was the same as in the other two systems. Either the cooling units or the dehumidifier (the first heating unit) controlled inside relative humidity. When the inside relative humidity levels exceeded relative humidity set points (70% or 80%), this heating unit operated as a dehumidifier to prevent excess moisture within the confined greenhouse system.

RESULTS AND DISCUSSION

An attempt was made to determine the effect of relative humidity management levels on water use in open and closed heat pump greenhouse systems. Table 2 summarizes the findings with respect to relative humidity set points of 70% and 80% in both greenhouse systems in winter, spring, and summer. In the confined system, no difference was observed in transpiration rates with respect to the relative humidity management levels. This was because different relative humidity set points did not actually maintain the inside relative humidity levels at the set points. Even though the set point was 70%, for instance, the actual inside relative humidity levels were higher than 70%. Therefore, using different relative humidity set points resulted in about the same relative humidity regimes within the closed greenhouse system, resulting in similar transpiration rates. However, almost all the water transpired was collected on the coils in the confined system. As well, no difference was observed in transpiration rates in the open heat pump system in winter. This was because the inside relative humidity levels never reached the set points. The actual levels were much lower than these set points (approximately 36%). However, some differences were observed during spring and summer. This was because the inside relative humidity levels reached and frequently exceeded the set point levels. In heat pump greenhouse systems, up to a 5.1% reduction was observed in transpiration rates by going from a 70% set point to an 80% set point.

The effect of light management levels on water use in an open heat pump system was also evaluated. Table 3 summarizes the effect of light management levels with different relative humidity set point levels on water use in summer. Low light level refers to a shading set point of 250 W/m^2 while the high light level referring to a shading set point of 350 W/m^2 inside the greenhouse. Maintaining an average solar radiation level of 250 W/m^2 instead of 350 W/m^2 inside the greenhouse reduced the transpiration rate approximately 12.5% at both relative humidity set points (Table 4).

The effect of minimum ventilation on water use in an open heat pump greenhouse system was evaluated. For this assessment, a minimum ventilation rate of 0.005 $m^3/s.m^2$ was used instead of the rate of 0.01 $m^3/s.m^2$ that was the minimum ventilation rate used in all the other simulations. Table 4 summarizes the findings with respect to these ventilation rates. Using a rate of 0.005 $m^3/s.m^2$ instead of 0.01 $m^3/s.m^2$ dropped the transpiration rates approximately 16%, 11%, and 3% in winter, spring, and summer, respectively. The reason for having a greater drop in winter was the increase in inside relative humidity when a lower ventilation rate was used. When the rate of 0.01 $m^3/s.m^2$ was used, the average inside air relative humidity was about 40% whereas it was about 55% when the rate of 0.005 $m^3/s.m^2$ was used in winter. Inside relative humidity levels in spring and summer were higher than the levels in winter when the rate of 0.01 $m^3/s.m^2$ was used; and high ventilation rates were being used for extended times in spring and summer. Therefore, the decrease in the minimum ventilation rate did not affect the transpiration rates in spring and summer as much as it did in winter.

An attempt was also made to evaluate the effect of enriching the greenhouse air with carbon dioxide at a level of 1000 ppm practiced as a standard enrichment level. Table 5 summarizes the predicted effects of CO_2 enrichment on water use in spring. A number of studies reported that elevated CO_2 concentration reduces the transpiration of plants due to increased stomatal resistance and enhanced leaf area index (LAI) (Mortensen, 1987, 1998; Allen et al., 2003; Bhatt et al., 2007). Effect of CO_2 enrichment on water consumption in our study was caused mainly due to self-shading resulting from the enhanced LAI, not due to stomatal acclimation. Stomatal resistance to water vapor in this study was defined as a function of solar radiation derived from daytime data only, hence slightly overestimating night-time transpiration. By reducing light penetration through the canopy, the enhanced self-shading at elevated CO_2 enrichment decreased transpiration especially at the middle and bottom of the canopy. This is in agreement with the findings provided by Li et al. (2003). In another study, Li et al. (2004) reported that the CO_2 enrichment-induced decrease in transpiration almost compensated for the increase in transpiration brought by the higher leaf area. Similar findings were reported in a number of studies (Mauney et al., 1994; Kimbal et al., 2002; Triggs et al., 2004)) stating that crops with large growth responses to elevated CO_2 had near zero water savings while crops with modest growth responses had a water savings of about 7%. In our simulation study, CO_2 enrichment during the day caused a decrease in leaf and air temperatures. Daytime decrease in the air temperature was 0.4°C. The reason for the temperature decrease was the increase in LAI and self-shading, as well as the increase in metabolic activity (high CO_2 fixation) due to the CO_2 enrichment during the day. The 1000 ppm level reduced the transpiration rates in all the three greenhouse systems used. The drop was about 14% in the confined system, while it was about 5% in both the conventional and open heat pump systems. Although preliminary comparisons with some previous studies seemed promising, further experimental validation have been planned.

