Enhancing the evaporative cooling performance of fan-pad system using alternative pad materials and water film over the greenhouse roof

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Abstract: Greenhouse technology is a viable option for sustainable crop production in the regions of adverse climatic conditions. During hot seasons the heat input to a greenhouse causes the internal temperature to exceed its optimal value. The present study was devoted to construct an evaporative cooling system to reduce heat stress inside a greenhouse. Two identical small-scale greenhouses were designed, constructed, and installed on an open roof of a domestic house. The two greenhouses were cooled using fan-pad system. In addition, a thin water film was applied on the roof of one greenhouse to study the effect of roof water film and fan-pad (combined system) on the cooling performance. The two cooling systems were compared under the same condition. Three new evaporative cooling pads represented by Cryperus Alopecuroides Rottb (Samar), Cyerus Alternifolius (Purdy) and Cyperus Rotundus l (Nut-grass or Se'd) were adapted and evaluated. Three pad face air velocities ranged between 0.45 and 1.01 m s^{-1} and two thicknesses of 10 and 15 cm were used in the investigation of the cooling performance criteria. Results showed that the proposed cooling pads in the suggested evaporative cooling systems were able to maintain acceptable microclimatic conditions for greenhouse models. Se'd pad material proved more efficiency in temperature reduction. It was revealed that the temperature inside the greenhouse operated under the combination of roof water flow and fan-pad system was less than that for fan-pad greenhouse by about 1.1 to 5.44° C in the morning and afternoon respectively. The air relative humidity was increased due to humid effect provided by cooling system which protects crops from excessive transpiration and crop damage. The daily average cooling efficiencies of 88.4, 83.1 and 79.6% were obtained for Se'd, Purdy and Samar, respectively during testing days inside the combined system at 15 cm pad thickness and 0.45 m s^{-1} pad face air velocity. The Se'd pad material showed the highest efficiency as compared to other pad materials and could be used as an alternative pad material.

Keywords: greenhouse, evaporative cooling, fan-pad system, pad material, roof water flow

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1 Introduction

Greenhouse cultivation creates favorable microclimates for crop production to obtain the prevalent air temperature, humidity levels and reduced the disease rates. Since the greenhouse glazing materials allow the short wavelength to pass through but long wavelength radiation such as infrared is trapped inside the greenhouse (greenhouse phenomena). Therefore, the greenhouses will be out of work during the hot periods, which will result in minimizing utilization equipment. Removing the greenhouse cover throughout the year is advised but this adds an extra cost expenses. For successful crop

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production during summer it is necessary to reduce the air temperature inside the greenhouse or regulate the temperature closer to the ambient temperature.

The effect of solar radiation distribution in a typical agricultural building was numerically investigated, taking into account the thickness of the cover, its spectral optical and thermal properties (Catherine et al., 2010). Harmanto et al. (2006) investigated the effect of the use of nets with different mesh-sizes on the internal microclimate and ventilation rate in greenhouses located on the humid tropics was carried out.

To overcome the problems of high temperatures during summer months, cooling the greenhouse is considered as the basic necessity for crop production in tropical and subtropical regions. A breakdown of cooling system for even one day may result in complete crop failure. Improvement of cooling system that provides favorable microclimate for crop growth is a difficult task because the design is closely related to the local environmental conditions. Also the choice of the crops to be grown, maintenance, ease of operation and economic viability are considered the key factors for selecting appropriate technology for cooling (Kumar et al., 2009; Sethi and Sharma, 2007).

Cooling systems are presented in ventilation shading and evaporative cooling. Evaporative cooling system has been used in greenhouses regarding to its simplicity of operation and control. The main evaporative cooling methods in use today are fogging, fan-pad method, and misting (Arbel et al., 1999).

Abdel-Ghany and Kozai (2006) and Fuchs et al. (2007) revealed that the evaporative cooling systems have become the standard for many greenhouses. The principles of evaporative cooling indicates that the evaporative cooling systems can only remove room sensible heat, thus the evaporative cooling systems works best in hot and dry climate where the maximum evaporative cooling will result.

Eltawil and Samuel (2007) developed a 1 m^3 evaporative cooled rice straw storage structure with length-breadth ratio of 1.0 which was used for curing process.

It is intuitively apparent that the evaporative cooling in Egypt produces insufficient cooling and increases room relative humidity and absolute humidity. Meteorological data showed that the average minimum and maximum temperature ranged from 14ºC to 30ºC during winter and summer respectively. Variations of daytime temperatures and prevailing winds made the only differences between the seasons. For these conditions, the greenhouses can do without additional heating and the cooling technologies are needed where the warm season can exceed six months (El-Zan, 2008).

The evaporate cooling substantially increases the rates of heat and mass transfer by forcing the movement of air past an enlarged liquid water surface area for evaporation by using fans. The vertically mounted porous pad can be wetted by dripping water onto the upper edge. The wet porous cooling pad can provide large water surface in which the air moisture contact is achieved (Liao and Chiu, 2002).

Al-Jamal (1994) studied the evaporative cooling based on fan-pad system in a commercial greenhouse during the summer period in arid countries. He indicated that changing the air volume of 20 times per hour is necessary for favorable condition in the greenhouse under dry weather conditions. A mathematical model of water evaporation rate, airflow rate and cooling effect in an evaporative cooling system was developed by Abdel-Wahab (1994) for farm structures in Saudi Arabia. He pointed out that an appreciable amount of energy and water consumption can be saved by covering the roof of the greenhouse with external shading.

The commercial pad cooling materials are usually complicated to manufacture and they are costly and are not available. Therefore, it is necessary to investigate and evaluate the locally available materials to be used as cooling pads in rural agriculture areas. Several researchers investigated the feasibility of some alternative cooling pads to be used in the greenhouses. Under the local condition of each investigation the proposed pad materials were able to create acceptable performance (Abdel-Rahman, 2000; Abdel-Rahman, 2006; Liao and Chiu, 2002).

Kittas et al. (2003) applied a partially shading to a large greenhouse equipped with cooling pads to eliminate the temperature gradients between inlet and outlet associated with fan-pad system. Davies (2005) enhanced the cooling performance of an ordinary evaporatively cooled greenhouse by means of regeneration of desiccation of the incoming air. The investigated system reduces the greenhouse temperature by 5°C as compared with the conventional evaporative system.

Jain (2007) developed an evaporative cooler named "two stages evaporative cooler" that reduces the wet-bulb temperature of outside air before it passes through the evaporative cooling pads using a heat exchanger. Thus, more temperature drop is possible with the evaporative cooling system.

Sprinkling of thin layer free water onto a surface of the greenhouse roof leads to the increase of the water evaporation rate and lower the air wet bulb temperature close to ambient air. The effect of flowing water film over the greenhouse roof on inside air temperature of a low cost plastic greenhouse at Delhi (India) climatic conditions was studied by Sutar and Tiwari (1995). They concluded that inside air temperature was observed to be 4–5ºC lower than control greenhouse. The inside air temperature dropped by about 10ºC when the greenhouse roof shaded with wet cloth (water film).

The commonly used cooling technologies for cooling greenhouses in the tropical area are not satisfactory. Therefore, there is a necessity to explore new and alternative cooling technology for greenhouse suitable for tropical climates (Rault, 1990; FAO, 1990).

The main purposes of the present study are: i) to investigate alternative, economic and more effective evaporative cooling pad materials and to evaluate their performance under different operating conditions of pad face air velocity and pad thickness; ii) to investigate the cooling effect of combined fan-pad system with thin film water flow over the greenhouse roof; iii) to estimate the economic utility of the greenhouse and proposed cooling systems.

