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Effect of pad thickness and air velocity on the performance of evaporative cooling system

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Abstract

The main aim of this work is to optimize the operational parameters of using evaporative cooling system such as thickness of pads and air velocity. To achieve that, study the effect of different pad thicknesses (10, 15 and 20 cm) 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 in greenhouse. The obtained results indicated that the hourly temperature of air increased gradually until it reached the peak at 12.00 PM 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 lowest value at 12.00 PM and then increased during period from 9 AM to 6 PM. The temperature reduction increased from 4.0 to 5.9, 6.9 to 8.4, 6.9 to 8.8 and 8.4 to 11.6 °C when the pad thickness increased from 10 to 20 cm, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The highest value of temperature reduction was 11.6 °C was found with 20 cm pad thickness and 6.0 m s^{-1}air velocity. The cooling efficiency increased from 41.2 to 58.8, 55.2 to 67.2, 50.4 to 80.7 and 64.1 to 88.6 % when the pad thickness increased from 10 to 20 cm, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The highest value of cooling capacity was 250.1 kW was found with 20 cm pad thickness 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)**.

The reduction of air temperature inside a greenhouse or the regulation of the temperature closer to the ambient temperature during summer is necessary for successful crop production. The growth conditions in a greenhouse system are usually achieved by monitoring effective growth factors, such as carbon dioxide, temperature, relative humidity, light and radiation. Greenhouses offer a better possibility for the off-season production of many crops **(Al-Amri, 2000)**. The increase in air temperature inside a greenhouse with a prevailing high outdoor air temperature in the tropics will stress the greenhouse crops **(Luo *et al.*, 2005)**. Thus, lowering the air temperature is a major concern for tropical greenhouse climate management. During the hot season, the temperature of ambient air inside greenhouses and animal houses increases to over 40°C because of thermal stress **(Öztürk, 2003)**. In greenhouses, thermal stress negatively affects the emergence, stem strength, flowering and fruit set and sizes of seedlings **(Liao and Chiu, 2002)**.

Evaporative cooling is wide spreading in controlling the environment inside agricultural structures. Its systems include fan-pad, misting and fogging systems. Each is affected by numerous factors such as pad material, density, configuration, dimensions and airflow rate regarding pad-fan system, nozzles pressure, discharge and air velocity for misting and fogging systems **(Khalifa *et al.*, 2018)**.

Evaporative cooling is a simple and economic cooling technique that has been used for centuries to reduce ambient temperatures to comfortable levels **(Willits, 2003)**. **Lertsatitthanakorn *et al.* (2006), Sethi and Sharma (2007a) and Haeussermann *et al.* (2007)**, among others, have shown that these systems substantially improve climate control in greenhouses and intensive livestock installations.

The efficiency of these systems is affected under conditions of high ambient humidity, such as in coastal regions. However, as the humidity in the greenhouse varies considerably throughout the day, evaporative cooling systems are more effective and more necessary during the middle of the day, when the ambient temperature is high and relative humidity is lower. A recent study by **Dagtekin *et al.* (2009)** of evaporative cooling systems in the Mediterranean region found that these systems are effective when the relative humidity drops below 50%. They are of particular interest in hot regions with strong winds (e.g., Almeria, Spain), since a fog system requires the windows to be open. If the wind speed is high, the windows must be closed to safeguard the greenhouse structure; this causes rapid saturation of the air in the greenhouse, and the fog system is no longer effective. However, an evaporative cooling system functions correctly almost irrespective of the outside air speed.

Evaporative cooling is one of the energy-saving, environment friendly and sustainable air-conditioning technologies, which is now widely used in residential and commercial buildings, especially in hot and arid areas **(Xuan *et al.*, 2012a and b)**. Evaporative cooling can be mainly classified as direct evaporative cooling, indirect evaporative cooling, and semi-indirect evaporative cooling. Direct evaporative cooling is the oldest and simplest type of evaporative cooling in which the process air contacts directly with water and thus be cooled following an approximately constant enthalpy process. In this case, the dry-bulb temperature of entering air will decrease. Theoretically, the leaving air temperature can approach its entering air wet-bulb temperature if the entering air can be humidified to saturation. Direct evaporative cooling is a simple and economical way to cool down the air because no mechanical refrigeration is needed and it only consumes little power by fan and pump. Therefore, combining a direct evaporative cooler with the condenser of an air-cooled chiller to cool down the incoming air for the condenser is an energy efficient, reliable and cost-effective method to improve the performance of air-cooled chiller **(Hao *et al.*, 2013)**.

Optimization of the operation parameters of using evaporative 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 thickness of pads and air velocity.

2. 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.