Table 6 summarizes the differences in water consumption with respect to different canopy sizes in winter. Partial canopy (0.4 m) had higher energy consumption than the full canopy (2.0 m) for the crop architectural parameters provided in Table 1. The same average leaf dimensions were used in both cases, LAI was defined as a function of plant height, and foliage area along the row direction was uniformly distributed. The model included a description of growth in height since absorption at a given level can not be determined from only LAI, but also depends on the geometry of canopy stand, the amount of diffuse and direct solar radiation. Yang et al. (1990) found that most of the daytime transpiration was from the top layer of the canopy where most of the solar radiation was intercepted. High water vapor content, low airflow, and old leaves in the lower part of the canopy all contributed to inverse (increasing with height) distribution of transpiration rate. This was also in agreement with the finding that transpiration rate of a mature plant canopy was not proportional to the size of the stand or LAI (Yang et al., 1989). Rather, it generally approached a maximum value regulated by radiation availability and other variables. Our findings also were in agreement with their observations. The partial canopy stand had more exposed surfaces (both the canopy stand and reflective floor) for longwave radiation exchange with the greenhouse glazing and sky. It should also be emphasized that stomatal resistance to water vapor in this study was defined as a function of solar radiation. Partial canopy stand had improved light penetration and higher leaf exposures to light as well, resulting in higher transpiration rates than those in the full canopy greenhouses (Table 6). Partial canopy stands had approximately 7%, 5%, and 6% higher transpiration rates than the full canopy stands in conventional, open, and closed heat pump greenhouse systems, respectively. Here as well, further experimental validation have been planned to see the complex relationship between the crop architectural parameters and water consumption.

CONCLUSIONS

In the confined heat pump system, using different relative humidity set points resulted in almost the same relative humidity resulting in similar transpiration rates. As in the closed system, no difference was observed in transpiration rates in the open system in winter, because the inside relative humidity levels never reached the 70% and 80% set points. Some differences were observed during spring and summer. This was because the inside relative humidity levels stayed within plus and minus 10% from the set point levels. Up to a 5.1% reduction was observed in transpiration rates by going from a 70% set point to an 80% set point. Maintaining an average solar radiation level of 250 W/m^2 instead of 350 W/m^2 inside the greenhouse reduced the transpiration rate approximately 12.5% at both relative humidity set points (70% and 80%). Using a minimum ventilation rate of 0.005 $m^3/s.m^2$ instead of 0.01 $m^3/s.m^2$ reduced the transpiration rates about 16%, 11%, and 3% in winter, spring, and summer, respectively. The higher decrease in winter was caused by the increase in inside relative humidity when the lower ventilation rate was used. The average inside relative humidity in winter was about 36% when a rate of 0.01 $m^3/s.m^2$ was used. It was about 55% when a rate of 0.005 $m^3/s.m^2$ was used. Since already high ventilation rates were being used due to high inside relative humidity levels in spring and summer, the decrease in the minimum ventilation rate did not affect the transpiration rates much in spring and summer. The CO_2 enrichment caused a slight decrease in leaf temperatures during the day, due to the complex relationships between transpiration, and stomatal resistance, crop architectural parameters and metabolic activity. The overall relationship resulted in transpiration rates that were predicted to be slightly lower in all the three greenhouse systems used. This decrease was 14% in the confined system, and about 5% in both the conventional and open heat pump systems. Partial canopy (0.4 m) stands had approximately 7%, 5%, and 6% higher transpiration rates than the full canopy stands in the conventional, open, and closed heat pump systems, respectively.