2 Materials and methods

2.1 Theoretical approach: Greenhouse with plant grown inside

Solar radiation entering a greenhouse is absorbed by plants, soil and greenhouse construction elements (Figure 1). The warm objects then re-radiate this energy outward. The amount of radiant heat loss depends on the type of glazing, ambient temperature, cooling/heating systems applied and amount of cloud cover. Rigid plastic and glass materials exhibit the "greenhouse effect" because they allow less than 4% of the thermal radiation to pass back through to the outside.

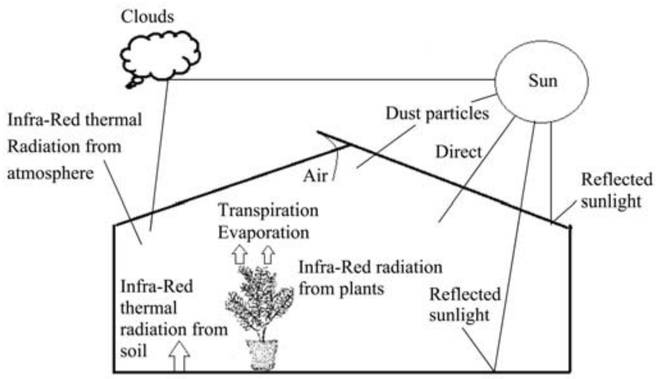


Figure 1 Energy exchange between the greenhouse equipped with a crop grown inside and the surrounding

Temperature inside a greenhouse depends on outside condition, greenhouse configuration, glazing material, heating/cooling strategies and grown crops.

Predicting greenhouse temperature during production season is a complex issue. Not only the existing of crop or its absence affects temperature prediction, but the plant variety, plant age, leaf area index, number of plants inside the greenhouse, light density, photosynthesis rate, plant containers and root media do. There are two ways to model the plants inside the greenhouse. The first method calculates internally the heat, moisture and CO_2 exchange between the plants and surrounding air, while the second method can be used as input to the model. The plant component is configured to allow the use of any of the two methods individually for the heat, latent heat and CO_2 gains. Thus the heat flux internally was calculated and used with an outside more detailed component for the calculation of the other gains (Frausto et al., 2003; Katsoulas et al., 2001; Kittas et al., 2001; Tangka, 2003).

2.1.1 Plants contribution in internal environment

The sensible heat flux H_c in W m^{-2} exchanged between the canopy and the air is estimated from Equation (1) (Katsoulas et al., 2001)

$$H_c = R_{n,int} - \lambda E_c \quad (1)$$

where, H_c = The sensible heat flux, W m^{-2}; $R_{n,int}$ = The intercepted net radiation and equal to ($R_{n,a} - R_{n,b}$); $R_{n,a}$ = Net radiation above the crop, W m^{-2}; $R_{n,b}$ = Net radiation below the crop, W m^{-2}; λ = Latent heat of vaporization of water, J kg^{-1} [vapour] and λE_c = Transpiration rate, W m^{-2} [ground covered by crop].

The highest possible temperature a canopy can achieve at an air temperature T_i is given by Equation (2)

$$T_M = T_i + R_{n,int} / g_a \rho C_p \quad (2)$$

where, T_M = The highest possible temperature of a canopy, K; g_a = Bulk aerodynamic conductance, m s^{-1}; C_p = Specific heat of air at constant pressure, J kg^{-1} [air] K^{-1} and ρ = Air density, kg [air] m^{-1} [air].

The canopy-to-air temperature difference was significantly different, being less negative under forced ventilation

The energy balance of the greenhouse, according to the ASAE (1999) can be written in the following simplified form Equation (3):

$$(1-\varepsilon)\, G_i = U\,(T_i - T_o) + \rho\, C_p\, Q_v\,(T_c - T_o) \quad (3)$$

where, ε = Evaporation coefficient, dimensionless; G_i = Incoming solar radiation over the rose crop, Wm^{-2}; U = Heat transfer coefficient through the cover, Wm^{-2} K^{-1}; T_i = Greenhouse air temperature, K; T_o = Outside air temperature, K; T_c = Canopy temperature, K and Q_v = Ventilation flux, m^3 [air] m^{-2} [ground] s^{-1}.

In what follows, the heat load is assumed to be equal to the net radiation measured above the canopy, $R_{n,a}$ The concrete floor and substrate evaporation are considered as negligible, so that the evaporation coefficient is calculated as Equation (4)

$$\varepsilon = \lambda E_g / R_{n,a} \quad (4)$$

where, E_g = transpiration rate, kg m^{-2} [total ground area] s^{-1}.

Canopy transpiration, which represents the major cooling process in greenhouses, depends strongly on the crop leaf area index. Transpiration represents, through the evaporation process, a major mechanism for cooling plant leaves and their environment. This explains why maintaining high levels of canopy transpiration rate in greenhouses is one of the most efficient and least costly ways in cooling the greenhouse environment during warm days with high radiation load, prevailing for most of the time in Mediterranean and hot countries.

Kumar and Kaushik (2005) reported that planted roofs contribute not only to reducing the thermal loads on the building's shell but also to reducing urban heat island effects in densely built areas having a little natural environment.

Tiwari (2002) presented an Equation 5 for the thermal energy absorbed by the plant inside a greenhouse:

Rate of thermal energy absorbed by the plant = Rate of thermal energy lost due to transpiration, convection and radiation by the plant + Rate of thermal energy stored by the plant.

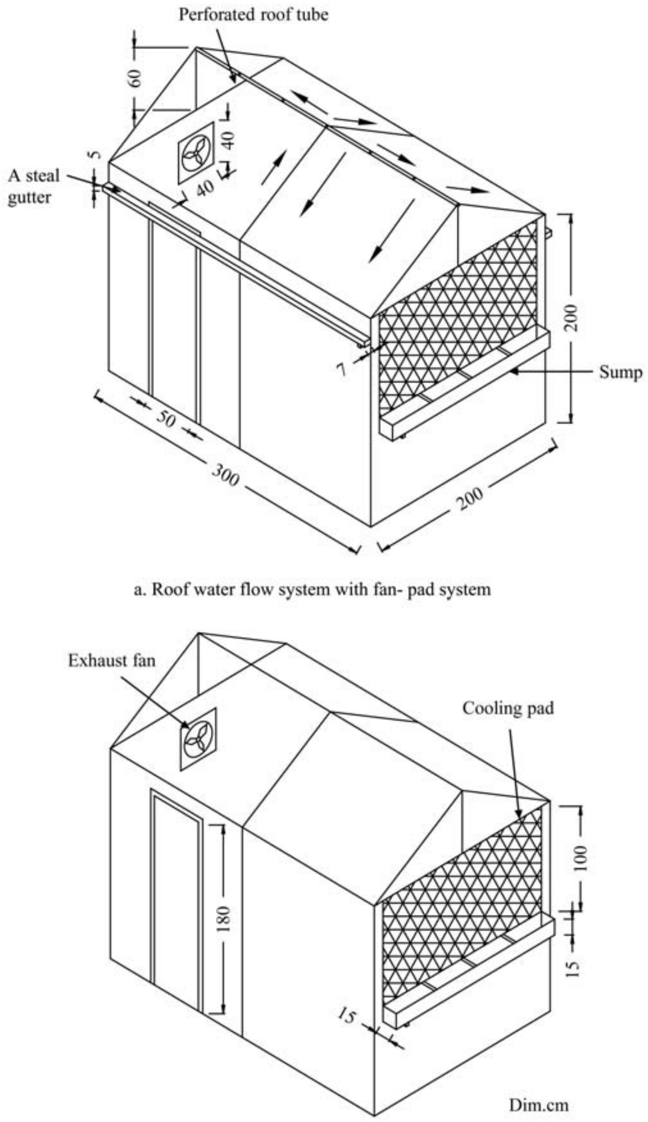
$$\alpha_p (1-r_p) F_p (1-F_n)(1-r)\tau S(t) = [q_{ep} + q_{cp} + q_{rp}] A_p + M_p C_p \frac{dT_p}{dt} \quad (5)$$

The solar radiation, S(t), is incident on the canopy of greenhouse. A fraction of solar energy $\{rS(t)\}$ is reflected back from canopy and apart of the rest of radiation, $\{(1-r)S(t)\}$, is transmitted inside the greenhouse. Out of this transmitted radiation, $\{(1-r)\tau S(t)\}$, a fraction of this $\{F_n\,(1-r)\tau S(t)\}$, falls on the canopy.

