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Evaporative Cooling Efficiency of a Fogging System for Greenhouses

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Abstract: The objective of this study was to investigate the efficiency of fogging system (FS) for greenhouses. The experiments were carried out in a multi-span plastic greenhouse (PG), 105.6 m wide and 205 m long, made of 11 spans. The FS consists of a water softener and filters to prevent nozzle clogging, a water reservoir, pumps and a pressure regulator, and fog generating nozzles (FGN). The required pressure for FGN was 4.5 atm. Three nozzle lines with 82 FGN were installed in each span of the PG. At each nozzle line, 82 FGN were uniformly located at 2.5 m nozzle spacing. The FGN parameters were determined in order to characterize the efficiency of the FS based on air flow rate (AFR) and evaporation flow rate (EFR). The results showed that the FS was able to keep the air temperature inside the PG 6.6 °C lower than the outside. The average ventilation rate of the PG was 13.64 $m^3 s^{-1}$ during the experimental period. The efficiency of the FS ranged from 11.7% to 80%. The efficiency of the FS increased as the difference between the dry-bulb temperature (DBT) and wet-bulb temperature (WBT) rose. The results indicated that air relative humidity (RH) inside the PG was increased by 25% on average by means of the FS examined in this study. The EFR varied between 130.3 $g\ m^{-2} h^{-1}$ and 1223.4 $g\ m^{-2} h^{-1}$, while the AFR ranged from 39.3 $kg\ m^{-2} h^{-1}$ to 298.7 $kg\ m^{-2} h^{-1}$. Fogging system efficiency (FSE) increased linearly with EFR and absolute humidity difference (AHD) between the inside and outside air.

Key Words: Greenhouse, Fogging system, Air flow rate, Evaporation flow rate

Seralar İçin Sisleme Sisteminin Serinletme Etkinliği

Özet: Bu çalışmada, seralarda kullanılan sisleme sisteminin etkinliğinin belirlenmesi amaçlanmıştır. Denemeler, genişliği 105.6 m ve uzunluğu 205 m olan, 11 bölmeden oluşan büyük bir ticari serada yürütülmüştür. Seradaki sisleme sistemi, su yumuşatıcı, memelerin tıkanmasını önleyen filtreler, su kaynağı, pompalar ve basınç düzenleyici ve sisleme yapan memelerden oluşmaktadır. Sisleme memeleri için gerekli basınç 4.5 Atm'dir. Plastik seradaki her bölmeye üç sıra şeklinde toplam 82 adet meme yerleştirilmiştir. Sisleme memeleri 2.5'ni eşit aralıkla yerleştirilmiştir. Sisleme sisteminin etkinliğinde etkili olan havalandırma ve buharlaşma miktarları belirlenmiştir. Araştırma sonuçlarına bağlı olarak, sisleme sisteminin iç ortam hava sıcaklığını dış ortamdan 6.6 °C daha düşük sıcaklıkta tutabileceği belirlenmiştir. Deneme süresince seradaki havalandırma debisi ortalama 13.64 $m^3 s^{-1}$ olarak saptanmıştır. Sisleme sisteminin etkinliği % 11.7-80 arasında değişmiştir. Sistemin etkinliği, havanın kuru ve yaş termometre sıcaklıkları arasındaki farkına bağlı olarak artmıştır. Sisleme sistemi, plastik sera içerisindeki hava bağıl nem oranını ortalama % 25 oranında artırmıştır. Serada taban alanı başına hava akış hızı 39.3-298.7 $kg\ m^{-2} h^{-1}$ arasında değişmesine karşılık, buharlaşma miktarı 130.3-1223.4 $g\ m^{-2} h^{-1}$ arasında değişmiştir. Sistemin etkinliği, iç ve dış ortam havasının mutlak nem farkına bağlı olarak doğrusal olarak artmıştır.

Anahtar Sözcükler: Sera, Sisleme sistemi, Havalandırma miktarı, Buharlaşma miktarı

Introduction

Ventilated greenhouses frequently become too warm when high levels of solar radiation occur. If interior summer temperatures are to be kept near or below outside ambient temperatures, some form of cooling must be provided. Evaporative systems for cooling greenhouses have been developed to provide the desired growing conditions in the greenhouse during the hot season. Evaporative cooling (EC) is a process that reduces the temperature of air by the evaporation of water into the air stream. As water is evaporated, energy is lost from the air reducing its temperature. To reduce interior greenhouse temperatures, water evaporation systems, which not only cool the air but also increase the humidity, are more feasible than mechanical cooling systems (Hellickson and Walker, 1983). The humidity is important due to its effect on the rate of water loss from plants.

