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Performance of Evaporative Cooling System As Influenced By Air Speed and Pad Height

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Abstract

The main aim of this work is to optimize the operation parameters of using evaporative cooling system such as height of pads and air velocity. To achieve that study the effect of different pad height (1.0 and 2.0 m) and different air velocities (1.5, 3.0, 4.5 and 6.0 m s^{-1}) on air temperature, relative humidity, temperature reduction, cooling efficiency and cooling capacity. The obtained results indicated that the hourly temperature of air increased gradually until it reached the peak and then decreased during period from 9 AM to 6 PM. Also, the air temperature decreases with increasing pad height. The hourly relative humidity of air decreased gradually until it reached the peak and then increased during period from 9 AM to 6 PM. The temperature reduction increased from 3.3 to 8.8, 6.4 to 14.4, 5.5 to 16.5 and 5.3 to 18.4 °C when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocities. The highest value of temperature reduction was 18.4 °C was found with 2.0 m pad height and 6.0 m s^{-1}air velocity. The cooling efficiency increased from 34.3 to 61.7, 53.4 to 94.6, 49.6 to 94.4 and 54.1to 98.8 % when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The highest value of cooling capacity was 629.1 kW was found with 2.0 m pad height and 6.0 m s^{-1}air velocity.

Keywords: Evaporative cooling, Temperature, Relative humidity, Cooling efficiency, cooling capacity

Introduction

A greenhouse is a structure used for protecting plants from adverse climatic effects and for supplying a favorable environment for plant production. This technique is necessary to overcome the high hazards of open field production, such as high rainfall, inters solar radiation, weed rivalry, as well as damages caused by diseases, insects, high temperature and relative **(Sharma and Salokhe, 2006)**.

Evaporative cooling is one of the passive cooling techniques that can reduce energy consumption in buildings **(Oropeza-perez and Østergaard, 2018)**. Due to its simplicity and the many examples that can be found in nature, it is in fact the oldest strategy humankind has used to cool ambient air. As water evaporates within the surrounding non-saturated air, this leads to heat absorption due to the latent heat required for vaporization. Consequently, there is heat and mass transfer. Moist air becomes further saturated, while its dry bulb temperature (DBT) decreases towards its wet bulb temperature (WBT). Contact between air and water can be enhanced in two ways: by providing a large, wetted surface, or by directly spraying water. The former option can increase the water evaporation rates that can be achieved **(Naveenprabhu and Suresh, 2020)**.

Evaporative cooling systems are based on the evaporation of water inside the greenhouse, producing lower temperature and higher humidity. The change from liquid to vapor requires energy, which is extracted from the greenhouse air, cooling it and increasing its humidity. This brings about a change from sensitive heat (drop in temperature) to latent heat (increase in water content in the mix of humid air). In thermodynamics, this is known as the adiabatic process, and the enthalpy remains practically constant **(ASHRAE, 2005)**.

Forced ventilation, fans, air conditioning, shade, evaporative cooling, feeding management, water spraying, shearing and chilled water are considered most important ways to mitigate heat stress. Most methods rely on evaporative cooling, which is suppressed by high humidity. Water is an excellent cooling factor due to its high latent heat of evaporation and high thermal capacity. **Khobragade and Kongre (2016)** mentioned that direct evaporative cooling systems are inexpensive and provide an attractive alternative to traditional summer air conditioning systems in hot and arid places. Evaporative cooling system is based on the principle that when damp but unsaturated air meets a wet surface whose temperature is higher than the temperature of the dew point of the air, some water evaporates from the wet surface into the air. Thus, the air is cooled and moistened. Cold and humid air can be used to provide thermal comfort. **Porumb *et al.* (2016)** indicated that evaporative cooling technology is relied on heat and mass transfer between air and cooling water. Direct evaporative cooling depends on mechanical and thermal contact between air and water and is characterized by highly efficient in energy use with highly water consumption rates. The major feature of direct evaporative cooling is the simple construction of the equipment, while the main disadvantage is to increase the moisture content of the air, which may be undesirable for some applications.

Optimization of the operation parameters of using cooling pad system is curial, therefore, the main aim of this study is to optimize the operation parameters of using evaporative cooling system such as height of pads and air velocity.

Materials and Methods

The main experiment was carried out in a greenhouse at Fish Farms and Protected Houses Center, Faculty of Agriculture Moshtohor, Benha University, Egypt (latitude 30° 21` N and 31° 13` E). During summer season of 2021.

2.1. Materials

2.1.1. System Description

Fig. 1 illustrates the experimental setup. It shows the system which consists of greenhouses, evaporating cooling system and irrigation system.

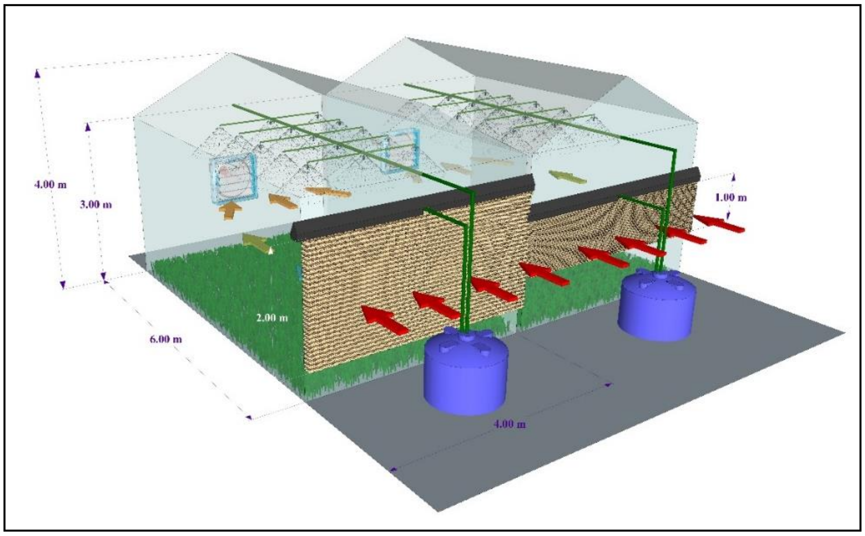


Fig. 1: The experimental setup.

2.1.1.1. Greenhouse's construction

Two identical gable-even-span from greenhouse are used during this research work. Each one having a geometrical characteristic of: total length of 6 m, total width of 4 m, vertical wall height of 3.0 m, and floor surface area of 24 m^2. The greenhouse structural frame is formed of 4 x 4 cm hot dipped galvanized box with excellent anti-corrosion. The walls of greenhouse are covered by using 4 mm thick polycarbonate panels and the roof of greenhouse is covered by using 200 micron Polyethylene sheets. The structure frame consisted of many parts (posts, beams, rafters and trusses) which easily assembled on the spot with joining parts and bolts and nuts, without any welding points to prevent damage the zinc coating on the material, which guarantee the optimal performance of anti-corrosion. The space between each two successive spans on the longitudinal direction is 2.0 m. Fig. 2 shows the schematic diagram of gable-even-span greenhouse. The three greenhouses were orientated in East-West direction, where the southern longitudinal direction faced into the sun's rays and the northern longitudinal direction faced into the cold sky.

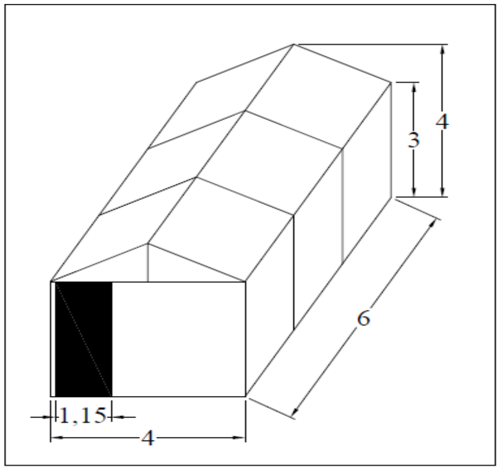


Fig. 2: The schematic diagram of gable-even-span greenhouse.

2.1.1.2. Evaporative Cooling System components: -

The evaporative cooling system is based on the process of heat absorption during the evaporation of water supplied. It is mainly consisted of cooling pad and extracting fan, in addition to the water cycle.

- Evaporative cooling pads: -

A six cross-fluted cellulose pad plates were vertically placed in the opposite wall of the extracting fans (western direction) in the greenhouse. Each cellulose pad plate having a gross dimensions of 10 cm thickness, 60 cm wide and two heights were used namely 100 and 200 cm. Fig. 3 shows the evaporative cooling pad.