2.2 Experimental greenhouses

The experiments were carried out in the premises of an open roof (seventh floor) of a domestic house, kafr Elsheikh city, Kafr Elsheikh, Governorate, Egypt. The location lies at latitude 31.07 N and longitude 30.57 E.

The experiments were conducted during summer season 2006/2007 in two identical experimental greenhouses, gable even span type oriented East-West and covered with single layer polyethylene plastic cover (120 μm thick). Each greenhouse has gross dimensions (L×W×H) of 3 m × 2 m × 2.6 m, with a net floor surface area of 6 m^2. Each greenhouse was equipped with a vertical evaporative cooling pad located at the west wall. The cooling pad dimensions were 1.8 m long and 1 m high as shown in Figures 2 and Figure 3. One axial flow suction fan, direct driven, 40 cm diameter, four blades and 120 m^3 h^{-1} discharge was located on the leeward side of each greenhouse. The fans were connected to a potentiometer to regulate fans speed.



a. Roof water flow system with fan- pad system

b. Fan-pad system

Figure 2 A Schematic diagram for the two experimerntal greenhouses to be cooled

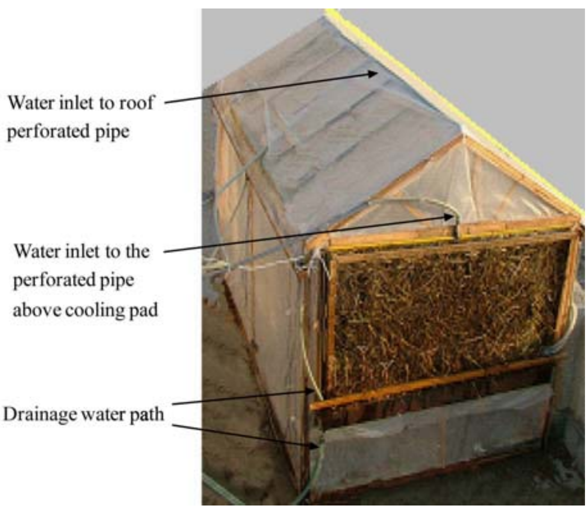


Figure 3 Greenhouse operated under the combination of roof water flow and fan-pad system using Se'd as an evaporative cooling material (A)

A water tank with net volume of 500 L was used for water storage and recirculation in both greenhouses. The tank was sited outside the greenhouse at 1m under greenhouse floor level and at 2 m distance from the cooling pads.

A centrifugal water pump was used to pump water into pad through water distribution system for each greenhouse, where water was drawn from water tank. A valve was placed in the line from the pump, so that the water flow through the distribution pipe can be adjusted. Water pump of 373 W (24 L min^{-1} and 15 m head) was used for fan-pad ystem. While pump of 418 W (29 L min^{-1} and 30 m head) was used for combined system (fan-pad and roof water flow). The water collected by the bottom gutter was returned to a sump from which the water is pumped to the upper distribution pipe.

2.2.1 The combined roof water flow and fan-pad system

One of the experimental greenhouses was provided with a perforated PVC tube to creat a thin roof water film over the external cover of the greenhouse. The PVC tube (12.5 mm diameter and 3 m length) was fixed longitudinally above the greenhouse roof. Both ends of this tube were capped and water inlet to the tube from middle. Holes with about 1.5 mm diameter were drilled in a line about 5 cm apart along the bottom side and used to discharge water to the greenhouse roof.

To redirect drain water back to water tank a steal gutter of 3.2 × 0.12 × 0.12 m was laterally mounted on each side of the greenhouse. Additional single polyethylene film (120 μm thick) was hanged over greenhouse main roof at about 5 cm above the perforated pipe to condensate the evaporated water. Figure 4 shows a side view of the combined cooling systems arrangement. It should be noted that in case of large scale multisapn greenhouse, it is possible to use one gutter between each two adjacent spans and one sump for all the adjacent spans. Meanwhile the water pump capacity should be increased to be capable of providing the sufficient amount of water on the roof. The rest of the system components could be adapted according to the multispan dimensions and the area covered by greenhouse.

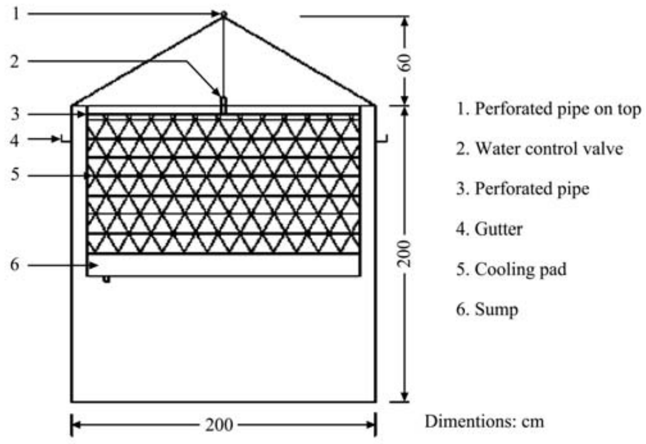


Figure 4 Schematic diagram of combined cooling systems arrangement

2.3 Cooling media properties

Several preliminary experiments were carried out using some agricultural residuals and weeds in order to test and stand on the best and more suitable materials that can be used as pad. Based on their cooling effect, three of them were selected (Table 1). Some of these materials affect the agricultural crops growing and the other spreads rapidly clogging drainage, ditches, shedding out other vegetations and interfering with shipping and recreation. The materials were collected from fields, drainage and ditches and left for one week in open area, for air drying. A preliminary experiment was conducted to select pad thickness, pad face air velocity and to evaluate the cooling performance of the two proposed cooling systems and stand on expectant problems.

Table 1 The characteristics of evaporative cooling pad materials

Items	Name of pad material		
	Cyperus Rotundus l (Nut-grass or Se'd)	Cyerus Alternifolius (Purdy)	Cryperus Alopecuroides Rottb (Samar)
Location	Field	Ditches, channel, drainage	Field
Cross-section	Triangle	Semi-cercle	Triangle
Structure	Hollow	Spongy	Solid

Three new pad materials were tested at 10 and 15 cm thicknesses. The evaporative cooling pads were exposed to pad face air velocity between 0.45 and 1.01 m s^{-1}. The pad materials were supported by a wire mesh at specified pad thickness to provide a constant density of about 32 kg m^{-3}. Care was taken to close all gaps and homogenize the intended pad thickness. A wooden framework was used as a pad support. The pad materials were wetted using a perforated steel tube mounted horizontally above the pads.