Fogging is another system that can be used for the direct evaporative cooling of greenhouses. In recent

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years, high pressure fogging systems (FSs) have started to be used in greenhouses. These FSs can be designed and operated to maintain more uniform temperatures and humidity in greenhouses than those possible with the fan-pad system (FPS). FSs are more expensive than an FPS, but when uniform temperatures and humidity levels are important they are considered the best method for EC (Öztürk and Başçetinçelik, 2002). A system applying the same principle as an FPS are FSs. FSs are based on spraying the water in small droplets (in the fog range 2-60 µm in diameter) in order to increase the water surface in contact with the air (Arbel et al., 2000). Water is forced through the nozzles placed above the crop in a greenhouse, producing a fog. The free-fall velocity of the droplets is slow and the drops are easily carried by the air stream inside the greenhouse. Fog droplets can be generated by several methods. Droplets less than 30 µm in diameter are created using high-pressure pumps and nozzles or spinning atomizers (Öztürk and Başçetinçelik, 2002).

The cooling achieved from high-pressure fog or mist is comparable to that obtained from an FPS, but some problems have been experienced with nozzles clogging. FSs can provide more uniform temperature distribution than an FPS and also provide uniform high humidity levels (Hellickson and Walker, 1983). FS typically have relatively low evaporative efficiency compared to the FPS. Values of saturation efficiency range from 10% to 37% with an average of 23.5% for FSs having water pressures ranging from 275 to 1380 kPa while its value range from 6% to 95% with an average of 77.5% for an FPS at the same range of water pressure (Critten, 1988). The type and efficiency of the EC system used in the greenhouse may strongly influence its temperature and humidity profiles. Comprehensive studies have been carried out concerning the efficiency and modeling of EC systems by many researchers. Giacomelli (1993) tested various cooling systems to compare cooling potentials and to get maximum uniformity throughout the greenhouse. The evaporative cooling efficiency (ECE) ranged from 40% to 70%, and the minimum gradients of temperature were obtained with high ventilation rates and water flow rates.

Kittas et al. (2001) investigated temperature and humidity gradients during summer in a commercial greenhouse producing cut roses, equipped with an FPS and a half-shaded plastic roof. In a steady-state regime, the cooling process reached 80% efficiency and succeeded in maintaining greenhouse temperatures that were cooler (up to 10 °C lower) than outside. Cladding materials used in the greenhouse may influence the ECE. Al-Amri (2000) found that a fiberglass cover mainly increased the ECE by 28.43% compared with a polyethylene (PE) cover.

Seginer (1994) found that artificial EC is mainly effective when crop transpiration is low, and Fuchs (1993) reported that a highly transpiring crop combined with a proper ventilation rate is the most effective mechanism to keep leaf temperatures moderate (Kittas et al., 2001). Previous work on EC systems, mainly with FS, applied to greenhouses considered thermodynamic system efficiency and environmental effects. Giacomelli et al. (1985) investigated the effects of EC systems on greenhouse micro-climate. Montero et al. (1990) carried out a research on cooling a greenhouse with compressed air fogging nozzles. A theoretical study was conducted by Arbel et al. (2000) to evaluate an EC system for greenhouses by installing uniformly distributed fog generating nozzles (FGN) in the space over the plants.

The objectives of this study were to evaluate the effects of an FS on a micro-climate in a rose greenhouse, determine the efficiency of FS for greenhouses, investigate the cooling and humidifying effects of the FS in a plastic greenhouse (PG), and determine air flow rate (AFR) and evaporation flow rate (EFR) in order to characterize the efficiency of the FS. For this purpose, climatic measurements from a large commercial greenhouse equipped with an FS were collected, presented and discussed. The efficiency of the FS was calculated based on the dry-bulb temperature (DBT) inside and outside the greenhouse and the wet-bulb temperature (WBT) outside the greenhouse. The FS parameters were also determined in order to characterize the efficiency of the FS based on the AFR and EFR.

Materials and Methods

Materials

Plastic Greenhouse

The experiment was carried out from 16 May to 12 June, 2002, in a large commercial greenhouse located in the Çukurova region (Yenice-Adana). The multi-span PG, 105.6 m wide and 205 m long, was made of 11 spans.

Each span was 9.6 m wide by 205 m long, with a ridge at 5.6 m and a gutter 4 m above the soil surface (Figure 1). The cladding material was 150 µm PE film, with terrestrial infrared and UV absorbing additives.

The PG, which had continuous roof ventilation at the ridge, was oriented in an east-west direction. For the experimental period, the meteorological parameters in the PG were measured at the maximum roof-opening angle. Each span of the PG included a computer-controlled FS. The PG has been used commercially for cut rose production.

The rose plants were cultivated in 0.56 (width) x 1.04 (length) x 0.23 (depth) m containers, filled with volcanic scoria and organic materials. The containers were laid parallel to the nozzle lines nine 200 m rows, in each span, 1.82 m between row centers.