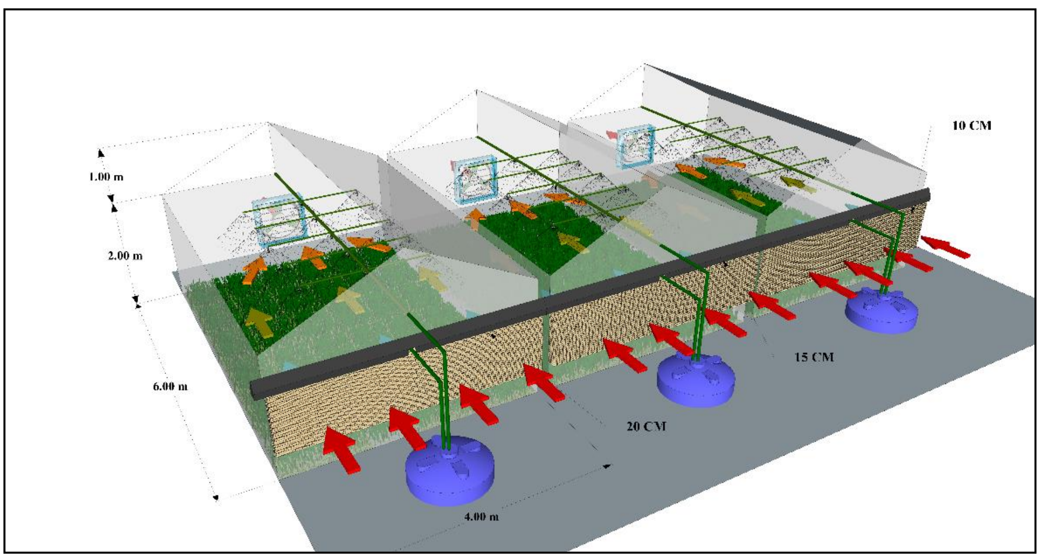


Fig. 1: The experimental setup.

2.1.1.1. Greenhouse’s construction

Three identical gable-even-spans 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.

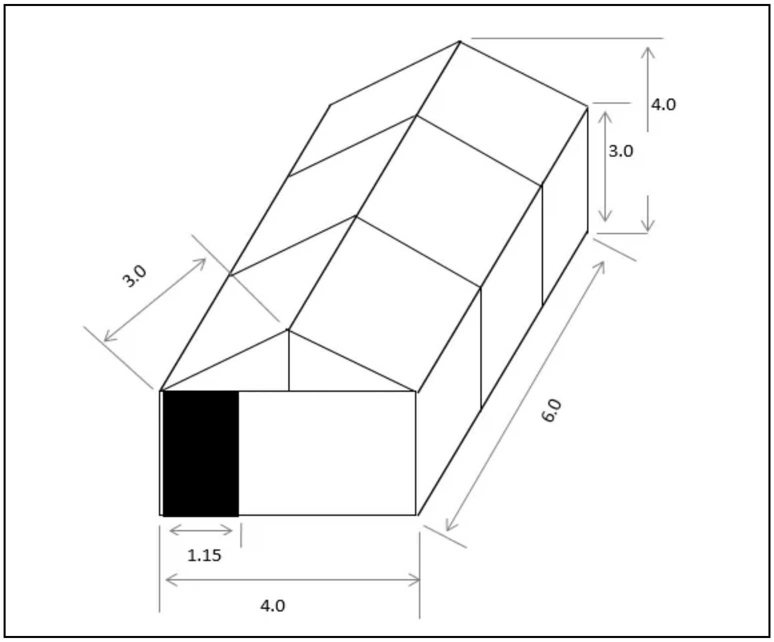


Fig. 2: The schematic diagram of gable-even-span greenhouse.

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.

2.1.1.3. 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 dimension of 100 cm high, 60 cm wide and three thicknesses were used namely 10, 15, and 20 cm. Fig. 3 shows the evaporative cooling pad.

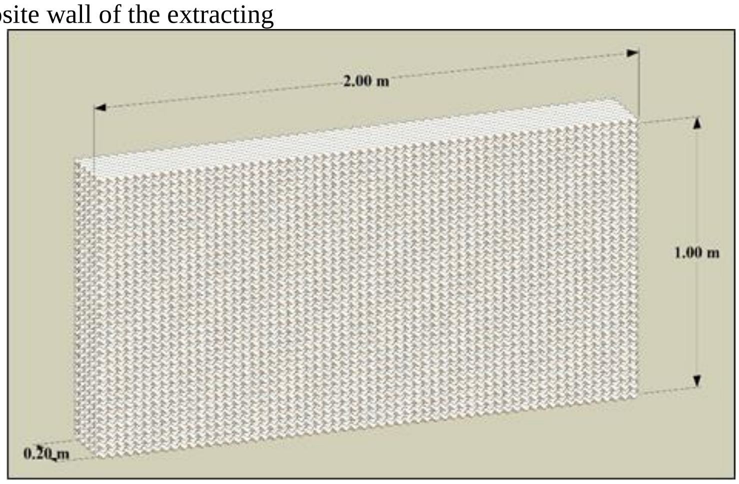


Fig. 3: Evaporative cooling pad

2.1.1.4. 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 $m^3\ min^{-1}$ 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).

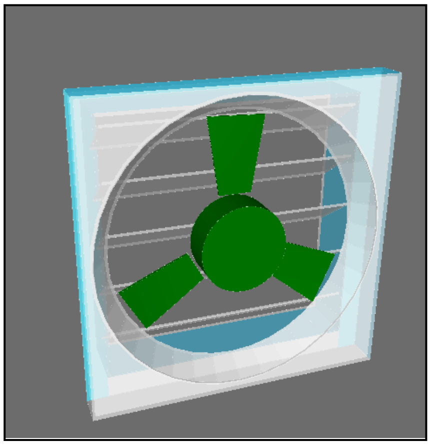


Fig. 4: extracting fan.

2.1.1.5. 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.