2.4 Procedure and instrumentation

Experimental cooling systems were tested including a pad materials and pad thicknesses of 10 and 15 cm.

For every pad material and specific pad thickness nine points on pad surface were used for pad face air velocity estimation. The rotating speed of the exhaust fan (airflow rate) was changed using electrical switch (potentiometer) and the pad face air velocity was measured at the nine points from the inside pad face using digital Vane type anemometer (ranged from 0.1 to 10 m s^{-1} with an accuracy of ± 0.1 m s^{-1}). A unique average value was determined for each pad material at specific thickness. Finally three pad face air velocities were investigated (0.42, 0.85 and 1.01 m s^{-1}) for different pad thicknesses and pad materials.

Insolation was measured with the help of thermoelectric pyranometer (identification No. 8-S-1-2, make of TWC Tokyo, 100 mV/cal cm^{-2} m^{-1} output, and total accuracy of ±5%), which set horizontally inside and outside the greenhouses for instantaneous insolation measurements.

All temperatures were measured with the help of copper-constantan thermocouple and digital temperature thermometer (model HH 26J, temperature span -80 to 760°C, resolution 1°C, accuracy ± (1% + 1°C), Omega.com). The thermocouples wires were sited adjacent to the pad material (at the centre of the greenhouse) and beside the exhaust fan. Also, thermocouples were arranged vertically on centered locations at top, centre and bottom to measure the fluctuation of dry bulb temperatures inside the greenhouse. In addition, pad and water temperatures were measured with thermocouple wires. All thermocouples were calibrated at the freezing and boiling points of water.

Figure 5 shows the temperature readings that were taken at different positions and levels inside the greenhouses. Dry and wet-bulb temperatures were manually recorded at the measuring positions during each test. These measured values used as inputs variables to the computer program that depending on psychometric relations to determine the air properties (Albright, 1990).

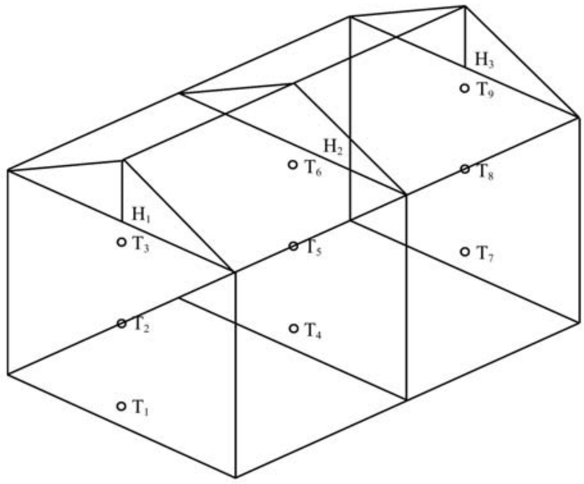


Figure 5 Three central locations ($H_{1,2,3}$) of air dry and wet-bulb temperature sensors (T) inside the experimental greenhouse

Flow rate of water was measured by allowing water to fill a storage tank of known volume with recorded time and the measured flow rate was kept constant throughout the experiment.

The energy required to operate load (water pump and exhaust fan) was measured in terms of kWh with the help of energy meter (190-230 V, 50 Hz, AC 1 phase, 2 wires 480 Rev/kWh). It was connected at the inlet source power.

Thermostats were located in central position inside the greenhouse and were used to turn pumps and fans on and off as were required to optimize response to outdoor climate changes, and maintain more uniform greenhouse temperatures with lower operating costs.

The thermostats were set to stop the water pumps before fans go off so that the pad could dry out. Each thermostat has provided with manual control switch wired in parallel with it so that manual control can be used when desired.

Initially, the experiments were carried out to determine the maximum cooling efficiency that could be achieved by the new adapted pad materials. Therefore, the control unit (thermostat) was turned off and separated from the system, and the consumed energy was measured as total energy consumption per day (10 h). After identifying the best conditions of each pad materials, the energy consumption was measured at hourly intervals, and the thermostat was connected to the system.

2.5 Cooling efficiency

The greenhouse cooling efficiency was estimated for both cooling systems at different operation conditions using the following Equation (6) (Koca et al., 1991):

$$\eta_{cool} = \frac{(T_o - T_i)}{T_o - T_{owb}} \times 100 \tag{6}$$

where, η_{cool} = the greenhouse cooling efficiency, %; T_i and T_o = the inside and outside air dry temperatures, ºC; respectively and T_{owb} = wet bulb temperature of outside air, ºC.

2.6 Temperature reduction

The difference between the temperature outside the greenhouse and air temperature inside the greenhouse is used as an important parameter to describe the cooling performance of evaporative cooling systems. The temperature reduction describes the cooling effect inside the two greenhouses and easy criteria to evaluate the effectiveness of cooling system (Equation (7)).

$$\Delta T = T_o - T_i \tag{7}$$

where, ΔT is the cooling effect, ºC.

2.7 Pad water hold capacity and water release rate

Small samples of 150 g of each pad material were taken and submerged in water for 24 h to ensure the maximum absorption capacity. They were taken out and left until the end of dripping. Then they were weighed again at different time intervals to get the maximum water holding capacity.

2.8 Economic utility

To estimate the economic utility of the greenhouse and proposed cooling systems, the break-even point method was used. In case that break-even point method the money is taken for certain investment in the industry at a given interest rate and the same is paid back in a given period such that no profit occurs. The cost economics for the greenhouse cooling systems with the following assumptions:

- The greenhouse structure has been placed on the farmer's own premises roof and no rent is paid for the space.
- The main frame of the greenhouse to be fabricated and assembled on the site.

- The structure is used for year round.
- The running period of the cooling system is 200 days.
- The thermostat and fan would be replaced every five years.
- The pad material would be replaced every year.
- The cost of pad materials wasn't considered in the calculations.
- No insurance and taxes are involved in the structure.
- The plastic glazing sheet would be replaced every 5 years.
- The total initial investment being small, and is met from the farmer's own resources.
- The farmer (housekeeper) makes the arrangement of periodic refilling the water sump.
- Total life of the project is 10 years.
- About 15 % of the area is left for movement in the greenhouse, and the planting is done on the remaining area.

The recorded data was analyzed to determine the cooling performance of the two proposed fan-pad system and fan-pad system combined with roof water film. Several multiple regression equations were obtained and can be used to predict the cooling performance of the two proposed cooling systems under different operating conditions.

3 Results and discussions

3.1 Water holding capacity of pad materials

Preliminary experiments were carried out to explore the water holding capacity of three pad materials namely: Cryperus Alopecuroides Rottb (Samar), Cyerus Alternifolius (Purdy) and Cyperus rotundus l (Nut-grass or Se'd). Figure 6 shows the results of water holding capacity of the three different pad materials. It clearly showed that the Purdy material held higher amount of water reached to 800 g as compared with Samar and Se'd. Also the Purdy material has higher water release rate of about 510 g $(19\ h)^{-1}$ as compared with other two materials. This means Cyerus Alternifolius (Purdy) needs to be misted more frequently than other pad materials, which is considered to be negative point in term of water and energy consumptions and consequently, in operation costs.