Fogging System

The FS consists of a water softener and filters to prevent nozzle clogging, a water reservoir, pumps and a pressure regulator, and the FGNs. The main elements of the FS used in the PG are given in Figure 1. The FGNs were distributed uniformly over the PG. Pressure required for the FGNs was 4.5 atm. Three nozzle lines with 82 FGN were installed in each span of the PG. At the each nozzle line, 82 FGN were uniformly located with 2.5 m nozzle spacing. The central water feed system was electrically operated depending on the relative humidity (RH) value inside the PG.

Meteorological Measurements

A measuring system, including psychometric units for measuring the WBT and DBT, was installed in order to control the operation of the FS. The WBT and DBT were measured on top of the canopy at 1.5 m inside each span of the PG. Solar radiation was measured by Li-Cor Silicium probes. The velocity and direction of the wind were also recorded with vector instruments. The analogue signals from the sensors were sampled at 30 s intervals, averaged every 30 min, and stored in a data-logger connected to the sensors.

Methods

Air Flow Rate

Based on the assumptions of a steady-state condition and that the desired temperature and the RH in the greenhouse are known, the required air mass flow rate can be approximated by the equation (Arbel et al., 1999)

$$\mathrm{AFR} = \frac{I\tau\alpha - U(T_g - T_o)}{h_g - h_o} \qquad \text{for } h_g > h_o \quad \ldots\ldots\ldots (1)$$

where AFR is the air (ventilation) flow rate (kg $s^{-1}m^{-2}$), I is the solar radiation (W m^{-2}), τ is the radiation transmission of the greenhouse, α is the proportion of the solar radiation entering the greenhouse used to increased the internal air enthalpy, U is the overall heat loss coefficient of the greenhouse (W m^{-2} °C^{-1}), T_g is the

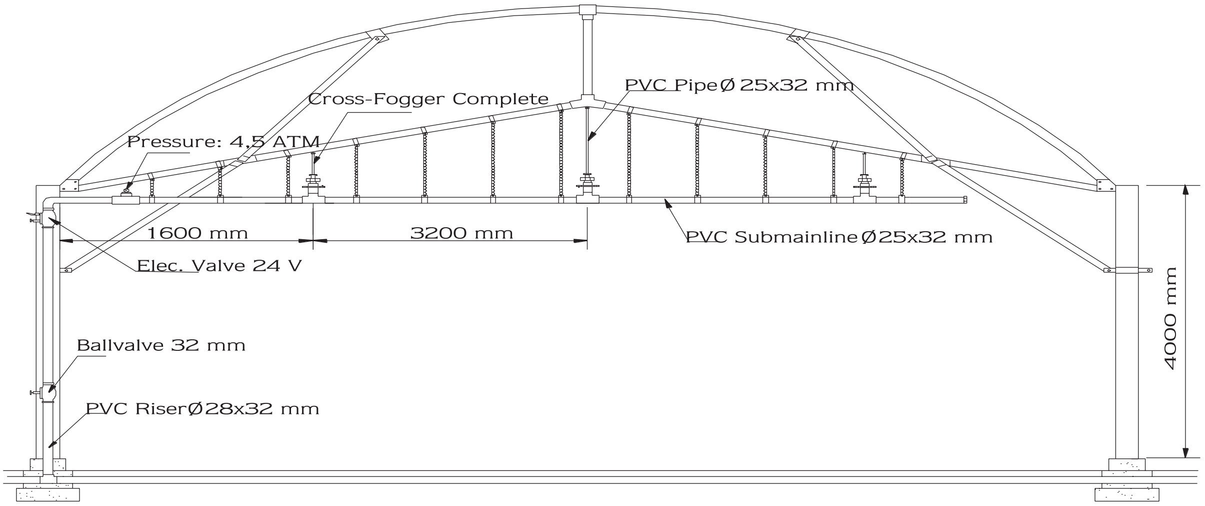

Figure 1. Plastic greenhouse equipped with the fogging system.

air temperature inside the greenhouse (°C), T_o is the air temperature outside the greenhouse (°C), h_g is the air enthalpy inside the greenhouse (J kg^{-1} $_{dry\ air}$), and h_o is the air enthalpy outside the greenhouse (J kg^{-1} $_{dry\ air}$).

The value of α depends on the proportion of the floor covered by plants, and generally lies in the range of 0.3-0.7 (Öztürk and Başçetinçelik, 1997). In this study, the values of 0.5 and 0.75 were used as α and τ, respectively. The value of U for single cover PGs varies in the range 6.0-8.0 W m^{-2} $°C^{-1}$, as reported by Başçetinçelik and Öztürk (1997). In this study the U value of 7.0 W m^{-2} $°C^{-1}$ was used to determine the AFR in the PG.