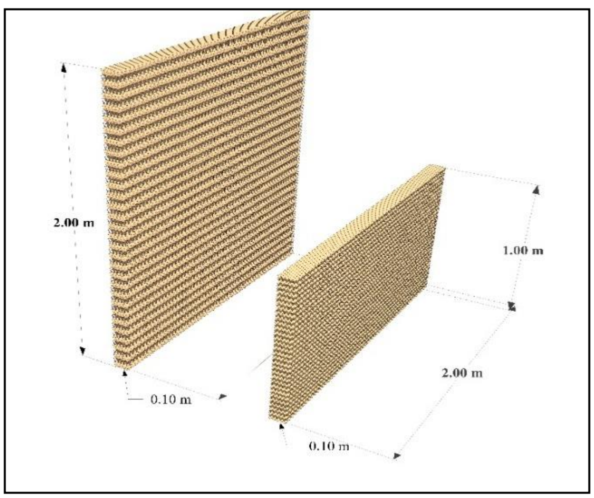


Fig. 3: Evaporative cooling pad

Extracting fan:

One extracting fan was located on the leeward side of the greenhouse (negative pressure). Its specifications were as follow: the fan was an axial low type, its dimensions are 90 x 90 cm. It has 3 blades as shown in fig. 4, and its volumetric flow rate was 297.5 m^3/min. the fan velocity was controlled by inverter. Inverter was used to control the electricity input of the belt motor (model IP65 (IEC-60529) NEMA-4 and 230v 5060/Hz phase output 0- v 3phase 5hp – Italy).

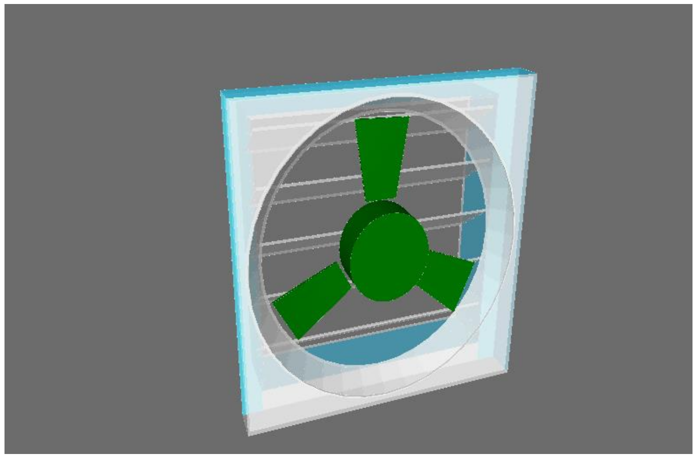


Fig. 4: extracting fan.

- **Water cycle of evaporative cooling:**

The water cycle consists of a tank, a pump, polyvinyl chloride tubes, a distributor, and a steel gutter as shown in Fig. 5.

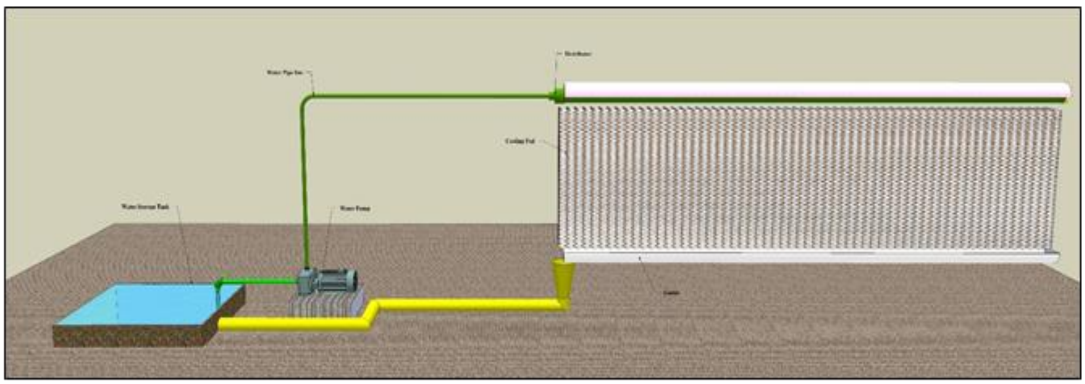


Fig. 5: Water cycle of Evaporative cooling

A polyethylene storage tank of 500 liter capacity was used to store water during the experimental, it was contained a centrifugal water pump with float inside it to save water at constant level.

A centrifugal water pump 1.0 hp (746 Watt) was used to pump water into the pad through tubes and distribution system, its maximum discharge is 54 L/min, maximum head is 10 m. The water pumped to perforated polyvinyl chloride tube used as a distributor. A polyvinyl chloride pipe (25 mm diameter) has been suspended directly above the cooling pad. Holes were drilled (3 mm diameter) in a line about 10 cm apart along the top side, and the end of this pipe was capped. A baffle has been placed above the water pipe to prevent any leaking of water from the system. A sump has mounted under the cooling pad to collect the water and return it into the cooling pad by the water pump, as shown in Fig. 5.

The evaporative pad and the fans were turned on when the air temperature in the greenhouse exceeded 28 ^{o}C and off when the air temperature dropped below 26 ^{o}C when in operation, about 90% of the pad surface was wet. In the direct evaporative cooling system, the transformation of heat and mass between air and water causes a decrease in the air-dry-bulb temperature and an increase in its humidity, while the enthalpy is constant in a perfect process. A wet pad equips a water surface in which the air has humidified, and the pad is wetted by dripping water.

2.1.1.3. Irrigation system:

Drip irrigation system is installed inside the three greenhouses to provide the crop with the necessary water during the growth period. It consists of water pump, fertigation unit, maim pipe line (φ50 mm diameter) and sub-main pipe line (φ16 mm diameter).

2.2. **Methods**

2.2.1. Experimental design

The treatments were arranged in a split plot design. Table 1 shows the experimental design.

Table (1): The experimental design.

Variables	Levels	Variables Levels
Pad heights	2	100 cm
		200 cm
Air velocities	4	1.5 m s^{-1}
		3.0 m s^{-1}
		4.5 m s^{-1}
		6.0 m s^{-1}

2.2.2. Measurements

2.2.2.1. Environmental Conditions:

Greenhouse climate conditions and their uniformity were monitored with air temperature, and relative humidity sensors, which were protected. Sensors were located at height (1 and 2 m) at 5 greenhouse locations (outside the pad, behind the pad and at 1, 3, and 5 m distances from the pad) along the centerline of the greenhouse (2 m from sidewalls) as shown in Fig. 6.

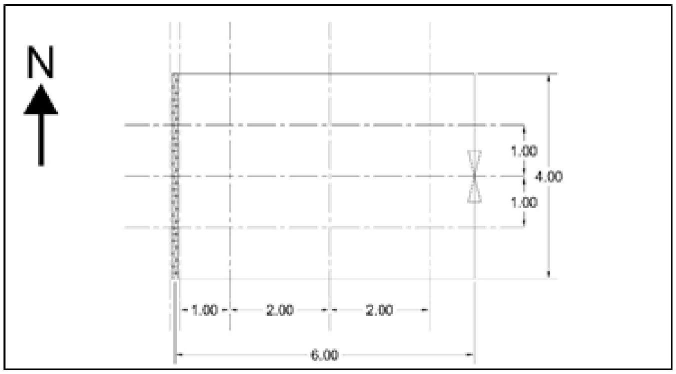


Fig. 6: A schematic diagram of sensors locations inside the greenhouse

2.2.2.2. Measuring temperature:

Dry bulb temperature and dew point temperature were recorded behind the pad, at the center and outside greenhouse using a Digital thermometer data logger (Model Lutron BTM-4208SD – Range -100 to 1300 °C, Accuracy 0.4 °C, resolution 0.1 °C, Saving data along with time stamp to SD card, USA) every ten minutes. Also, dry bulb temperature, dew point temperature, and relative humidity were recorded outside greenhouse, behind the pad, and at the fan using a HOBO Data Logger (Model HOBO U12 Temp/RH/Light – Range -20 to 70 °C and 5 to 95% RH, USA) every ten minutes.

2.2.2.3. Air velocity measurement:

The air velocity was measured inside the greenhouse using anemometer (Model DOSTMANN – Range 0.4 – 30 m s^{-1}, with accuracy ±3%, resolution 0.01 m s^{-1}, temperature measuring range -10 : 60 °C, USA).

2.2.2.4. Temperature reduction (ΔT):

The different between outside dry bulb temperature (T_o) and inside dry bulb temperature just behind the pad (T_i), is an important parameter to describe the cooling efficiency for the evaporative cooling system.