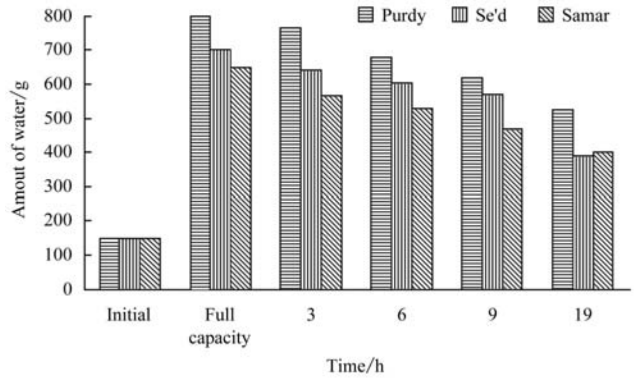


Figure 6 Water pattern release for the three different pad materials

3.2 Environmental conditions

The environment inside the greenhouse is strongly affected by the outside conditions including the time of year, the intensity and duration of natural sunlight, the air relative humidity. Any evaporative cooling system is influenced by such factors, thus a typical day has been chosen for the diagram (Figure 7).

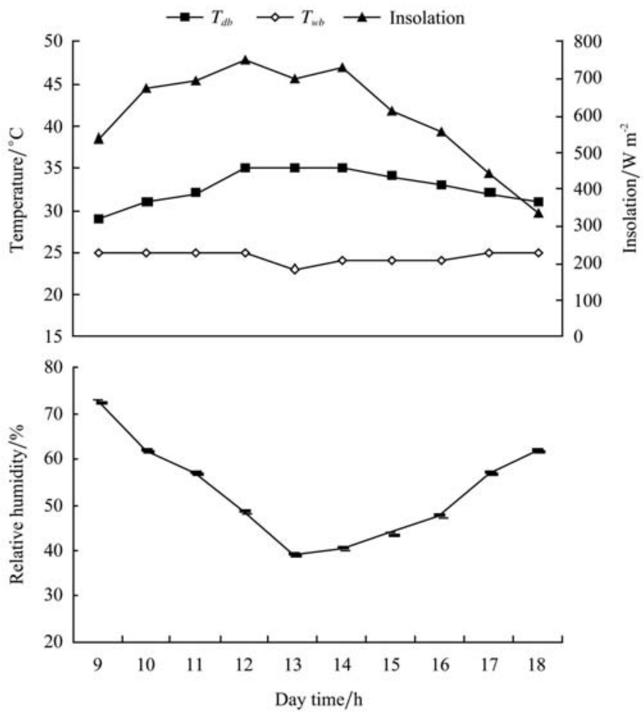


Figure 7 Outside air temperatures dry and wet bulb (T_{db} and T_{wb}), relative humidity (RH) and insolation on a typical summer day (16/8/2006)

3.3 Temperature of inlet air flowing in the pads and water

Beside the inside temperature, the pad, water tank (sump) and water gutter temperatures were measured in each treatment. From the observation on water and incoming air temperatures, it was noticed that the temperature of incoming air, pad and water didn't differ for the three pad materials. The temperature of air just leaving the pads was always lower than the temperature of the water arriving on top of the pads by up to 2°C as is shown in Figure 8. The correlation between pad temperature, T_{pad}, and water tank temperature, $T_{w.Tank}$, was computed and expressed as Equation (8):

$$T_{pad} = -22.86 + 1.73\ T_{w.Tank} \quad (R^2 = 0.7) \tag{8}$$

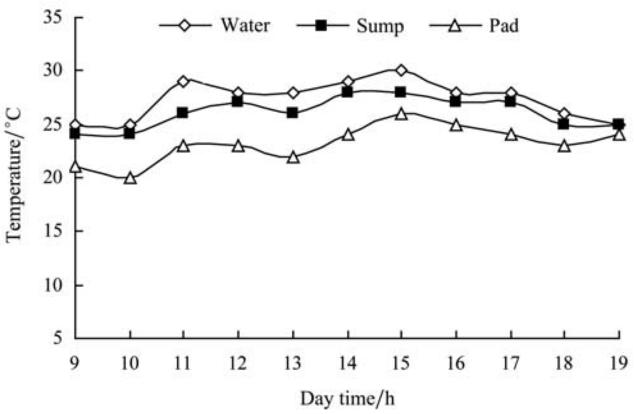


Figure 8 Hourly variation in temperature for water in the tank (sump), water in the gutter and incoming air through pad

3.3.1 Air temperature profiles throughout the greenhouse

Two evaporative cooling systems passed on fan-pad method were investigated to improve and provide the desired level of microclimatic conditions for the greenhouse. The experiments were carried out in the experimental greenhouses from August to September 2006 without load (no crop was planted inside).

The ambient dry bulb temperature ranged from 26 to 36°C. While, the internal greenhouses air temperature remained at the range of 20.5 to 32.7°C, which was below ambient air by 1.1 to 13°C and this is in agreement with the desirable range of 16 to 32°C as is mentioned by Ozturk (2003).

Comparison between roof water flow and fan-pad greenhouses revealed that the first one provides better cooling process than the later regarding to temperatures patterns. This was obvious from low temperature values occurred inside roof water flow greenhouse combined with fan-pad system. That was due to the cooling effect of thin water film flowing over greenhouse cover. The water film reduced the amount of solar radiation entering the greenhouse and subsequently minimized the heat stress inside the greenhouse. Moreover it absorbs heat from greenhouse cover. Care was taken to ensure that the thin water film running over the greenhouse roof didn't block or disturb much amount of insolation. The maximum difference between the two greenhouses was 5.44°C which achieved by 15 cm thick Samar pad material at 0.85 m s^{-1} pad face air velocity. Whereas the ambient temperature was 30°C the internal air temperature was 22.5 and 27.94°C for roof water flow (double covers) and fan-pad greenhouses, respectively as is shown in Figure 7.

The temperature fluctuation inside the two greenhouses depends on the space between the cooling pad and extracting fan. For example, Figure 9 shows the temperature at various positions inside the greenhouses with the time of the day for 15 cm Samar pad material at 0.85 m s^{-1} pad face air velocity. A gradual temperature rise, from the pads to the fans, reaches to 4.67°C as a maximum was found. A difference of 7°C is considered to be acceptable (Arbel et al, 2003).

The minimum mean (mean of pad, centre and exist) value of about 21.84°C was found when using the combination of roof water flow and fan-pad system at 1.01 m s-1 pad face air velocity and 15 cm Se'd pad material. Corresponding outside temperature was 33°C at 54.7 % relative humidity. While the minimum mean value achieved by fan-pad system was 24.94°C during the operating period of 15 cm Se'd pad material with 0.45 m s^{-1} pad face air velocity. The ambient temperature was 35°C with 58.5% relative humidity.

For all pad materials, results of the two cooling systems were sufficient to maintain the greenhouse microclimatic conditions within the desirable range and suitable for crop growth and production as it is noticed from the internal values of temperatures as is mentioned previously. The results showed that the water flow system was able to keep the air temperature inside the greenhouse at 13°C lower than that inside the fan-pad greenhouse. This good performance is due to the high efficiency of the proposed cooling system.