Evaporation Flow Rate

The solar energy absorbed inside the greenhouses can be converted to latent heat by the evaporation of the water droplets generated by the FS and by plant transpiration. The EFR was calculated by the following equation:

$$EFR = AFR(x_g - x_o) \quad \text{..} \quad (2)$$

where EFR is evaporation mass flow rate (kg s^{-1} m^{-2}), AFR is air (ventilation) flow rate (kg s^{-1} m^{-2}), x_g is the absolute humidity of the air inside the greenhouse (kg $kg^{-1}_{dry\ air}$) and x_o is the absolute humidity of the air outside the greenhouse (kg $kg^{-1}_{dry\ air}$).

As can be seen in Eq. 2, the EFR was calculated based on the AFR and the AHD between the inside and outside air. It is clear that there are two factors influencing the absolute humidity of the air inside the PG: (1) water droplets generated by FGN, and (2) the process of plant transpiration. Thus the total evaporation from the FGN and plant transpiration was taken into account in the calculation of the EFR.

Efficiency of the Fogging System

The ECE is a common term used to indicate saturation efficiency. This is the ratio of change in saturation achieved to potential change in saturation. EC systems are normally evaluated in terms of EC or saturation efficiency, which is defined as the ratio of temperature drop provided by the EC system to the difference between DBT and WBT. The WBT is important in the ECS. The WBT, not the RH, determines to what extent air temperature can be cooled by the evaporation of water. Fogging system efficiency (FSE) was determined by the following (Gupta et al., 1995; Yağcıoğlu, 1999; Al-Amri, 2000; Kittas et al., 2001):

$$FSE = \frac{DBT_o - DBT_g}{DBT_o - WBT_g} \times 100 \qquad (3)$$

where FSE is fogging system efficiency (%), DBT_o is the dry-bulb temperature outside the greenhouse (°C), DBT_g is the dry-bulb temperature inside the greenhouse (°C) and WBT_o is the wet-bulb temperature outside the greenhouse (°C).

Results and Discussion

The experiment was carried out in the PG from 16 May to 12 June 2002. The efficiency of the FS in the PG was especially investigated for the hottest recorded sunny days (8, 9 and 10 June 2002). The air temperatures inside the PG were compared to the outside air temperatures as one important measure of the FS. From all the recorded climatic values, the results of the three consecutive days when the outside air temperatures were highest are discussed in this paper. Table 1 and Figure 2 summarize the outside and inside climatic conditions during the experimental period.

Table 1. The values of the inside and outside climate parameters.

Climate parameters	Values		
	Minimum	Maximum	Average
Outside solar radiation (W m^{-2})	322	1243	791.3
Outside air temperature (°C)	23.7	40.4	35.4
Inside air temperature (°C)	23.1	34.3	31.6
Outside wind speed (m s^{-1})	0.6	4.1	2

Solar radiation outside the PG varied between 322 W m^{-2} and 1243 W m^{-2} in the period of 8, 9 and 10 June 2002. Solar radiation reached its maximum value at 13:00, as shown in Figure 2. The average daily value (ADV) of outside solar radiation was 791.3 W m^{-2} for the period of time, as shown in Figure 2. The air temperature inside the PG ranged from 23.1 °C to 34.3 °C, while the outside air temperature varied between 23.7 °C and 40.4 °C. The air temperature inside and outside the PG was generally stable during the morning and afternoon. It was calculated that the ADV of the inside and outside air

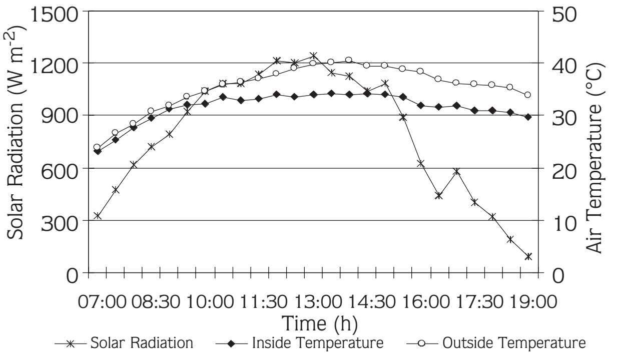

Figure 2. The changes inside and outside air temperatures as a function of time.