This difference is call (ΔT),

$$\Delta T = T_o - T_i \qquad (1)$$

Where:

ΔT is the temperature reduction, °C

T_o is the temperature outside greenhouse, °C

T_i is the temperature inside greenhouse (behind the pad), °C

2.2.2.5. Calculation of cooling efficiency:

Saturation efficiency is defined as the ratio between the temperature drops resulted from the system to the different between dry-bulb and wet-bulb temperature for outside air, according to **(ASHRAE, 2005).**

$$\eta = \frac{T_{ao} - T_{ai}}{T_{ao} - T_{wb}} \qquad (2)$$

where:

η is the evaporative cooling efficiency, %

T_{ao} is the temperature outside greenhouse, °C

T_{ai} is the temperature inside greenhouse just behind the pad, °C

T_{wb} is the Wet-bulb temperature of air outside greenhouse, °C

2.2.2.6. Calculation of cooling capacity:

The cooling capacity is calculated by the temperature difference at the inlet and the outlet according to **Sohani and Sayyaadi (2017) and Laknizi et al. (2019)**:

$$P_{pad}\ \text{cooling} = m_{air} \cdot C_p \cdot (T_{out} - T_{in}) \quad (3)$$

$$m_{air} = V \cdot L \cdot H \cdot \rho \quad (4)$$

Where:

m_{air}, is the flow rate of air supply, kg s^{-1}
C_p is the specific heat capacity of air,J kg^{-1} $°C^{-1}$
T_{out} is the outdoor temperature, °C
T_{in} is the indoor temperature, °C
ρ is the volume mass of air, kg m^{-3}
V is the velocity. m s^{-1}
L is the width of the pad cooling, m
H is the height of the pad cooling, m

3. RESULTS AND DISCUSSION

3.1. Hourly air temperature:

Fig. 7 shows the effect of pad height (1.0 and 2.0 m) on hourly temperature of air inside greenhouse (besides pad cooling and besides extracting fan) and compared with hourly air temperature outside greenhouse at 1.5 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly temperature of air increased gradually until it reached the peak at 1.30 PM and then decreased during period from 9 AM to 6 PM. It could be seen that the maximum hourly air temperatures were 33.4, 36.2 and 37.1 and 32.0, 38.2 and 34.9 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. While, the minimum hourly air temperatures were 25.4, 25.8 and 25.5 and 24.6, 26.8 and 27.5 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height compared the minimum hourly air temperature outside the greenhouse was 30 °C. The results indicate that the air temperature besides pad cooling was lower than those of mid of greenhouse and besides extracting fan. It could be seen that the air temperatures were 29.5, 33.5 and 34.8 and 26.9, 32.1 and 32.8 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height at 10.30 AM. The results also indicate that the air temperature decreases with increasing pad height, it could be seen that the temperature decreased from 31.3 to 24.3, 34.3 to 26.6 and 34.6 to 26.9 °C, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.

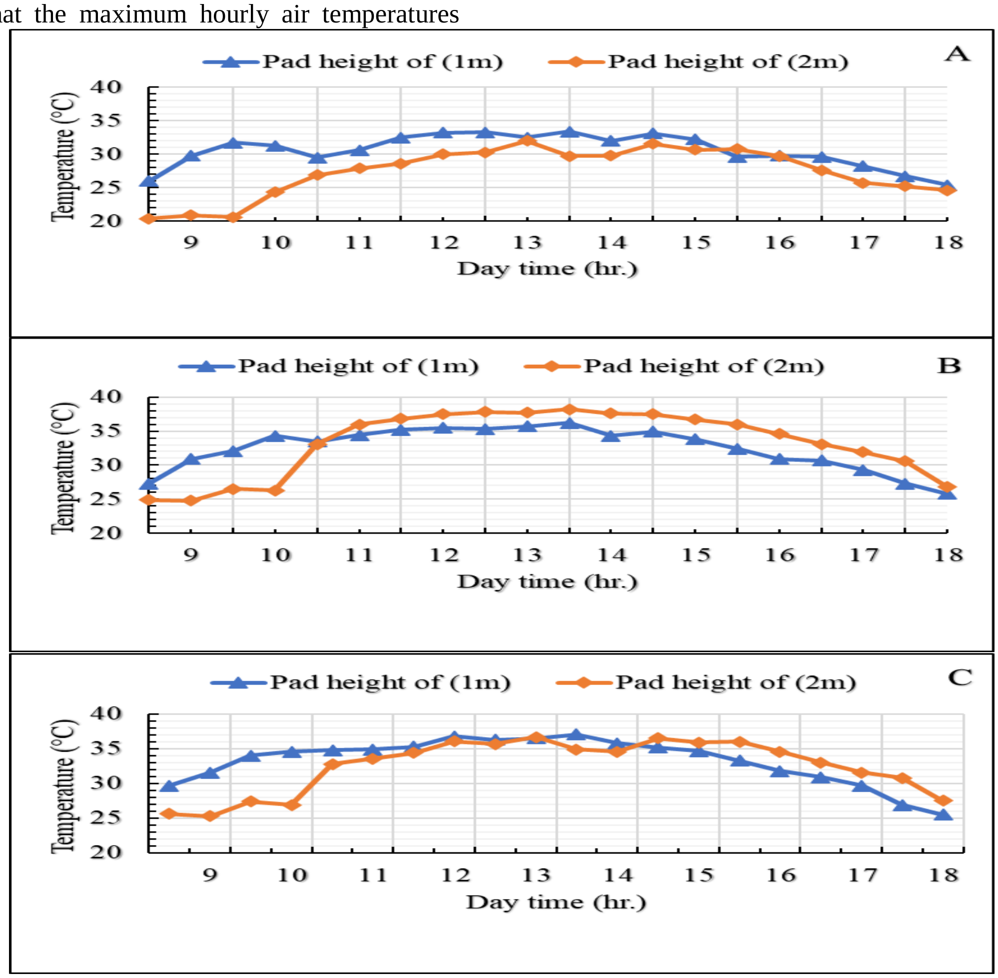


Fig. 7: Hourly temperature of air inside and outside greenhouse at different pad height with

1.5 m s-1 air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

Fig. 8 shows the effect of pad height (1.0 and 2.0 m) on hourly temperature of air inside greenhouse (besides pad cooling, mid of greenhouse and besides extracting fan) and compared with hourly air temperature outside greenhouse at 3.0 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly temperature of air decreased gradually until it reached the peak and then increased during period from 9 AM to 6 PM. It could be seen that the hourly temperature ranged from 22.4 to 30.1, 24.2 to 34.2 and 24.1 to 34.4 and 21.0 to 25.8, 23.9 to 32.0 and 24.7 to 32.5 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. The results indicate that the air temperature besides pad cooling was lower than those of mid of greenhouse and besides extracting fan. It could be seen that the temperature were 28.8, 34.4 and 34.4 and 24.9, 28.8 and 30.2°C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height.

The results also indicate that the air temperature decreases with increasing pad height, it could be seen that the air temperature decreased from 25.8 to 24.9, 34.2 to 28.4 and 34.4 to 30.2°C, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.

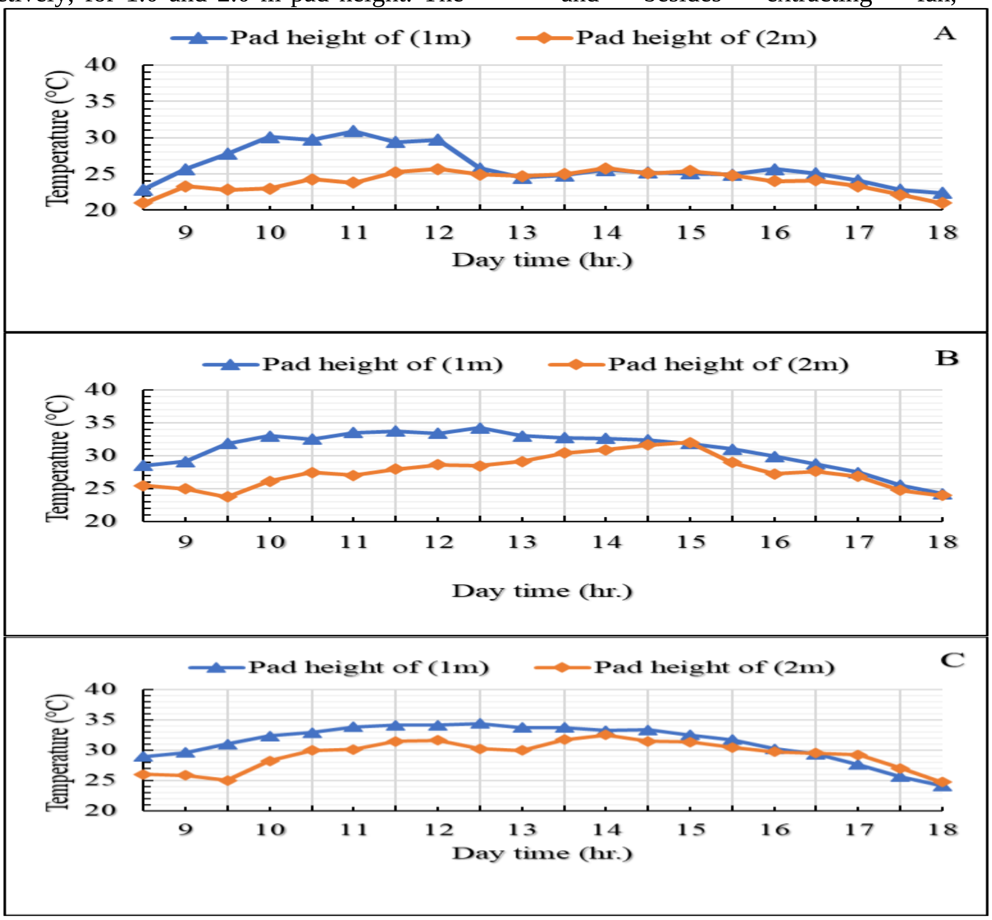


Fig. 8: Hourly temperature of air inside and outside greenhouse at different pad height with 3.0 m s^{-1} air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

Fig. 9 shows the effect of pad height (1.0 and 2.0 m) on hourly temperature of air inside greenhouse (besides pad cooling, mid of greenhouse and besides extracting fan) and compared with hourly air temperature outside greenhouse at 4.5 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly temperature of air decreased gradually until it reached the peak and then increased during period from 9 AM to 6 PM. It could be seen that the hourly temperature ranged from 22.1 to 25.9, 21.9 to 29.7 and 22.6 to 30.3 and 21.4 to 23.4, 23.1 to 26.8 and 23.0 to 28.0 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. The results indicate that the air temperature besides pad cooling was lower than those of mid of greenhouse and besides extracting fan. It could be seen that the temperature were 23.1, 29.7 and 29.9 and 23.1, 25.9 and 28.1°C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height.