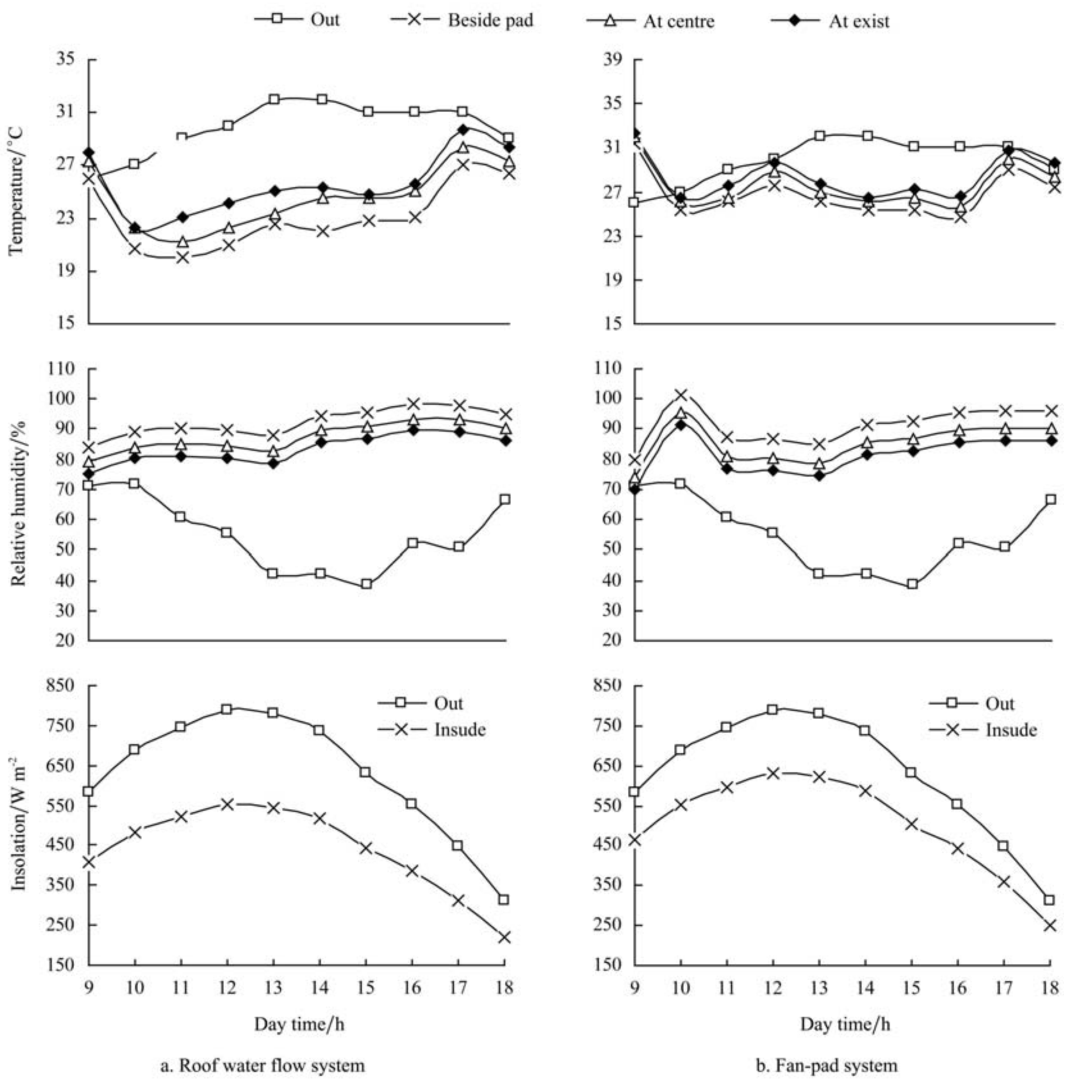


Figure 9 Variations of insolation, air temperature and air relative humidity throughout the operating period for both greenhouses at 15 cm Samar pad material and 0.85 m s^{-1} pad face air velocity

3.4 Cooling effect

The air temperatures inside both greenhouses were compared with the outside air temperatures as one important criteria to measure the cooling effect of the cooling systems. It was observed that the temperatures measured inside the two greenhouses remain below that of outside since the sensible heat was converted into latent heat through evaporation of water. Meanwhile the internal air relative humidities for both greenhouses remain higher than that of outside air. At beginning, before starting the cooling system, the inside air temperature was higher or almost close to ambient air conditions (i.e. Ambient temperature ±0.9-2.2°C), and then the cooling effect started to take place. The maximum difference in air temperature between inside and outside occurred in the midday where the outside air relative humidity was at its minimum value. The difference of air temperature between inside and outside the greenhouse was about 1.1°C at 09:00 am (when the cooling system started) and increased until reached 13°C at 12:00 h (at noon). The average difference of air temperature between inside and outside the greenhouse was 7.5°C for the period of time that covered by experiments.

Values of temperature reduction differ with the operating conditions which was represented by pad material, pad thickness, pad face air velocity and cooling system used.

Figure 10 shows the temperature difference (reduction) that was estimated from the two investigated systems as function of input experimental parameters.

The temperatures reduction resulted inside the greenhouse operated under the combined cooling system was higher than that operated under fan-pad system by 4.7 degree as a maximum. This was due to the evaporation of water from pads; and the thin layer of the free water surface (roof water flow) that cause an increase in the evaporation rate and to fall to the wet bulb temperature of the closely surrounded air.

Such a result reflects more cooling effect when applying a thin water film over the external cover of the greenhouse.

The investigated cooling systems are passed upon using new alternative evaporative cooling pads. Cooling potential derived varied at each pad material when other conditions remained constant.

Values of temperature reduction throughout the operation period indicated that temperature reduction obtained from all the Se'd (Nut-grass) pad material treatments was higher than that of the other pad materials.