temperatures was 31.6 °C and 35.4 °C, respectively. While the air temperature difference (ATD) inside and outside the PG was only 0.63 °C at 07:00 in the morning, the ATD reached 6.6 °C at 16:00 in the afternoon. The average ATD between the inside and outside of the PG was 3.84 °C for the period of time covered by Figure 2. The ATD between the inside and outside the PG was lower in the morning since the efficiency of the FS was lower. The ATD between the inside and outside of the PG increased as the efficiency of the FS rose during the afternoon. In other words, the air temperature inside the PG decreased as the efficiency of the FS increased during the afternoon. The air temperature inside the PG decreased with increasing the sensible and latent heat transfer from the PG to the outside. Figure 2 clearly shows that a substantial decrease in ambient air temperature inside the PG occurred when the air temperature outside the PG exceeded 40 °C. Under these conditions, the FS provided a cooling effect (ATD between the outside and inside) of 6.6 °C. The results showed that the FS was able to keep the air temperature inside the PG 6.6 °C lower than that outside. This good performance is due to the high efficiency of the FS, which is calculated according to Equation 3. Abdellatif (1993) found that the greatest value of cooling effect (13.2 °C) was achieved with the greatest value of WBD (16.2 °C) and the lowest value of air RH (26%) and vice versa. Kittas et al. (2001) also succeeded in maintaining greenhouse temperatures that were cooler (up to 10 °C lower) than outside by means of the FPS. In this experiment the cooling effect of the FS was lower in comparison with the results obtained by Abdellatif (1993) and Kittas et al. (2001). The FS did not substantially reduce the average air temperature around the rose plants in the PG. This result is due to the fact that the WBT depression at Adana is normally low, and therefore the potential cooling effect of the FS is limited. The evaporation in the PG increases the RH of the incoming air and of the PG.

The change of the wind speed and the ventilation rate of the PG are shown as a function of time in Figure 3. Ventilation rate is influenced by environmental factors such as wind speed, wind direction, and the ATD between the inside and outside of the greenhouse. The required ventilation rate increased as the air temperature rose outside the PG. A similar result was obtained by Arbel et al. (1999). The wind speed outside the PG was in the range 0.6-4.1 m s^{-1}. The main value of the wind speed was 2 m s^{-1} during the experimental period. The ventilation rate was only 5.46 m^3 s^{-1}at 07:00 in the morning. One factor that indirectly influences the ventilation rate is solar radiation, since it is an important component of the energy balance in greenhouses. Since air temperature and solar radiation increased outside the PG, the ventilation rate reached 41.56 m^3 s^{-1} at 13:30 in the afternoon. It was found that the highest ventilation rate (41.56 m^3 s^{-1}) occurred when the wind speed was 1.5 m/s at 13:30 in the afternoon, since the ATD between the outside and inside the PG was 5.7 °C. In this case, the ATD had a strong influence on the ventilation rate when the wind speed was lower. This result is in agreement with Babtista et al. (1999), who investigated the influences of the wind speed, wind direction and temperature difference on the ventilation rate in a four span glasshouse. They found that temperature difference affected the ventilation rates under low wind speed. The ventilation rate dropped from 41.56 m^3 s^{-1} to 12.28 m^3 s^{-1} at 19:00 in the evening. The average ventilation rate of the PG was 13.64 m^3 s^{-1} for the period of time covered by Figure 3. This means that 13.64 m^3 of warm and moist air per second was removed from inside the PG to the outside.

Figure 4 shows the variation of the efficiency of the FS as a function of time. The efficiency of the FS varied as a function of time of the days in which the experiment was carried out. The efficiency of the FS was strongly affected by the difference between the DBT and WBT of the outside air, which was affected mainly by air RH. The difference between the DBT and WBT is referred to as the WBD. The efficiency of the FS increased as the air RH outside the PG fell. Therefore, the FS's effect as an EC system was greater the lower the outside air RH was.

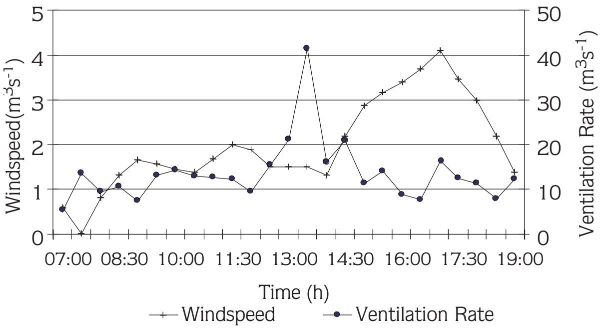

Figure 3. The changes in wind speed and the ventilation rate.

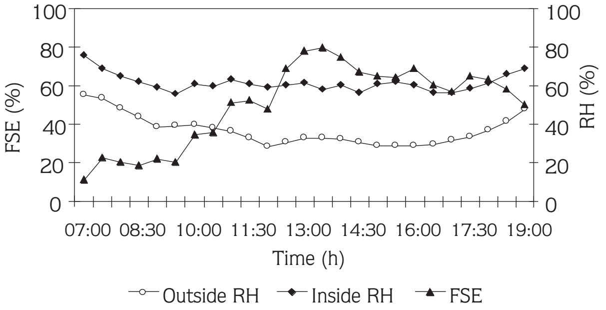

Figure 4. The changes in the FSE as a function of time and air RH.