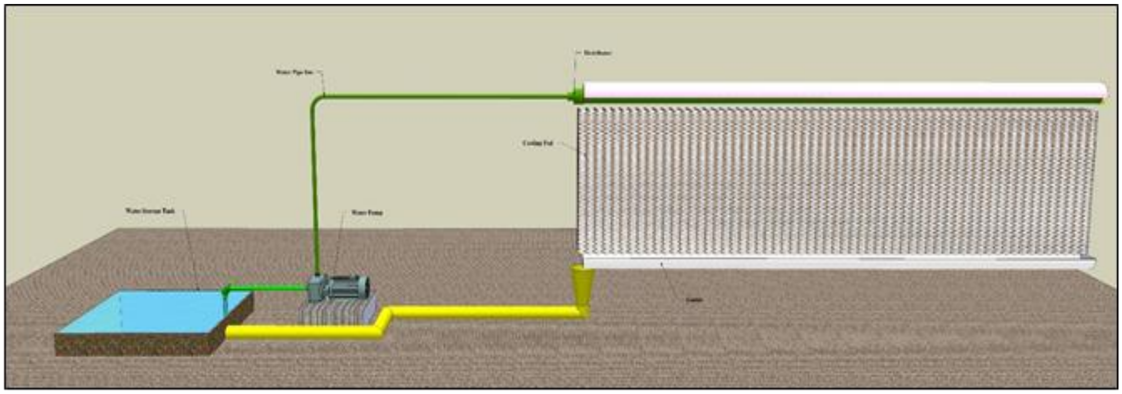


Fig. 5: Water cycle of Evaporative cooling

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.

2.1.1.6. 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 thickness	**3**	**10 cm**
		15 cm
		20 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.

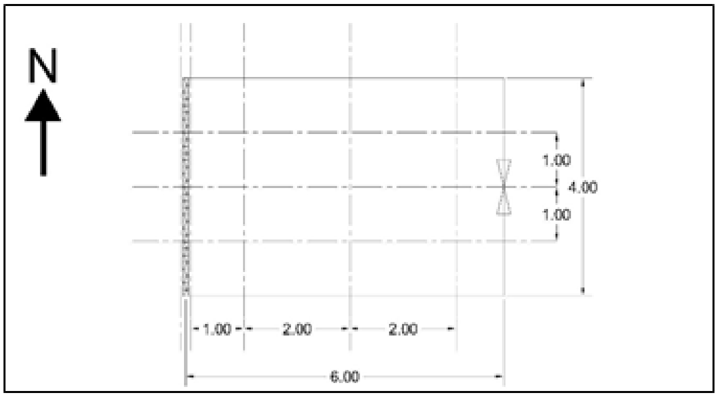


Fig. 6: A schematic diagram of sensors locations inside the greenhouse

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),

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

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).**

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

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

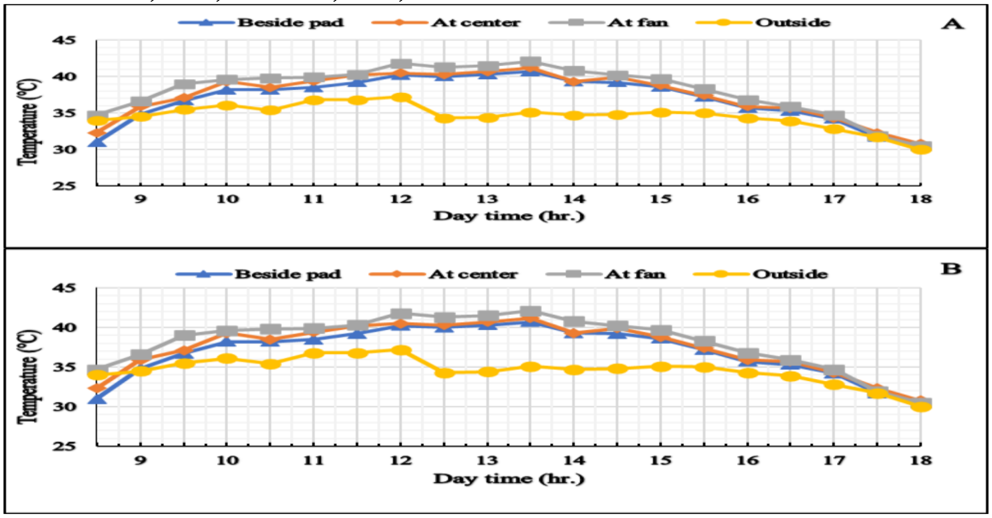
H is the height of the pad cooling, m

Results and Discussion

3.1. Hourly air temperature:

Fig. 7 shows the effect of pad thickness (10, 15 and 20 cm) on hourly relative humidity of air inside greenhouse (besides pad cooling 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 temperature of air increased gradually until it reached the peak at 12.00 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, 34.9, 34.8 and 37.8 and 35.7, 34.2 and 36.9 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness. While, the minimum hourly air temperatures were 25.4, 25.8, and 25.5, 24.4, 25.2, and 26.1 and 24.5, 24.6 and 24.8 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared the minimum hourly air temperature outside the greenhouse was 25 °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 25.4, 25.8, and 25.5, 24.4, 25.2, and 26.1 and 24.5, 24.6 and 24.8 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 6 PM.

The results also indicate that the air temperature decreases with increasing pad thickness, it could be seen that the air temperature decreased from 25.4 to 24.5, 25.8 to 24.8 and 25.5 to 25 °C, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively. Despite of use cooling system to reduce the temperature inside greenhouse, but the temperature inside greenhouse still over outside for air velocity of (1.5 m. s^{-1}), the maximum different was 5.9, 5.2, and 4°C during noon period for pad thickness of 10, 15, and 20 cm, respectively. While at morning period, temperatures inside greenhouse were lower than outside by 0.3, 0.1, and 1 °C for pad thickness of 10, 15, 20 cm, respectively.