The results also indicate that the air temperature decreases with increasing pad height, it could be seen that the air temperature decreased from 23.4 to 21.6, 27.5 to 24.1 and 28.8 to 26.0°C, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.

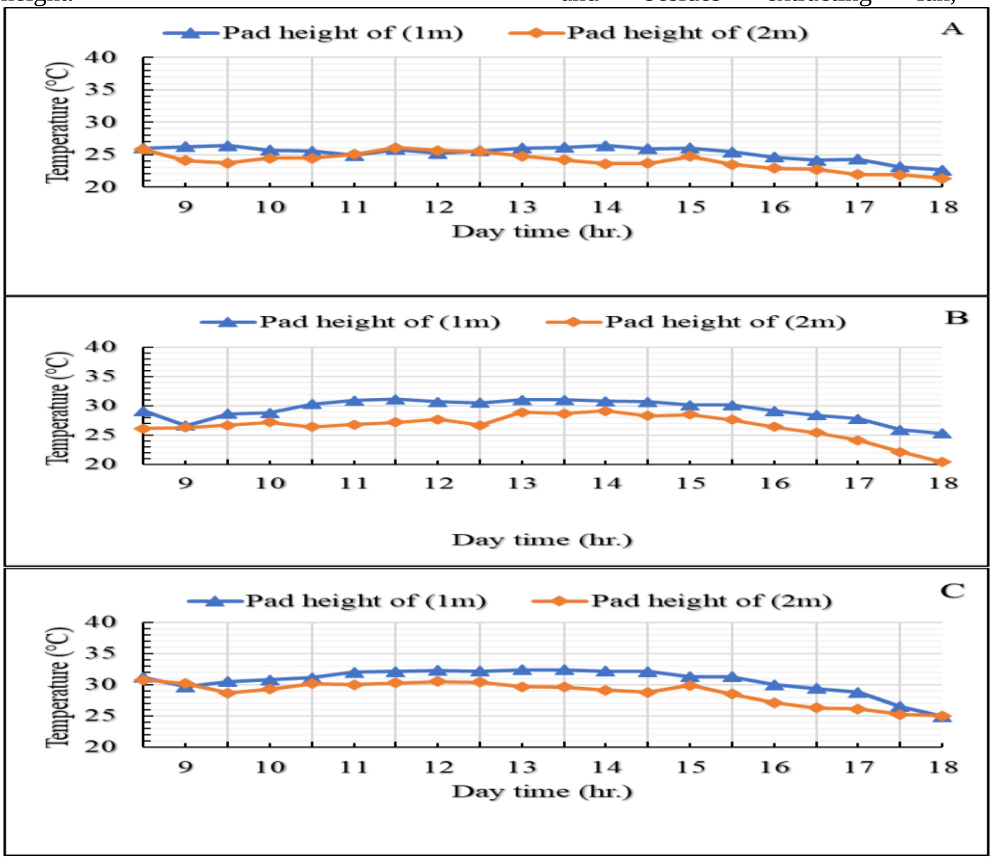


Fig. 9: Hourly temperature of air inside and outside greenhouse at different pad height with 4.5 m s^{-1} air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

Fig. 10 shows the effect of pad height (1.0 and 2.0 m) on hourly temperature of air inside greenhouse (besides pad cooling, mid of greenhouse and besides extracting fan) and compared with hourly air temperature outside greenhouse at 6.0 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly temperature of air decreased gradually until it reached the peak and then increased during period from 9 AM to 6 PM. It could be seen that the hourly temperature ranged from 22.6 to 26.4, 25.3 to 31.1 and 24.9 to 32.4 and 21.3 to 26.1, 21.4 to 29.1 and 25.0 to 30.5 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. The results indicate that the air temperature besides pad cooling was lower than those of mid of greenhouse and besides extracting fan. It could be seen that the temperature were 25.9, 30.7 and 32.1 and 23.7, 28.3 and 28.8°C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height.

The results also indicate that the air temperature decreases with increasing pad height, it could be seen that the air temperature decreased from 25.9 to 23.6, 30.8 to 29.1 and 32.2 to 28.8°C, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.

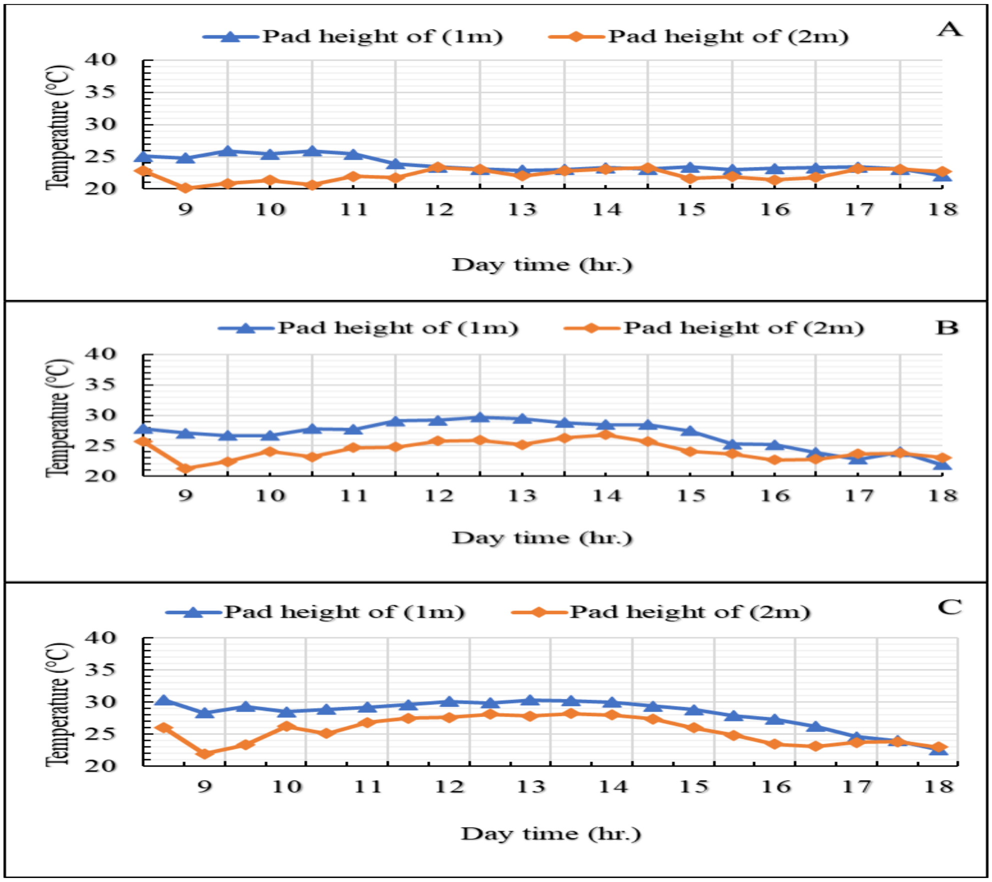


Fig. 10: Hourly temperature of air inside and outside greenhouse at different pad height with 6.0 m s^{-1} air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

3.2. Hourly Relative humidity:

Fig. 11 shows the effect of pad height (1.0 and 2.0 m) on hourly relative humidity of air inside greenhouse (besides pad cooling, mid of greenhouse and besides extracting fan) and compared with hourly air relative humidity outside greenhouse at 1.5 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly relative humidity of air decreased gradually until it reached the peak at 2.00 PM and then increased during period from 9 AM to 6 PM. It could be seen that the minimum hourly relative humidity were 43.1, 42.3 and 41.9 and 45.6, 53.5 and 48.1% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. While, the maximum hourly relative humidity were 64.9, 60.1 and 59.6 and 53.8, 57.1 and 53.8% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height compared the maximum hourly relative humidity outside the greenhouse was 51.4%. The results indicate that the relative humidity besides pad cooling was higher than those of mid of greenhouse and besides extracting fan. It could be seen that the relative humidity were 64.9, 60.1 and 59.6 and 53.8, 57.1 and 53.8% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height at 6.00 PM.