This is in agreement with Arbel et al. (1999). The efficiency of the FS ranged from 11.7% to 80% during the experimental period. It was found that the average daily efficiency of the FS was 50.5%. Al-Amri (2000) found that the average efficiency of the EC system was 46.19% in an experimental greenhouse covered by 0.1 mm thick double layers of PE sheets. The present FS was more effective than the FPS in comparison with the results obtained by Arbel et al. (1999) and Al-Amri (2000). Arbel et al. (1999) compared the FS and the FPS under similar conditions. According to their results, the efficiency of the FS is better than that of the FPS regarding the uniform distribution of temperature and humidity in a greenhouse. An efficiency of 75% was obtained for the FPS in their experiments. On the other hand, Giacomelli (1993) found that the efficiency of the EC of various cooling systems ranged from 40% to 70%.

Since the WBD was greatest at 13:30 in the afternoon, when the DBT was normally at its peak, the greatest efficiency of the FS (80%) was achieved at this time in the present experiment. The greatest efficiency of the FS (80%) was achieved at 33% outside air RH. This is in agreement with results obtained by Abdellatif (1993) and Kittas et al. (2001). As mentioned before, Abdellatif (1993) and Kittas et al. (2001) found that the cooling efficiency was 81.5% and 80%, respectively. Albright (1989) also reported that a well-designed ECS might have an operating efficiency of up to 80%. If the outside temperature and the air RH are known, the WBT that would be the temperature of the entering air can be calculated. For example, air at 35 °C and 20% RH has a WBT of 18.8 °C. The difference between 35 °C and 18.8 °C is the WBD, 16.2 °C. The greatest value of evaporative cooling efficiency of the FS was 80% in this experiment. This means that the FS would cool the air by 0.80 (16.2 °C) = 13 °C.

The air RH inside the PG ranged from 56.3% to 76.3%, whereas the air RH outside the PG in the range of 28.1-55.7%. The air RH inside the PG dropped from 76.3% (at 07:00 in the morning) to 56.3% at 14:30 in the afternoon. During the experimental period, the ADV of the inside and the outside RH was 61.7% and 37.1%, respectively. The air relative humidity difference (RHD) between inside and outside the PG was only 15.4% at 07:30 in the morning, the RHD reached to 33.3% at 15:30 in the afternoon. The average RHD between the inside and outside of the PG was 24.6% for the period of time covered by Figure 2. This means that the air RH inside the PG increased approximately 25% by means of the FS examined in this study. Similarly the ATD, the RHD between the inside and outside the PG increased as the efficiency of the FS during the afternoon increased. In other words, the air RH inside the PG increased as the efficiency of the FS rose during the afternoon. The RHD between the inside and outside of the PG reached 33.3%, when the ATD between the inside and outside of the PG was 5.33 °C at 15:30 in the afternoon. The FS provided a humidifying effect (RHD between the inside and the outside) of 33.3%. The results showed that the FS was able to keep the air RH inside the PG 33.3% higher than that outside. For the duration of the experimental work, the efficiency of the FS was found to be directly related to the outside air temperature, air RH and saturation pressure of the air.

The changes in the AFR and EFR calculated based on Equations 1 and 2, respectively are given in Figure 5 as a function of time. Data calculated from Equations 1, 2 and 3 are summarized in Table 2. The AFR indicates air exchange per hour per square meter of the ground surface area of the PG. The AFR was found to be linearly

Table 2. The values of the EFR, AFR and FSE during the experimental period.

Parameters	Values		
	Minimum	Maximum	Average
EFR (g $m^{-2} h^{-1}$)	130.3	1223.4	483.2
AFR (kg $m^{-2} h^{-1}$)	39.3	298.7	98.04
FSE (%)	11.7	80	50.5

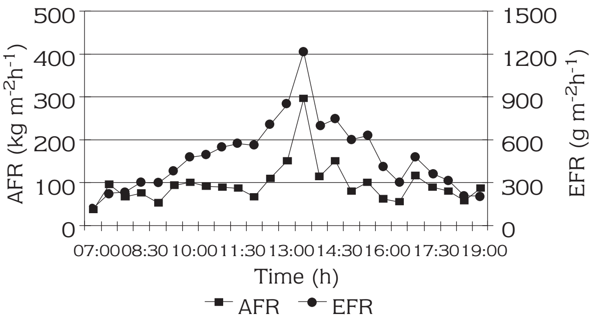

Figure 5. The changes in the EFR and AFR in the PG as a function of time.

affected as the ATD between the inside and outside the PG increased.