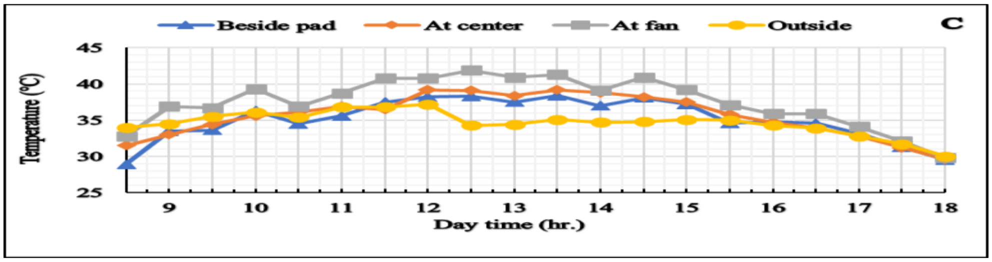
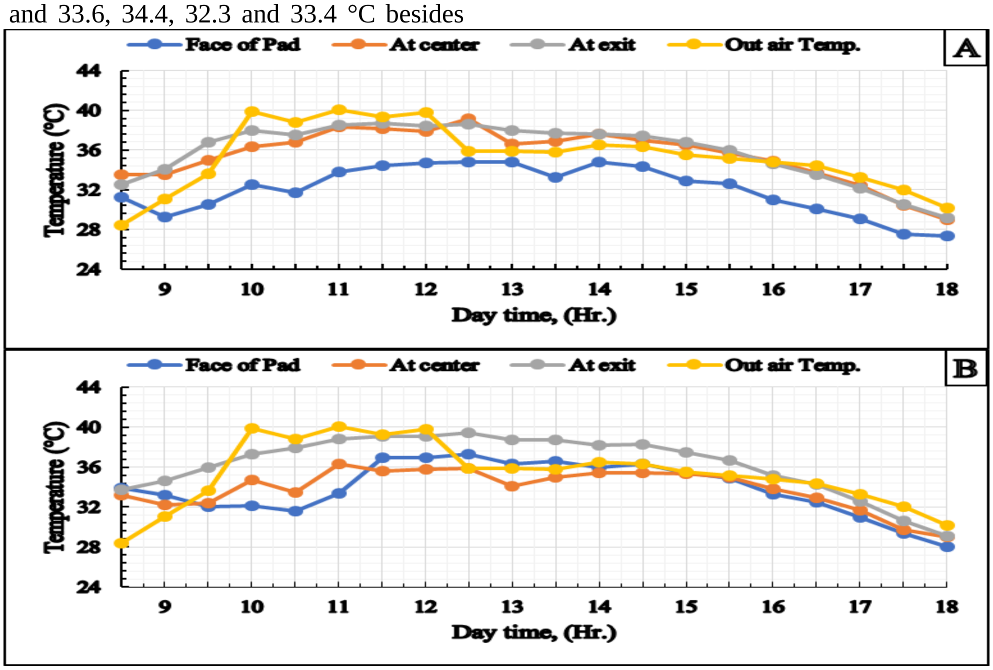


Fig. 7: Hourly temperature of air inside and outside greenhouse at different pad thickness with 1.5 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

Fig. 8 shows the effect of pad thickness (10, 15 and 20 cm) 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 air temperature decreases with increasing pad thickness, it could be seen that the air temperature decreased from 23.1 to 22.4, 24.2 to 23.0 and 24.8 to 24 °C, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.

The results indicate that, the hourly temperature of air increased gradually until it reached the peak at 12.30 PM and then decreased during period from 9 AM to 6 PM. It could be seen that the maximum hourly air temperatures were 30.9, 30.1, and 29.6, 34.2 30.9, and 33.6, 34.4, 32.3 and 33.4 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared he maximum hourly air temperature outside the greenhouse was 35.1 °C. While, the minimum hourly air temperatures were 22.4, 22.1 and 22.5, 24.2, 23 and 24, 24.1, 24.0 and 24.8 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared the minimum hourly air temperature outside the greenhouse was 25.2 °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 22.4, 22.1 and 23.1, 24.2, 23 and 24 and 24.1, 24.0 and 24.8 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 6 PM.