The results also indicate that the relative humidity increases with increasing pad height, it could be seen that the relative humidity increased from 43.1 to 45.6, 42.3 to 53.5 and 41.9 to 48.1%, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.

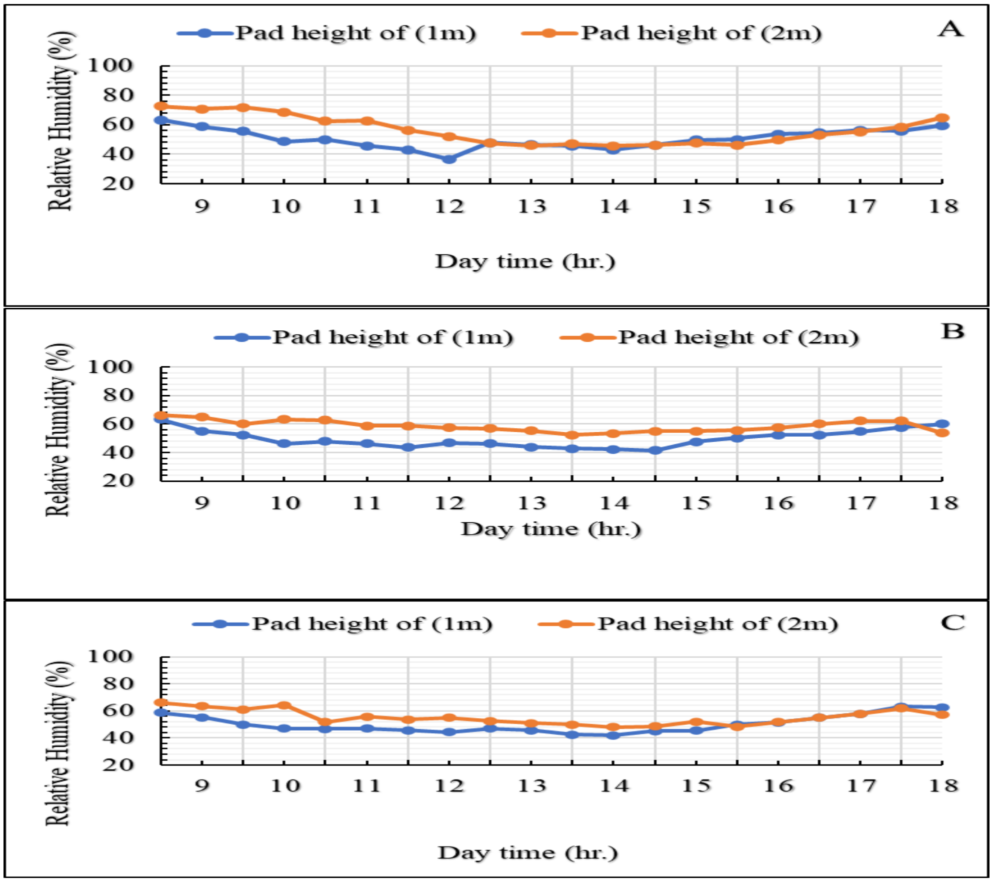
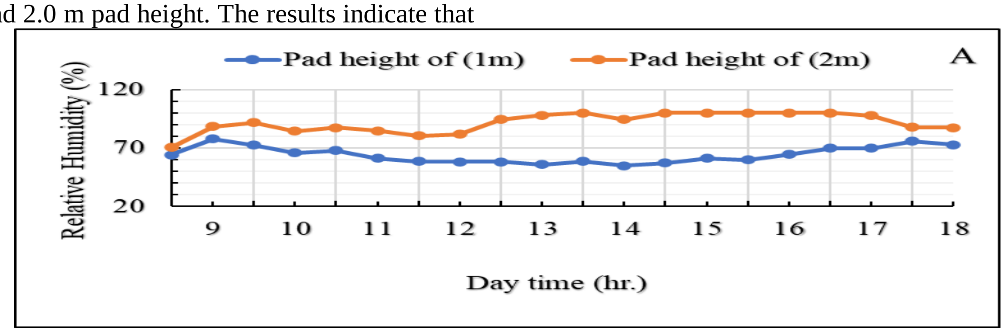


Fig. 11: Hourly relative humidity of air inside and outside greenhouse at different pad height with 1.5 m s^{-1} air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

Fig. 12 shows the effect of pad height (1.0 and 2.0 m) on hourly relative humidity of air inside greenhouse (besides pad cooling, mid of greenhouse and besides extracting fan) and compared with hourly air relative humidity outside greenhouse at 3.0 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly relative humidity of air decreased gradually until it reached the peak at 2.00 PM and then increased during period from 9 AM to 6 PM. It could be seen that the hourly relative humidity ranged from 54.8 to 75.7, 42.0 to 64.7 and 45.6 to 66.4 and 81.6 to 100, 44.0 to 61.1 and 44.3 to 67.8% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. The results indicate that the relative humidity besides pad cooling was higher than those of mid of greenhouse and besides extracting fan. It could be seen that the relative humidity were 67.7, 51.7 and 50.7 and 87.2, 53.5 and 51.0% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height.

The results also indicate that the relative humidity increases with increasing pad height, it could be seen that the relative humidity increased from 55.7 to 94.2, 45.3 to 45.6 and 46.0 to 47.0%, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



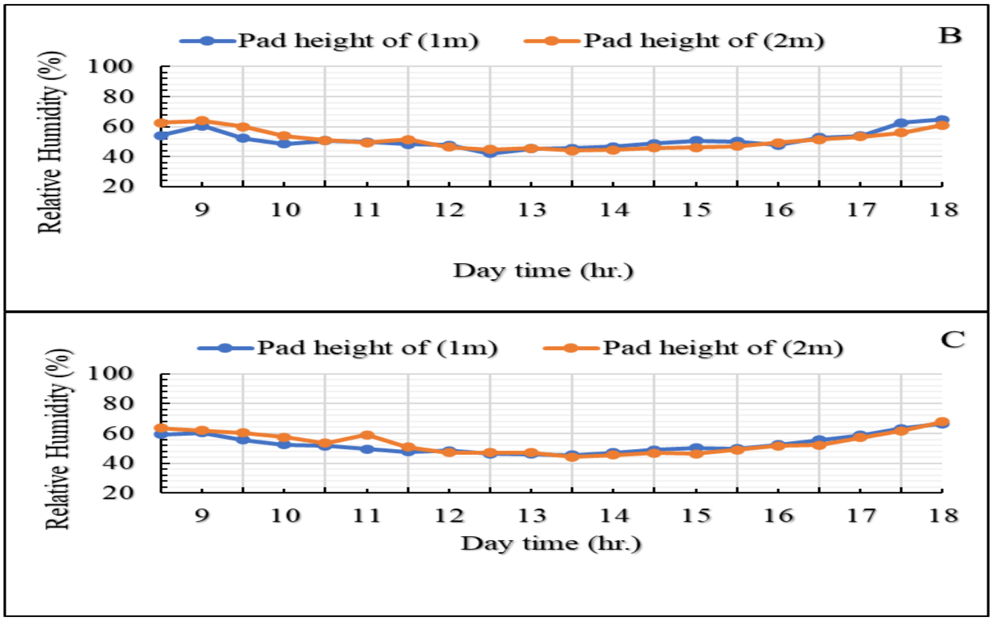
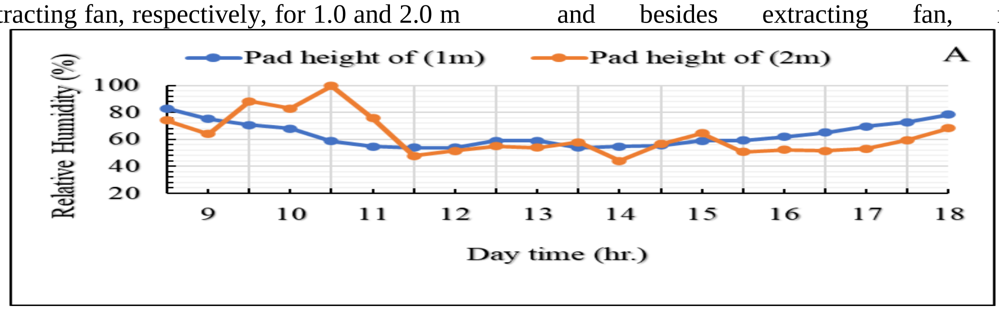


Fig. 12: Hourly relative humidity of air inside and outside greenhouse at different pad height with 3.0 m s^{-1} air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

Fig. 13 shows the effect of pad height (1.0 and 2.0 m) on hourly relative humidity of air inside greenhouse (besides pad cooling, mid of greenhouse and besides extracting fan) and compared with hourly air relative humidity outside greenhouse at 4.5 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly relative humidity of air decreased gradually until it reached the peak and then increased during period from 9 AM to 6 PM. It could be seen that the hourly relative humidity ranged from 53.9 to 78.5, 49.6 to 63.4 and 47.9 to 62.4 and 44.0 to 99.7, 38.2 to 58.3 and 42.8 to 67.6% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. The results indicate that the relative humidity besides pad cooling was higher than those of mid of greenhouse and besides extracting fan. It could be seen that the relative humidity were 53.9, 49.6 and 47.9 and 57.8, 43.4 and 40.1% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height.