The AFR ranged from 39.3 kg m^{-2} h^{-1} to 298.7 kg m^{-2} h^{-1} inside the PG. The AFR was only 39.26 kg m^{-2} h^{-1} at 07:00 in the morning and reached 298.7 kg m^{-2} h^{-1} at 13:30 in the afternoon because of the ATD between the inside and outside of the PG increasing, as shown in Figure 5. The AFR was 298.7 kg m^{-2} h^{-1} in the afternoon when the air temperature and RH were 34.3 °C and 58.5%, respectively. The calculated AFR was higher compared with the results of the Arbel et al. (1999). Arbel et al. (1999) also found that the AFR was 264 kg m^{-2} h^{-1} when the air temperature and RH were 24.5 °C and 90%, respectively. The average AFR in the afternoon (in the period 14:00-19:00; 91.7 kg m^{-2} h^{-1}) was 14.8% greater than that in the morning (in the period 07:00-12:00; 79.9 kg m^{-2} h^{-1}) due to lower ATD. The ADV of the AFR was 98.04 kg m^{-2} h^{-1} during the experimental period. This means that 98.04 kg of warm and moist air per hour per square meter of ground surface of the PG was exchanged with fresh air from outside.

The EFR indicates the evaporation of the water droplets generated by the FGN and by plant transpiration per hour per square meter of the ground surface of the PG. The AFR, ATD and absolute humidity difference (AHD) between the inside and outside air affected the EFR. The EFR varied between 130.3 g m^{-2} h^{-1} and 1223.4 g m^{-2} h^{-1} inside the PG. Similarly, the change in the AFR for the period of time covered by Figure 5, the EFR was only 130.3 g m^{-2} h^{-1} at 07:00 in the morning and reached to 1223.4 g m^{-2} h^{-1} at 13:00 in the afternoon because of increasing the AHD between the inside and outside air. The EFR increases as the temperature outside the PG increases. This is in agreement with the results of Arbel et al. (1999). The EFR was 1223.4 g m^{-2} h^{-1} in the afternoon when the air temperature and RH were 34.3 °C and 58.5%, respectively. The calculated EFR was lower compared with the results of Arbel et al. (1999). Arbel et al. (1999) also found that the EFR was 1850 g m^{-2} h^{-1} when the air temperature and RH were 24.5 °C and 90%, respectively. The EFR increased as the latent heat transfer from the PG rose. The average EFR in the afternoon (in the period 14:00-19:00; 455 g m^{-2} h^{-1}) was 16.8% greater than that of the morning (in the period 07:00-12:00; 389.6 g m^{-2} h^{-1}). During the experimental period, the ADV of the EFR was 483.2 g m^{-2} h^{-1}. This means that 483.2 g of water, generated by the FGN and by plant transpiration, was evaporated per hour per square meter of the ground surface of the PG.

The relationship between the EFR and AFR is given in Figure 6. The EFR increased linearly with increasing the AFR in the PG. The regression line between the EFR and AFR in the PG had a slope of 42.2 and an R^2 equal to 0.72. Since the EFR was calculated based on the AFR and AHD between the inside and outside air (see Equation 2), the EFR increased as the AFR rose during the experimental period. The square meter (m^2) in units of the AFR and EFR indicates the ground surface area of the PG.

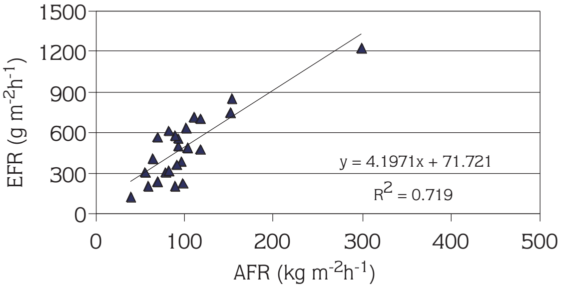

Figure 6. The relationship between the EFR and AFR in the PG.

Figure 7 clearly shows the relationship between the EFR and AHD between the inside and outside air (w_i-w_o); the coefficient of determination (R^2) is 0.30. As mentioned before, the AFR increased as the ATD between the outside and inside the PG rose. When the AHD between the inside and outside air the PG increased, the values of the EFR also rose (Figure 7). The AHD between the inside and outside air the PG varied between 0.73 g $g^{-1}_{dry\ air}$ and 8.28 g $g^{-1}_{dry\ air}$. While the EFR was only 0.73 g $g^{-1}_{dry\ air}$ at 07:00 in the morning, it reached 8.28 g $g^{-1}_{dry\ air}$ at 14:00 in the afternoon because the AHD between the inside and outside air increased. The average AHD was 4.58 g $g^{-1}_{dry\ air}$ during the experimental period. Due to the water droplets generated by the FGN and the process of plant transpiration, the absolute humidity of the air increased inside the PG. The process of plant transpiration is a mass-transfer process in which water vapor moves from the surface of the commodity to the surrounding air. Thus, the influence of the process of plant transpiration on the EFR was taken into account.