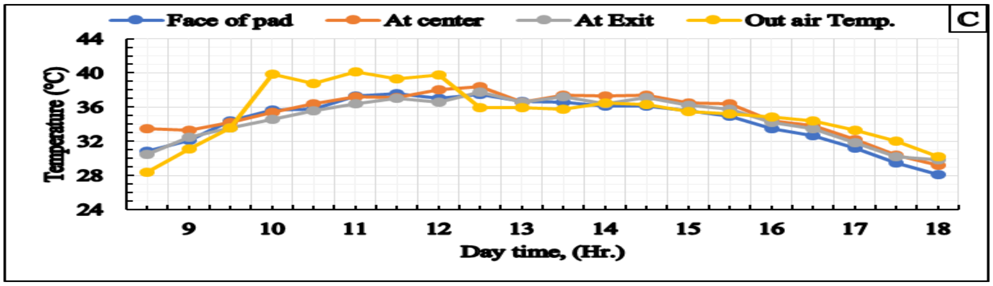
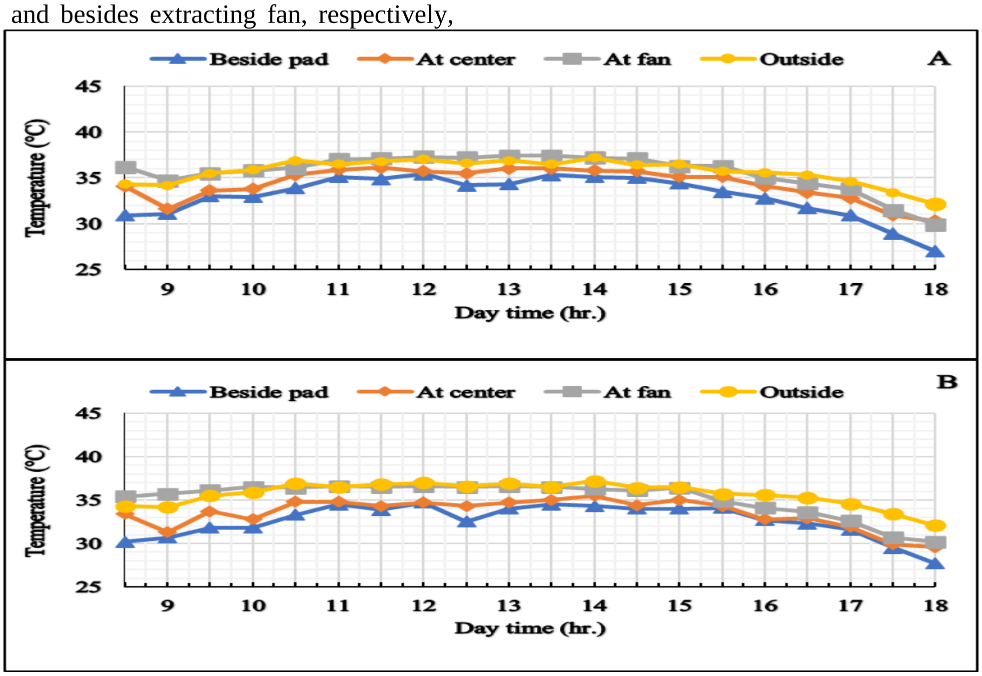


Fig. 8: Hourly temperature of air inside and outside greenhouse at different pad thickness with 3.0 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

Fig. 9 shows the effect of pad thickness (10, 15 and 20 cm) 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 increased gradually until it reached the peak at 12.00 PM and then decreased during period from 9 AM to 6 PM. It could be seen that the maximum hourly air temperatures were 26.4, 25.9 and 24.4, 31.1, 30.5 and 31.2 and 32.4, 31.6 and 30.7 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness. While, the minimum hourly air temperatures were 22.6, 22.7 and 21.4, 25.3, 24.6 and 24.1 and 24.9, 25.2 and 23.9 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared the minimum hourly air temperature outside the greenhouse was 27.1 °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 22.6, 22.7 and 21.4, 25.3, 24.6 and 24.1 and 24.9, 25.2 and 23.9 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 6 PM.

The results also indicate that the air temperature decreases with increasing pad thickness, it could be seen that the air temperature decreased from 22.6 to 21.4, 25.3 to 24.1 and 24.9 to 23.9 °C, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



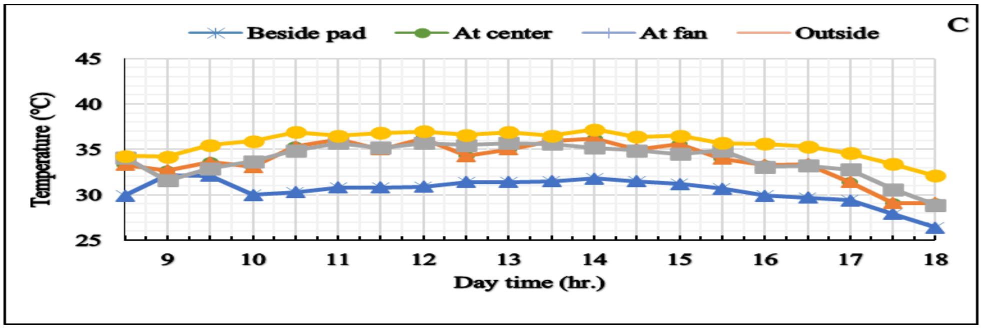
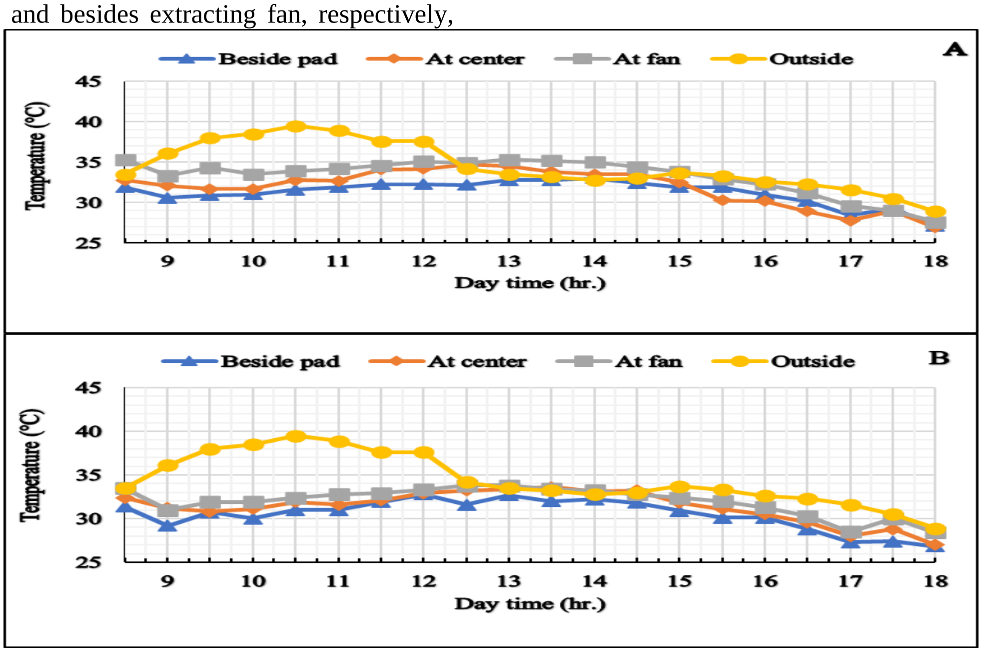