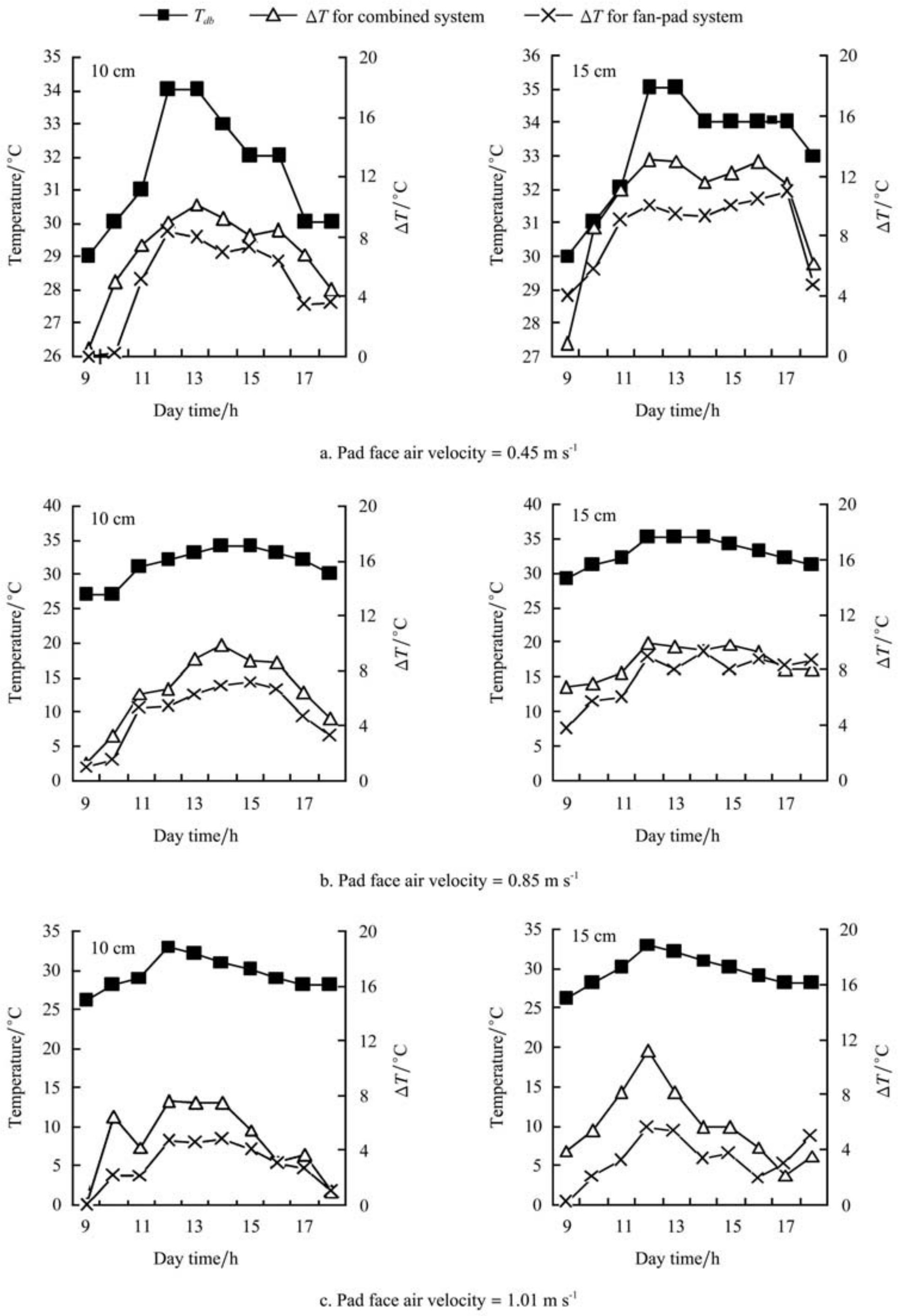


Figure 10 Variations of outside air temperature and air temperature reduction in greenhouses for fan-pad and combined systems using 10 and 15 cm Se'd pad material at 0.45, 0.85 and 1.01 m s^{-1} pad face air velocities

3.4.1 Cooling efficiency

The recorded results indicated that the cooling efficiency was low in the morning (starting the system), because the system is not yet stabilized and the greenhouse effect (thermal effect) takes place. Also, the cooling efficiency values were lower in the morning when relative humidity levels were high. Since the wet bulb depression was the highest at 12:00 to 14:00 h in the afternoon, when the dry-bulb temperature was normally at its peak, the highest efficiency of the evaporative cooling was achieved.

The estimated cooling efficiency varied with the two cooling systems presented in this investigation. Also, it varied with the operating conditions presented in pad face air velocity, pad thickness and pad material. The higher cooling efficiency was achieved with thicker pads and lower pad face air velocity as is shown in Figure 11. According to the recorded results, the efficiency of the combined cooling system was better than that of the fan-pad system. For example, the daily average cooling efficiencies were 71.6, 80.5 and 84.5% for combined system; 59.2, 63.3 and 74% for fan-pad system at 1.01, 0.85 and 0.45 m s^{-1} pad face air velocity, respectively at 10 cm Se'd pad thickness.

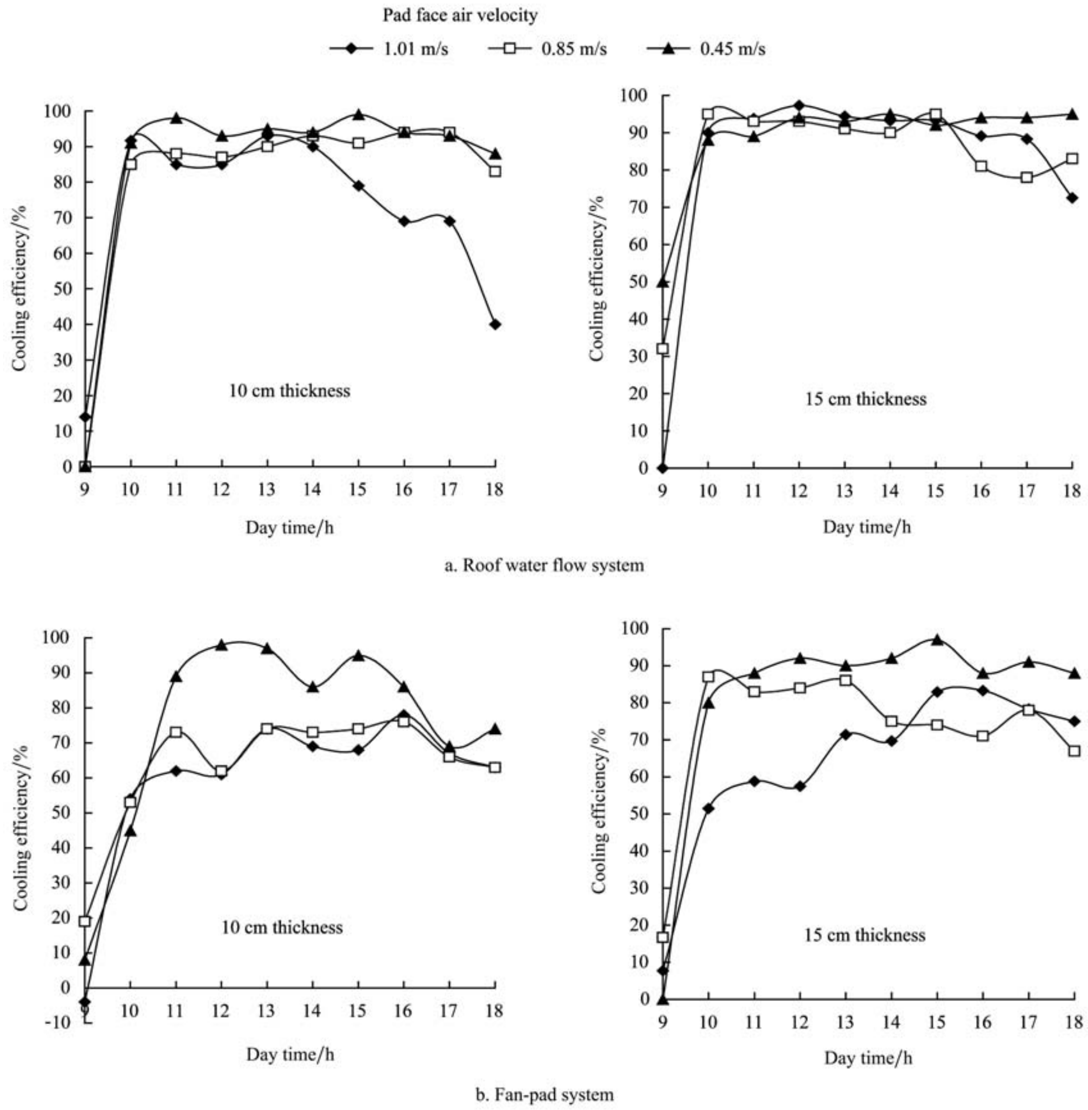


Figure 11 Variations of cooling efficiency with the time of the day for both greenhouses at 10 and 15 cm Se'd pad material within different experimental conditions

While the daily average cooling efficiencies were 81.2, 83.1 and 88.4% for combined system; and 63.6, 72.17 and 80.6% for fan-pad system at 1.01, 0.85 and 0.45 m s^{-1} pad face air velocity, respectively at 15 cm Se'd pad thickness.