The results also indicate that the relative humidity increases with increasing pad height, it could be seen that the relative humidity increased 67.9 to 83.0, 63.4 to 67.9 and 55.3 to 67.6%, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



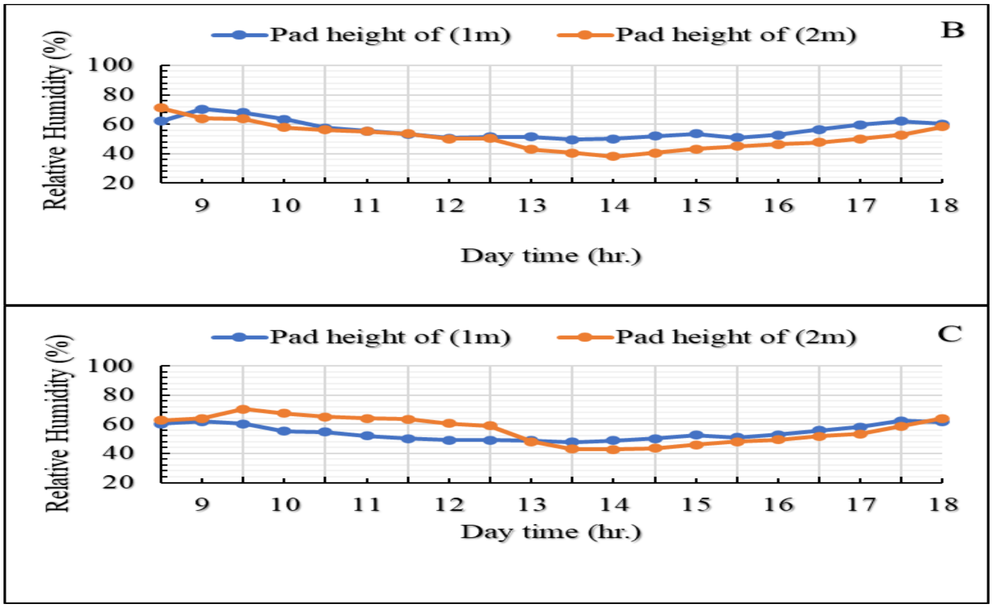
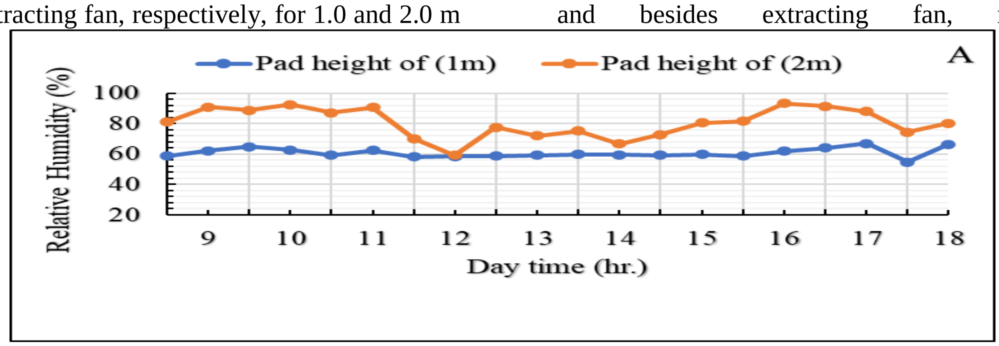


Fig. 13: Hourly relative humidity of air inside and outside greenhouse at different pad height with 4.5 m s^{-1} air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

Fig. 14 shows the effect of pad height (1.0 and 2.0 m) on hourly relative humidity of air inside greenhouse (besides pad cooling, mid of greenhouse and besides extracting fan) and compared with hourly air relative humidity outside greenhouse at 4.5 m s^{-1} air velocity which were recorded from 9 AM to 6 PM. The results indicate that, the hourly relative humidity of air decreased gradually until it reached the peak and then increased during period from 9 AM to 6 PM. It could be seen that the hourly relative humidity ranged from 54.8 to 66.5, 50.7 to 66.3 and 49.8 to 67.0 and 59.2 to 92.4, 43.6 to 65.0 and 41.1 to 59.8% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height. The results indicate that the relative humidity besides pad cooling was higher than those of mid of greenhouse and besides extracting fan. It could be seen that the relative humidity were 59.6, 54.0 and 51.7 and 66.8, 43.6 and 41.1% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 1.0 and 2.0 m pad height.

The results also indicate that the relative humidity increases with increasing pad height, it could be seen that the relative humidity increased 62.3 to 90.5, 50.4 to 52.4 and 53.4 to 53.6%, when the pad height increased from 1.0 to 2.0 m, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



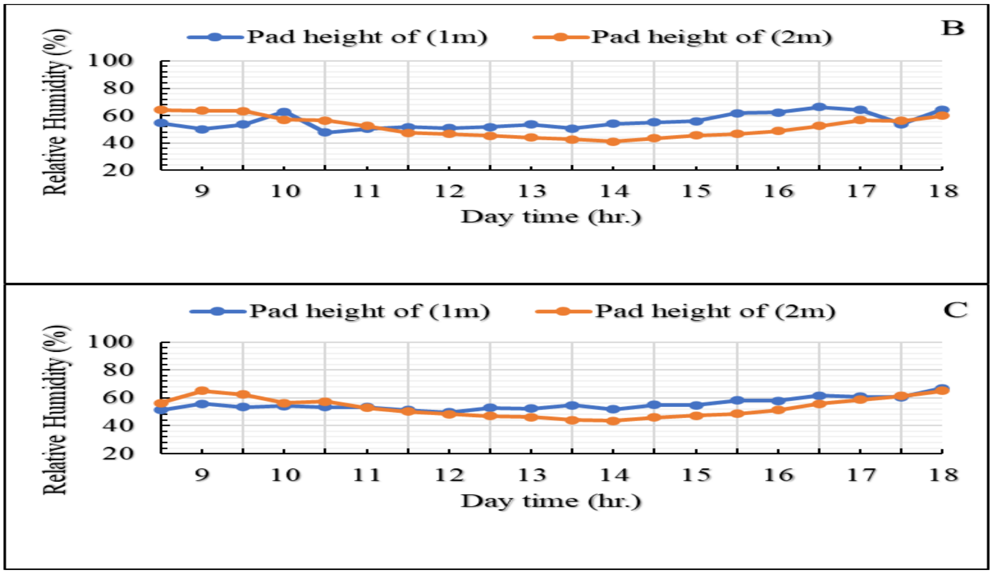
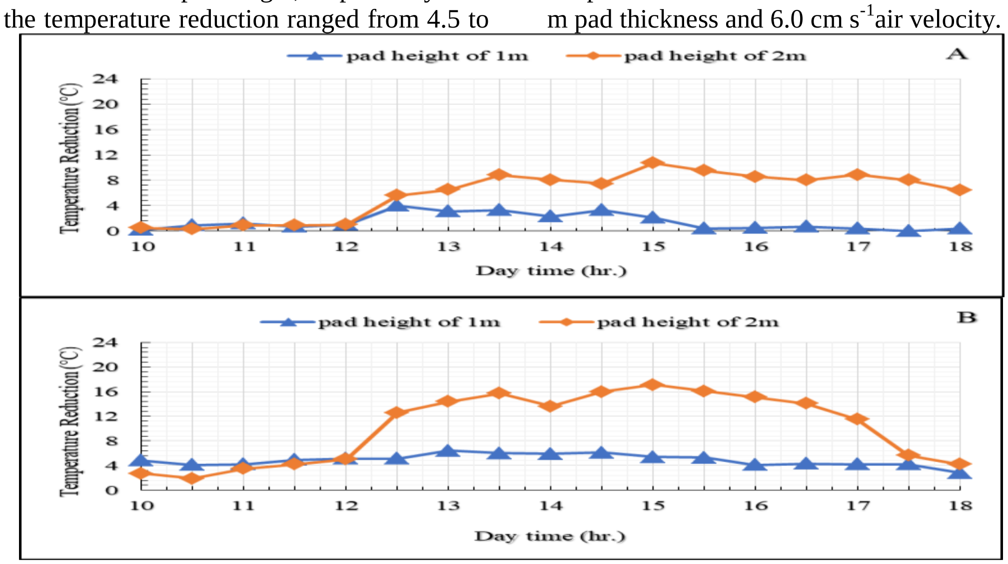