Fig. 9: Hourly temperature of air inside and outside greenhouse at different pad thickness with 4.5 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

Fig. 10 shows the effect of pad thickness (10, 15 and 20 cm) 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 increased gradually until it reached the peak at 12.00 PM and then decreased during period from 9 AM to 6 PM. It could be seen that the maximum hourly air temperatures were 25.9, 24.7 and 24.1, 29.7, 28.6 and 25.1 and 30.3, 28.8 and 30.7 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness. While, the minimum hourly air temperatures were 22.1, 21.8 and 19.7, 21.9, 22.0 and 20.8 and 22.6, 23.4 and 22.6 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness 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 22.1, 21.8 and 19.7, 21.9, 22.0 and 21.5 and 22.6, 23.4 and 22.6 °C besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 6 PM.

The results also indicate that the air temperature decreases with increasing pad thickness, it could be seen that the air temperature decreased from 22.1 to 19.7, 21.9 to 21.5 and 23.4 to 22.6 °C, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



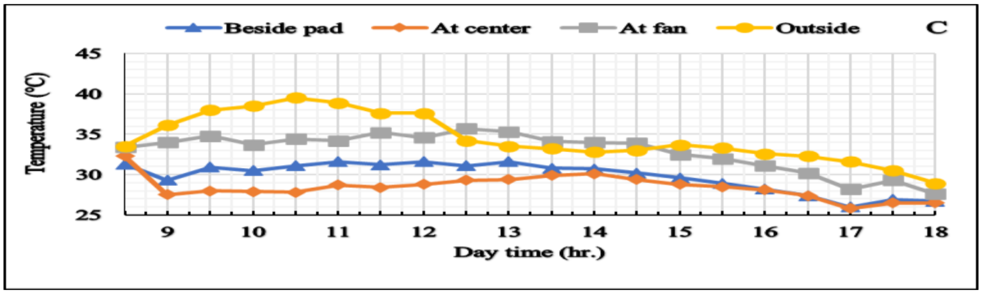
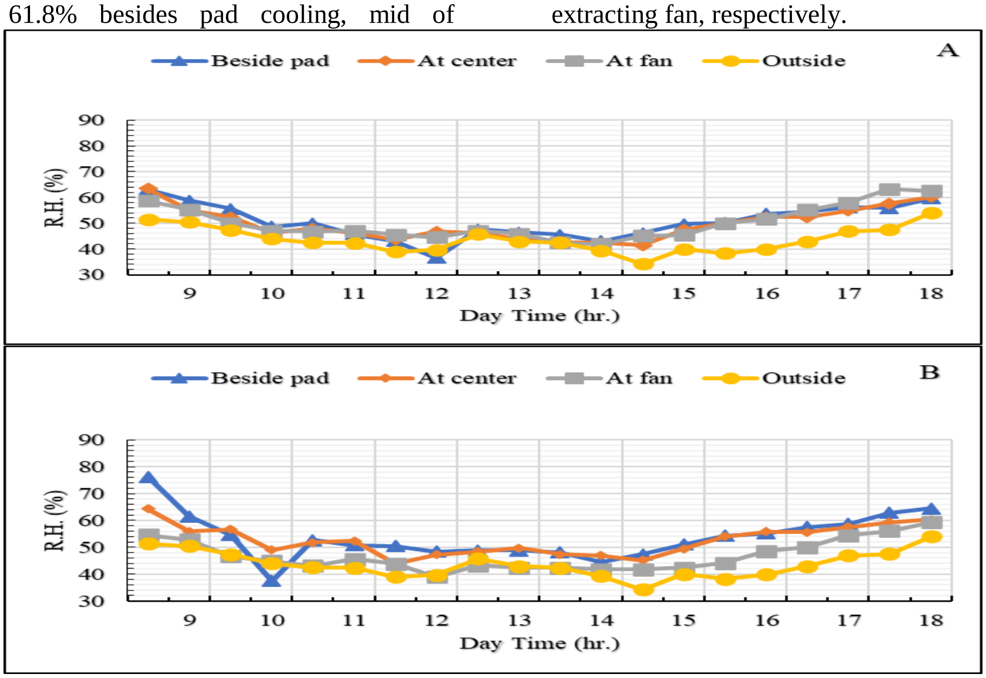