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Tables

Table 1. Greenhouse and crop characteristics used in the simulation model.

Greenhouse length	7.5 m (Conventional and OHP) and 25.m (CHP)
Greenhouse width	7.5 m
Greenhouse height at eaves	2.5 m
Greenhouse height at ridges	4.5 m
Glazing	Double polyethylene
Floor surface material	Reflective mulch
Crop type	Cucumber
Crop row orientation	North – South
Full plant height, h	2.0 m
Distance between plant rows, W	0.86 m
Width of row stand, w	w = 0.8 [1-exp (1.449 h)]*
Leaf area index, LAI	LAI = 0.886 h – 0.0965*
Avg. leaf length	0.30 m
Avg. leaf width	0.25 m

OHP: Open Heat Pump; CHP: Confined Heat Pump. *Cited from Yang et al. (1990)

Table 2. Water use with respect to relative humidity management levels in the open heat pump (OHP) and confined heat pump (CHP) greenhouse systems in winter, spring, and summer.

	WINTER				SPRING				SUMMER			
	CHP		OHP		CHP		OHP		CHP		OHP	
Rel. Humidity Set Point:	70%	80%	70%	80%	70%	80%	70%	80%	70%	80%	70%	80%
Avg. Inside Rel. Hum. :	84%	84%	36%	36%	85%	86%	66%	68%	89%	89%	78%	82%
WATER (kg H_2O/day.m^2)												
Transpiration	0.84	0.85	2.52	2.52	1.06	1.05	2.29	2.22	1.17	1.17	1.75	1.66
Water Collected	0.82	0.83	---	---	1.03	1.04	---	---	1.17	1.16	0.35	0.51
TOTAL	0.02	0.03	2.52	2.52	0.02	0.01	2.29	2.22	0.00	0.01	1.40	1.15

Table 3. Water use with respect to light management levels in the open heat pump (OHP) greenhouse system (summer).

Shading Level:	200-250 W/m^2		300-350 W/m^2	
Rel. Humidity Set Point:	70%	80%	70%	80%
WATER (kg H_2O/day.m^2)				
Transpiration	1.75	1.66	2.00	1.89
Water Collected	0.51	0.35	0.54	0.41
TOTAL	1.24	1.31	1.46	1.48

Table 4. Water use with respect to minimum ventilation rate in the open heat pump system (OHP) in winter, spring, and summer.

	WINTER		SPRING		SUMMER	
Vent Rate (m^3/s.m^2)	0.01	0.005	0.01	0.005	0.01	0.005
WATER (kg H_2O/day.m^2)						
Transpiration	2.52	2.12	2.22	1.97	1.66	1.61
Water Collected	---	---	---	---	0.35	0.35
TOTAL	2.52	2.12	2.22	1.97	1.31	1.26

Table 5. Water use with respect to CO_2 enrichment levels (spring).

	CHP		OHP		CON	
	350 ppm	1000 ppm	350 ppm	1000 ppm	350 ppm	1000 ppm
WATER (kg H_2O/day.m^2)						
Transpiration	1.06	0.91	2.29	2.16	2.17	2.06
Water Collected	1.03	0.90	---	---	---	---
Evaporative Cooling	---	---	---	---	---	---
TOTAL	0.02	0.01	2.29	2.16	2.17	2.06

Table 6. Water use with respect to canopy size in conventional (CON), open heat pump (OHP), and confined heat pump (CHP) greenhouse systems in winter (*0.4 m canopy stand; **2.0 m canopy stand).

	CHP		OHP		CON	
CANOPY SIZE:	Partial*	Full**	Partial	Full	Partial	Full
WATER (kg H_2O/day.m^2)						
Transpiration	0.90	0.85	2.64	2.52	2.71	2.54
Water Collected	0.87	0.83	---	---	---	---
Evaporative Cooling	---	---	---	---	---	---
TOTAL	0.03	0.02	2.64	2.52	2.71	2.54