Fig. 14: Hourly relative humidity of air inside and outside greenhouse at different pad height with 6.0 m s^{-1} air velocity. A: besides pad cooling, B: mid of greenhouse, C: besides extracting fan

3.3. Temperature reduction (ΔT):

Fig. 15 shows the effect of pad height (1.0 and 2.0 m) and air velocity (1.5, 3.0, 4.5 and 6.0 m s^{-1}) on temperature reduction which were recorded from 9 AM to 6 PM. The results indicate that, the temperature reduction increased gradually until it reached the peak and then decreased during period from 9 AM to 6 PM. It could be seen that the temperature reduction ranged from 0.2 to 3.3 and 0.3 to 10.8 °C for 1.0 and 2.0 m pad height, respectively for 1.5 m s^{-1}. For 3.0 m s^{-1}, the temperature reduction ranged from 2.8 to 6.4 and 2.7 to 17.1 °C for 1.0 and 2.0 m pad height, respectively. For 4.5 m s^{-1}, the temperature reduction ranged from 4.5 to 6.8 and 1.3 to 16.5 °C for 1.0 and 2.0 m pad height, respectively. For 6.0 m s^{-1}, the temperature reduction ranged from 1.8 to 9.2 and 2.2 to 18.4 °C for 1.0 and 2.0 m pad height, respectively.

The results also indicate that the temperature reduction increases with increasing pad height. It could be seen that, the temperature reduction increased from 3.3 to 8.8, 6.4 to 14.4, 5.5 to 16.5 and 5.3 to 18.4 °C when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The results also indicate that the highest value of temperature reduction was 18.4 °C was found with 2.0 m pad thickness and 6.0 cm s^{-1}air velocity.



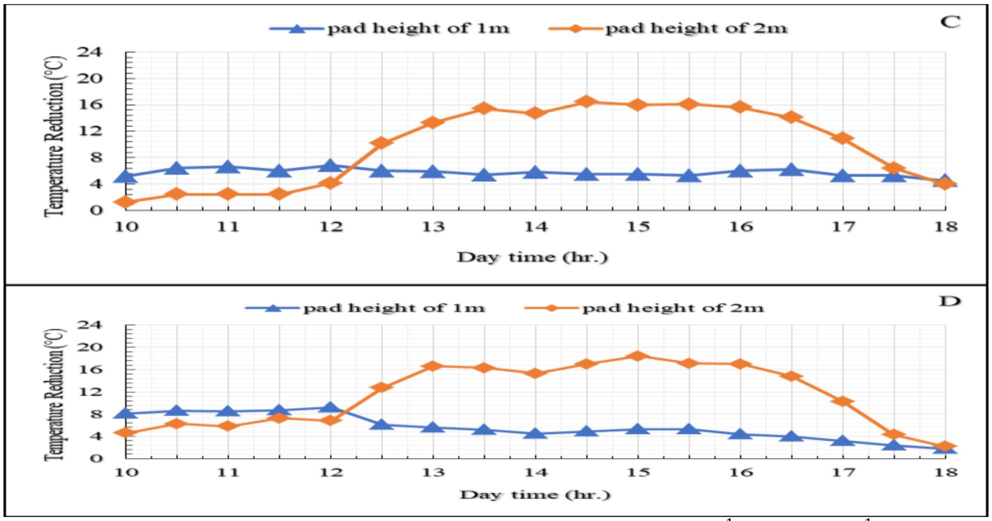
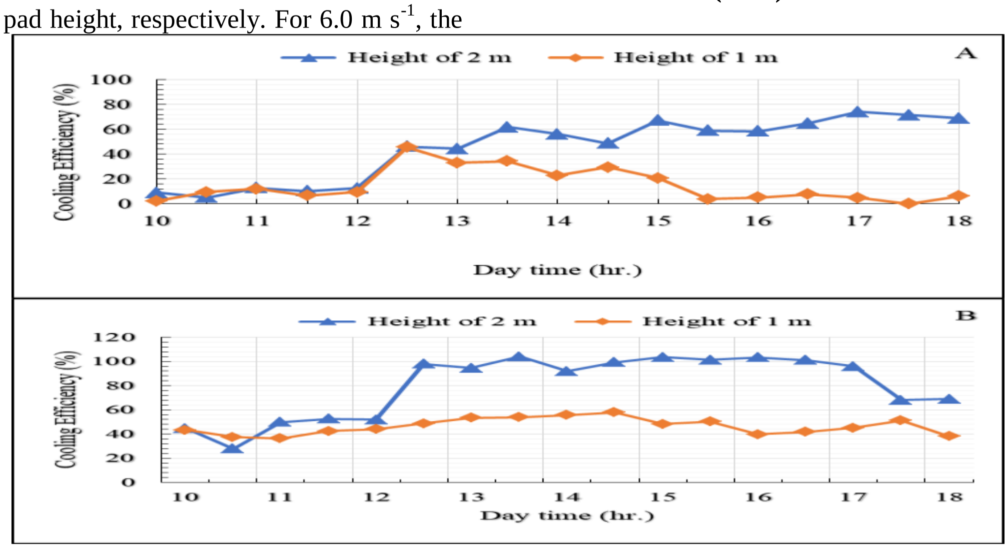


Fig. 15: Temperature reduction for different pad height. A: 1.5 m s^{-1}, B: 3.0 m s^{-1}, C: 4.5 m s^{-1}, D: 6.0 m s^{-1}

3.3. Cooling Efficiency:

Fig. 16 shows the effect of pad height (1.0 and 2.0 m) and air velocity (1.5, 3.0, 4.5 and 6.0 m s^{-1}) on cooling efficiency which were recorded from 9 AM to 6 PM. The results indicate that, the cooling efficiency increased gradually until it reached the peak and then decreased during period from 9 AM to 6 PM. It could be seen that the cooling efficiency ranged from 2.1 to 34.3 and 4.0 to 61.7 % for 1.0 and 2.0 m pad height, respectively for 1.5 m s^{-1}. For 3.0 m s^{-1}, the cooling efficiency ranged from 36.5 to 58.0 and 27.8 to 94.6 % for 1.0 and 2.0 m pad height, respectively. For 4.5 m s^{-1}, the cooling efficiency ranged from 49.6 to 67.5 and 24.4 to 97.1 % for 1.0 and 2.0 m pad height, respectively. For 6.0 m s^{-1}, the cooling efficiency ranged from 25.7 to 77.6 and 29.8 to 98.4 % for 1.0 and 2.0 m pad height, respectively.

The results also indicate that the cooling efficiency increases with increasing pad height. It could be seen that, the cooling efficiency increased from 34.3 to 61.7, 53.4 to 94.6, 49.6 to 94.4 and 54.1to 98.8 % when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The results also indicate that the highest value of cooling efficiency was 98.8% was found with 20 cm pad thickness and 6.0 cm s^{-1}air velocity. These results agreed with those obtained by **Laknizi *et al.* (2019)**.



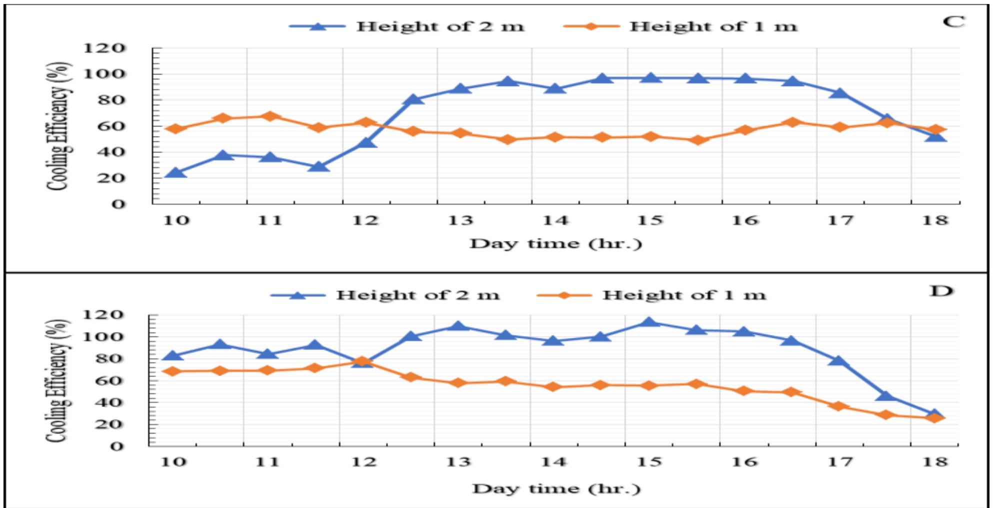
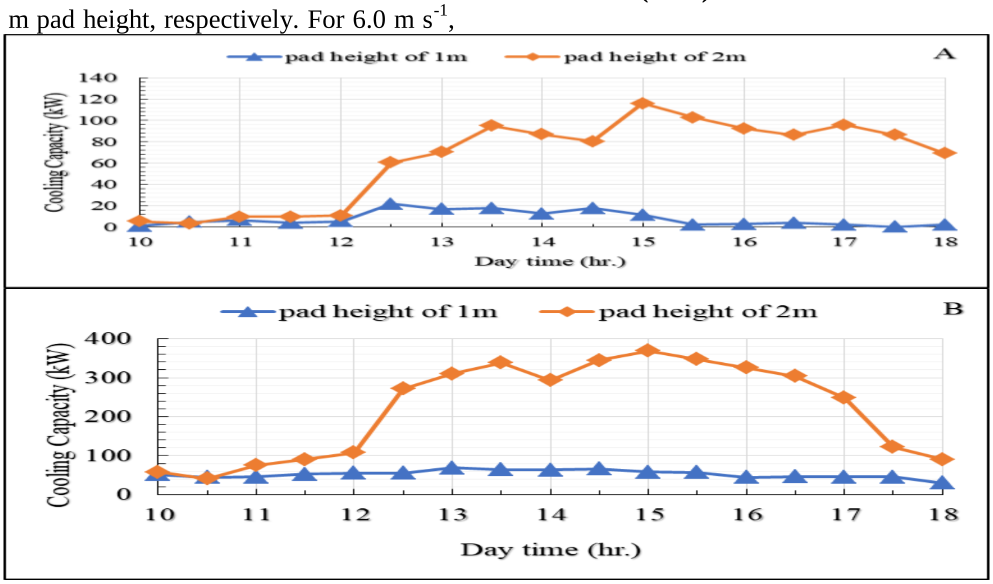