Fig. 10: Hourly temperature of air inside and outside greenhouse at different pad thickness with 6.0 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

3.2. Hourly Relative humidity:

Fig. 11 shows the effect of pad thickness (10, 15 and 20 cm) on hourly relative humidity of air inside greenhouse (besides pad cooling 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 12.00 PM and then increased during period from 9 AM to 6 PM. It could be seen that the minimum hourly relative humidity was 36.6, 37.5 and 47.9, 41.5, 43.9 and 44.7 and 41.9, 39 and 40% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness. While, the maximum hourly relative humidity was 63.1, 76.3 and 80.1, 63.4, 64.4 and 64.8 and 63.2, 59.3 and 61.8% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared the maximum hourly relative humidity outside the greenhouse was 54%. 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 was 63.1, 63.4 and 63.2, 76.3, 64.4 and 59.3 and 80.1, 64.8 and 61.8% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 8 AM.

The results also indicate that the relative humidity increases with increasing pad thickness, it could be seen that the relative humidity in 36.6 to 47.9, 41.5 to 44.7 and 40 to 41.9%, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



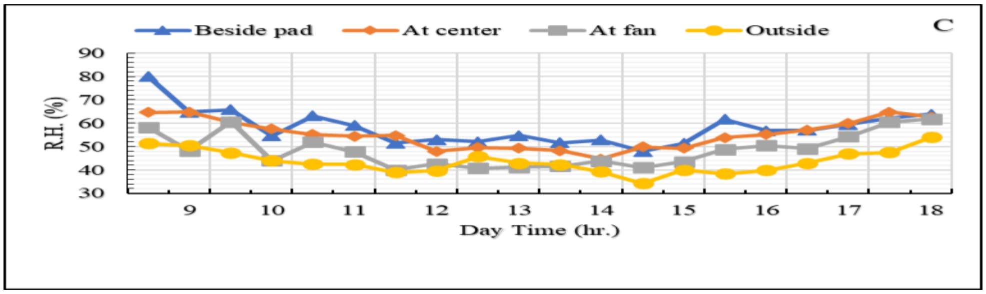
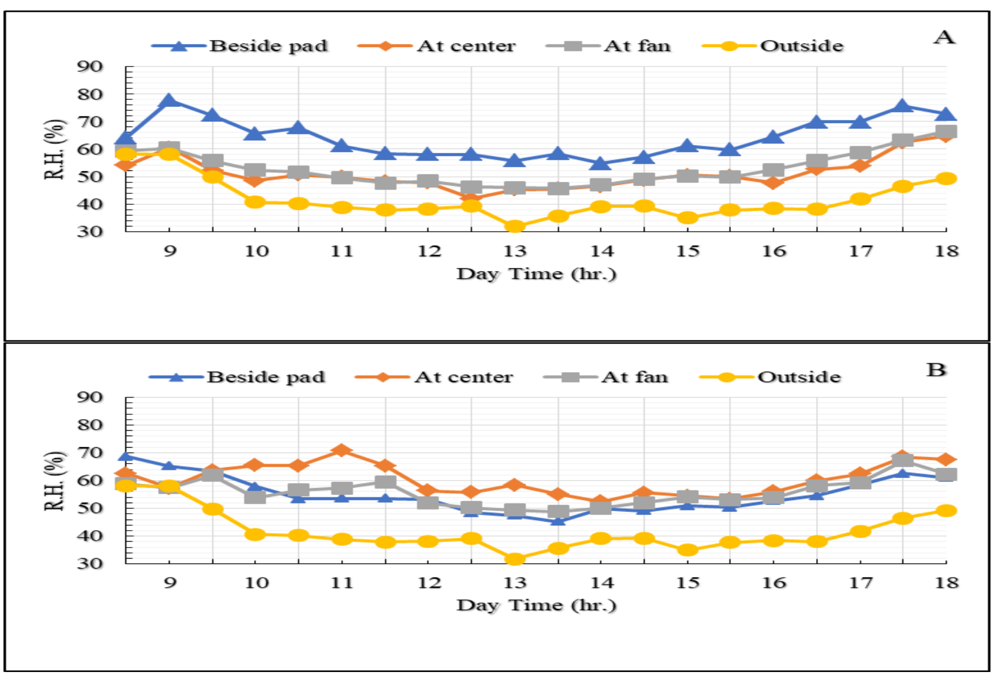


Fig. 11: Hourly relative humidity of air inside and outside greenhouse at different pad thickness with 1.5 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

Fig. 12 shows the effect of pad thickness (10, 15 and 20 cm) on hourly relative humidity of air inside greenhouse (besides pad cooling 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 12.00 PM and then increased during period from 9 AM to 6 PM. It could be seen that the minimum hourly relative humidity were 54.8, 45.2 and 48.1, 42, 52.5 and 48.1 and 45.6, 48.8 and 45.4% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness. While, the maximum hourly relative humidity were 77.6, 64.7 and 66.4, 68.7, 70.7 and 67.1 and 70.6, 63.8 and 64.6% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared the maximum hourly relative humidity outside the greenhouse was 58.2%. 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 72.7, 66.4 and 64.7, 67.6, 62.3 and 61.1 and 66.8, 63.8 and 59.6% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 6 PM.