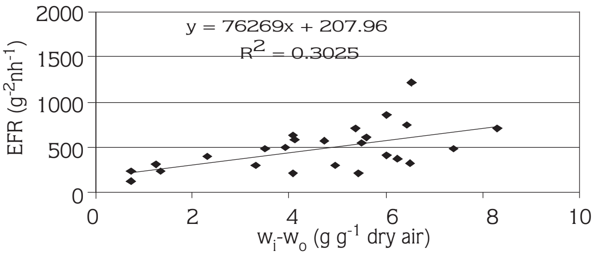

Figure 7. The relationship between the EFR and AHD (w_i-w_o).

The determined values of the FSE, as functions of time and EFR in the PG, are given in Figure 8. The greatest value of an EC effect of the FS (FSE; 80%) was achieved in the PG at the greatest value of the EFR (1223.4 g m^{-2} h^{-1}). Figures 9 and 10 represent the relationships between the FSE and EFR, and the FSE and AHD (x_i-x_o); the coefficients of the determination (R^2) are 0.42 and 0.80, respectively. The FSE increased as the EFR and the AHD between the inside and outside air increased.

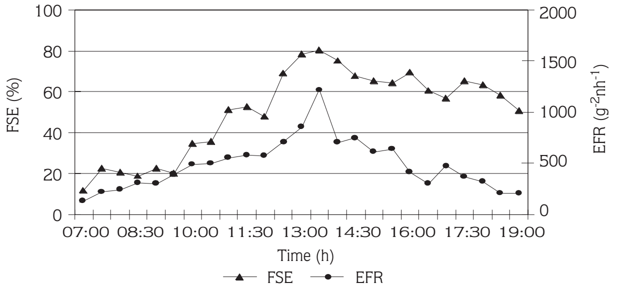

Figure 8. The FSE as functions of time and EFR.

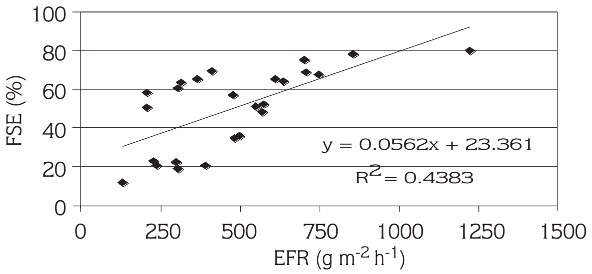

Figure 9. The relationship between the FSE and EFR.

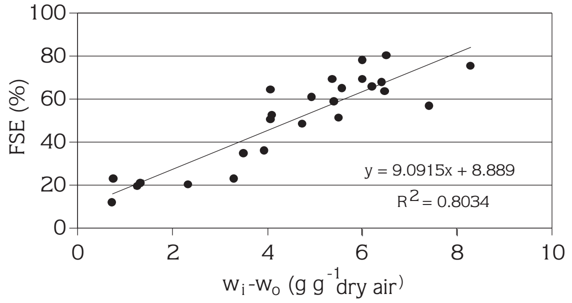

Figure 10. The relationship between the FSE and AHD (x_i-x_o).

Conclusion

Uniform conditions of temperature and RH in the PG were observed with the FS. The FS was able to keep the air temperature inside the PG 6.6 °C lower than that outside. Therefore, the air RH inside the PG was increased by 25% on average by means of the FS examined in this study. It was found that the average efficiency of the FS was 50.5%. The efficiency of the FS increased linearly with the EFR and AHD between the inside and outside air. The air RH outside the PG affected the FSE in this experiment. The efficiency of the FS increased when the outside air RH was lower. It is necessary to know the ventilation characteristics of a greenhouse in order to provide good control of the inside environmental conditions, and a good crop yield of high-quality produce.

The ventilation rate in this experiment was found to be affected mainly by the temperature difference. However, greenhouses must be equipped with side and ridge ventilators in order to increase air change due to wind and temperature difference. The preliminary results obtained from this study can be used to estimate the FSE in greenhouses for the hottest period of the year. The results could also be used to determine the inside air temperature and RH in greenhouses using a FS.

The FS could be operated at various pressures until the conditions in the greenhouse were stabilized. Thus, the adjustment of the pressure may provide the desired conditions of temperature and RH in the greenhouse. For the installation and operation of a FS in greenhouses built as large units, the FGN should be uniformly distributed in the space above the plant canopy, and the openings in the roof should be uniform. Future studies should focus on modeling the efficiency of the FS, and utilizing the FS with the natural ventilation in greenhouses. Such experimental studies will be very useful to optimize the management of FSs in hot and dry climates.

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