Fig. 16: Cooling efficiency for different pad height. A: 1.5 m s^{-1}, B: 3.0 m s^{-1}, C: 4.5 m s^{-1}, D: 6.0 m s^{-1}

3.4. Cooling Capacity:

Fig. 17 shows the effect of pad height (1.0 and 2.0 m) and air velocity (1.5, 3.0, 4.5 and 6.0 m s^{-1}) on cooling capacity which were recorded from 9 AM to 6 PM. The results indicate that, the cooling capacity increased gradually until it reached the peak and then decreased during period from 9 AM to 6 PM. It could be seen that the cooling capacity ranged from 1.1 to 21.6 and 3.2 to 115.9 kW for 1.0 and 2.0 m pad height, respectively for 1.5 m s^{-1}. For 3.0 m s^{-1}, the cooling efficiency ranged from 30.2 to 69.0 and 91.6 to 448.5 kW for 1.0 and 2.0 m pad height, respectively. For 4.5 m s^{-1}, the cooling efficiency ranged from 72.8 to 110.0 and 149.9 to 621.0 kW for 1.0 and 2.0 m pad height, respectively. For 6.0 m s^{-1}, the cooling efficiency ranged from 38.8 to 198.4 and 137.5 to 629.1 kW for 1.0 and 2.0 m pad height, respectively.

The results also indicate that the cooling capacity increases with increasing pad height. It could be seen that, the cooling capacity increased from 21.6 to 60.4, 69.0 to 373.6, 94.9 to 621.0 and 88.9 to 629.1 kW when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The results also indicate that the highest value of cooling capacity was 629.1 kW was found with 2.0 m pad height and 6.0 cm s^{-1}air velocity. These results agreed with those obtained by **Khater (2014)**.



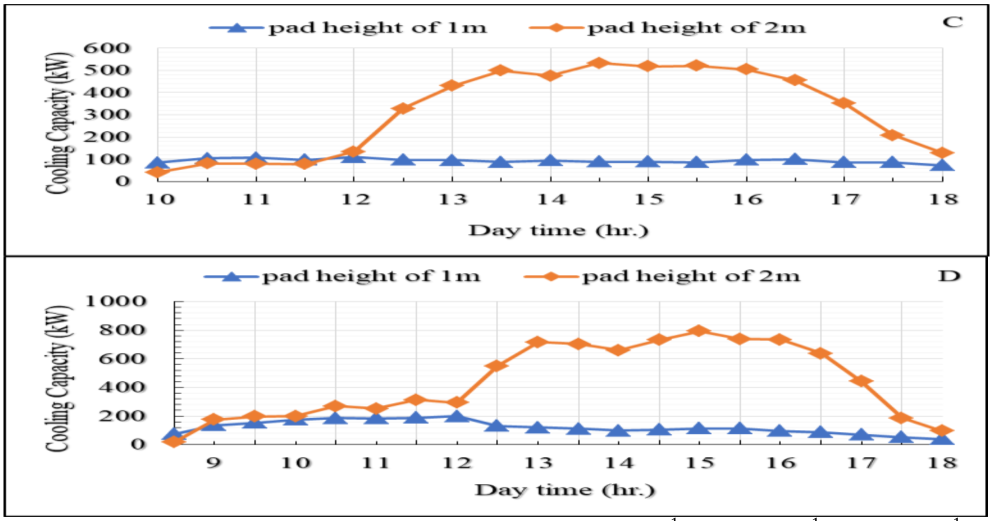


Fig. 17: Cooling capacity for different pad height. A: 1.5 m s^{-1}, B: 3.0 m s^{-1}, C: 4.5 m s^{-1}, D: 6.0 m s^{-1}

Conclusion

The experiment was carried out to study the effect of pad height (1.0 and 2.0 m) and air velocity (1.5, 3.0, 4.5 and 6.0 m s^{-1}) on air temperature, relative humidity, temperature reduction, cooling efficiency and cooling capacity. The obtained results can be summarized as follows:

- The hourly temperature of air increased gradually until it reached the peak and then decreased during period from 9 AM to 6 PM. Also, the air temperature decreases with increasing pad thickness.
- The hourly relative humidity of air decreased gradually until it reached the peak and then increased during period from 9 AM to 6 PM.
- The temperature reduction increased from 3.3 to 8.8, 6.4 to 14.4, 5.5 to 16.5 and 5.3 to 18.4 °C when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The highest value of temperature reduction was 18.4 °C was found with 20 cm pad thickness and 6.0 cm s^{-1}air velocity.
- The cooling efficiency increased from 34.3 to 61.7, 53.4 to 94.6, 49.6 to 94.4 and 54.1to 98.8 % when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity.
- The cooling capacity increased from 21.6 to 60.4, 69.0 to 373.6, 94.9 to 621.0 and 88.9 to 629.1 kW when the pad height increased from 1.0 to 2.0 m, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity.

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تأثير ارتفاع الوسادة وسرعة الهواء على معدل اداء نظام التبريد التبخيرى

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يهدف هذا البحث إلى تحسين العوامل التشغيلية لنظام التبريد التبخيرى مثل سمك الوسائد وسرعة الهواء. وتم إجراء هذه التجربة فى وحدة المزرعة السمكية والبيوت المحمية – كلية الزراعة بمشتهر – جامعة بنها – محافظة القليوبية لدراسة تأثير ارتفاع الوسائد (1.0 و2.0 م) وسرعة الهواء (1.5 و3.0 و4.5 و6.0 م ثانية$^{-1}$) . وكانت أهم النتائج المتحصل عليها كما يلى: زادت درجة الحرارة تدريجيا حتى وصلت الى اعلى قيمة لها ثم انخفضت على مدار اليوم من الساعة التاسعة صباحا حتى الساعة السادسة مساءا. انخفضت الرطوبة النسبية تدريجيا حتى وصلت الى اقل قيمة لها ثم زادت على مدار اليوم من الساعة التاسعة صباحا حتى الساعة السادسة مساءا. زاد الانخفاض فى درجات الحرارة من 3.3 الى 8.8 ومن 6.4 الى 14.4 ومن 5.5 الى 16.5 ومن 5.3 الى 18.4 °م بزيادة ارتفاع الوسادة من 1.0 الى 2.0 م على الترتيب لكل من سرعة الهواء 1.5 و3.0 و4.5 و6.0 م ثانية$^{-1}$. كانت اعلى قيمة للانخفاض فى درجة الحرارة 18.4 °م عند ارتفاع وسائد 2.0 م وسرعة هواء 6.0 م ثانية$^{-1}$. زادت كفاءة التبريد من 34.3 الى 61.7 ومن 53.4 الى 94.6 ومن 49.6 الى 94.4 ومن 54.1 الى 98.8% بزيادة ارتفاع الوسادة من 1.0 الى 2.0 م على الترتيب لكل من سرعة الهواء 1.5 و3.0 و4.5 و6.0 م ثانية$^{-1}$. كانت اعلى قيمة لسعة التبريد 629.1 كيلو وات عند ارتفاع وسائد 2.0 م وسرعة هواء 6.0 م ثانية $^{-1}$.

الكلمات المفتاحية: التبريد التبخيرى – درجة الحرارة – الرطوبة النسبية – كفاءة التبريد – سعة التبريد