Figure 12 shows the cooling efficiency of combined system (roof water flow and fan pad system) for the three investigated pad materials at the lowest pad face air velocity and 15 cm pad thickness. Cooling efficiency of other two pad materials (Purdy and Samar) followed the same trend (data not shown). The Se'd pad material recoded highest efficiency as compared with the other materials. The daily average cooling efficiency of 88.4, 83.1 and 79.6% were obtained for Se'd, Purdy and Samar, respectively during tested days inside the combined system at 15 cm pad thickness and 0.45 m s^{-1} pad face air velocity. These results are corresponding to daily average ambient temperature of 33.2, 32.6 and 31.3ºC; and daily average insolation of 661, 581.2 and 682.2 W m^{-2}, and daily average relative humidity of 58.4, 58.3 and 68.8%, respectively.

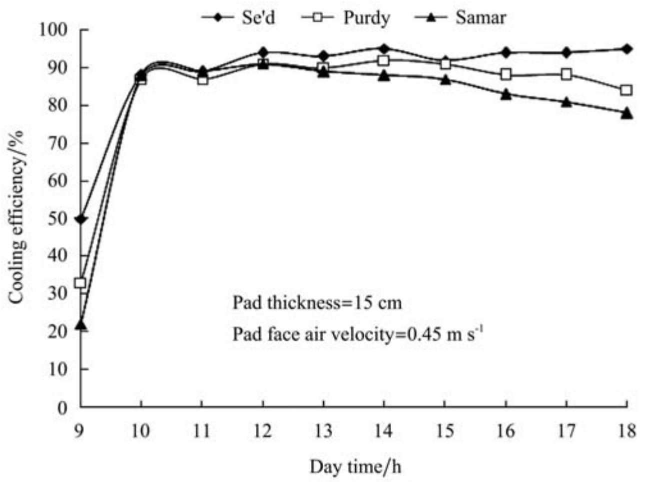


Figure 12 Variations of cooling efficiency with the time of the day for three pad material at 15 cm pad thickness and 0.45 m s^{-1} pad face air velocity inside the roof water flow greenhouse

Some multiple regression equations were obtained for the three pad materials (Se'd, Purdy and Samar) at 15 cm pad thickness and 0.45 m s^{-1} pad face air velocity inside the roof water flow greenhouse as Equation (9), Equation (10) and Equation (11):

$$\eta_{Se'd} = 143.5 + 0.31T_d - 0.02Ins - 0.92RH \quad R^2 = 0.71 \tag{9}$$

$$\eta_{Purdy} = -195.2 + 7.42T_d - 0.034Ins + 0.97RH \quad R^2 = 0.65 \tag{10}$$

$$\eta_{Samar} = -20.48 + 5.44T_d - 0.044Ins - 0.583RH \quad R^2 = 0.55 \tag{11}$$

where, T_d is ambient dry bulb temperature, ºC; Ins is the insolation, W m^{-2} and RH is the relative humidity, %.

3.5 Energy consumption by cooling systems

It was found that both of pad material and pad thickness parameters have negligible effect and did not influence power consumption. The power consumption was influenced by pad face air velocity, pump discharge and total dynamic head of the water pump.

It was found that the energy consumption by the roof water flow system was higher than that of fan-pad system at all pad face air velocities. The total energy consumption of roof water flow was higher than fan-pad system by 80, 79 and 78.2% at pad face air velocity of 0.45, 0.85, and 1.01 m s^{-1}. Figure 13 shows the total energy consumption by fan and water pump per day (kWh/day), when thermostat was not working (day time is 10 h) for both cooling systems.

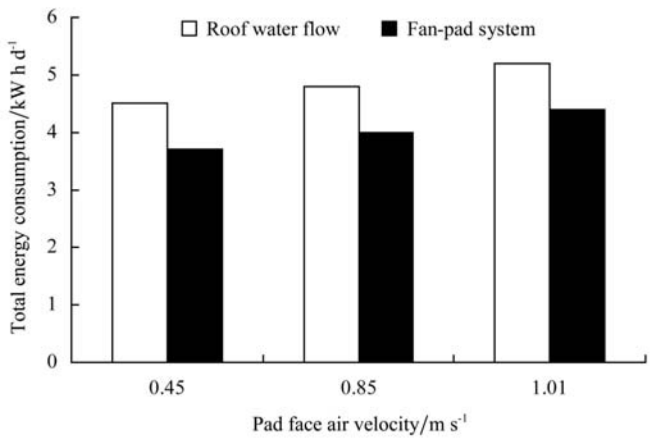


Figure 13 Total energy consumption by fan and water pump per day (kWh d^{-1}), when thermostat was not working (day time is 10 h) for both cooling systems

3.6 Economics of the evaporative systems

The economic cost was estimated for both cooling system using break-even point method. The total cost per year per m^2 of floor of the roof water flow system was 22.29 L.E. (1 US$= 5.50 L.E.). This value was 43.4% higher than that for fan-pad system. The total cost per year per m^2 of floor of fan-pad system was 20.13 L. E. The increment of the cost for the roof water flow had resulted from fabrication of the water film on the external cover of the experimental greenhouse. Bigger water pump was used to not only wet the evaporative pads, but also to pump water through the perforated tube to create the water film. For both cooling systems, the more effected items in the calculation were the cooling equipment that comprises on fans and water pump and the control devices. These items were preventative by 60.6 and 65.02 % of total fixed cost for roof water flow and fan-pad system, respectively.

Generally, it can be concluded that the higher efficiencies were obtained with thicker pads (15 cm), and with lower air velocities. The results showed that Se’d as an alternative evaporative cooling pad material was more effective. Also, the thin film roof water flow combined with fan-pads system achieved good results in comparison with that of fan-pad system alone. It should be noticed that the cooling efficiency had sometimes went up close to 100% (relatively high value) and this may be due to the system was tested without growing crops inside the greenhouse.

4 Conclusion

In tropical and subtropical regions, greenhouses may be exposed to the risk of heat when the outside environment tends to be hot. Adaptation of a greenhouse microclimate to local climate conditions is important for the improvement of resource use efficiency of greenhouse crop production. There is a necessity to develop cheap and effective technology suitable to local climatic conditions to boost up the greenhouse industry. In this case cooling systems are essential to achieve acceptable microclimatic, the maximum utilization of equipment and high returns commanded by manufactures, consequently, the evaporative cooling system is considered as an energy efficient cooling method that only uses water as the working fluid. Such cooling system is considered to be available solution for growers in regions where warm or hot seasons may spread throughout the most of the year months.

Using Se'd, Purdy and Sammer as pad materials for the evaporative cooling system based on pad and fan system reduced heat stress inside the greenhouse under the local Egyptian conditions. This had not only saved money, but had also solved problems resulted from the accumulation of the agricultural residues and had reduced water consumption by the herbicides. The maximum value of cooling effect was 13ºC achieved with 15 cm Se’d pad and 0.45 m s^{-1} pad face air velocity during midday.

Effect of combined system on the cooling performance was investigated. The daily average cooling efficiency of 88.4, 83.1 and 79.6% were obtained for Se’d, Purdy and Samar, respectively during tested days for combined cooling system.

The daily average cooling efficiencies were 81.2, 83.1 and 88.4% for combined system; and 63.6, 72.17 and 80.6% for fan-pad system at 1.01, 0.85 and 0.45 m/s pad face air velocity, respectively with 15 cm Se’d pad thickness. According to these results, the efficiency of the combined system is better than that of the fan-pad system. The cladding materials such as roof water flow may be used to diffuse direct insolation to prevent the plants from direct sun burning and to enhance photosynthesis.

Thin water film can be applied in the second half of the greenhouse that faces the southern direction in order to create a uniform environment inside the greenhouse provided with fan-pad system. Therefore, thermal gradients can be minimized inside the greenhouse. The durability of the investigated pad materials in the greenhouse will be investigated, in the further experimental work.

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