The results also indicate that the relative humidity increases with increasing pad thickness, it could be seen that the relative humidity were 64.7 to 66.8, 59.3to 60.7 and 54.1 to 55.8 %, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



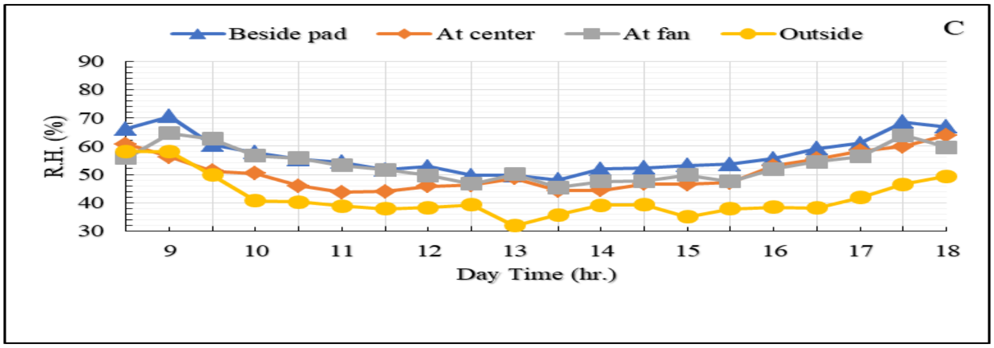
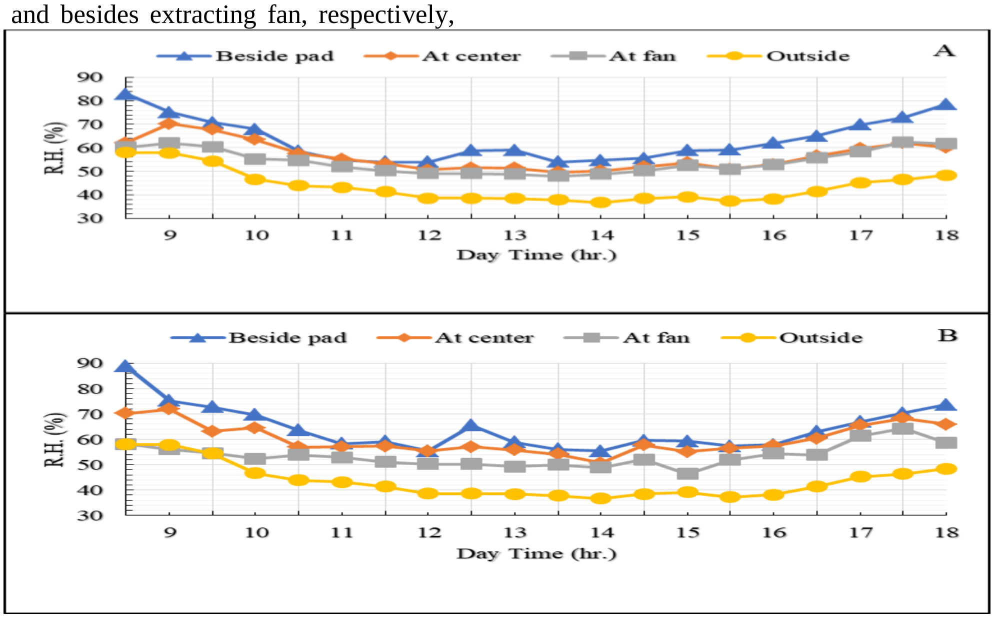


Fig. 12: Hourly relative humidity of air inside and outside greenhouse at different pad thickness with 3.0 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

Fig. 13 shows the effect of pad thickness (10, 15 and 20 cm) on hourly relative humidity of air inside greenhouse (besides pad cooling 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 at 12.00 PM and then increased during period from 9 AM to 6 PM. It could be seen that the minimum hourly relative humidity was 53.9, 49.6 and 47.9, 55.4, 50.6 and 46.3 and 63.6, 44.9 and 52.6% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness. While, the maximum hourly relative humidity was 82.9, 70.2 and 62.4, 88.8, 71.9 and 64.3 and 81.6, 69.8 and 72.40% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared the maximum hourly relative humidity outside the greenhouse was 48.4%. 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 was 78.5, 61.7 and 60.2, 73.7, 65.9 and 58.6 and 79.9, 67.4 and 67.0% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 6 PM.

The results also indicate that the relative humidity increases with increasing pad thickness, it could be seen that the relative humidity was 62.4 to 82.9, 64.3 to 88.8 and 72.4 to 81.6 %, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



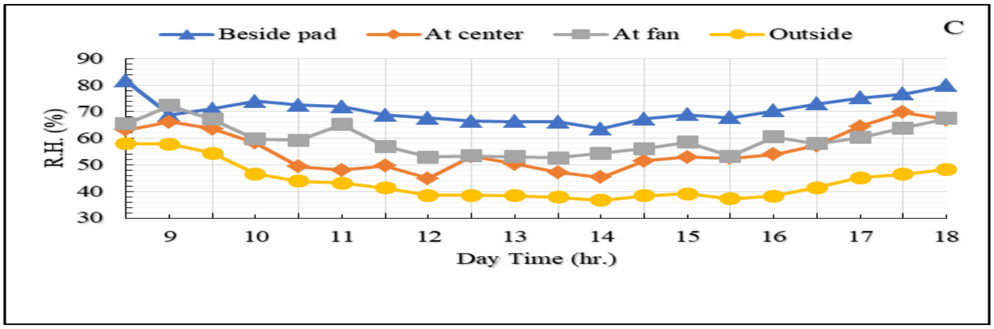
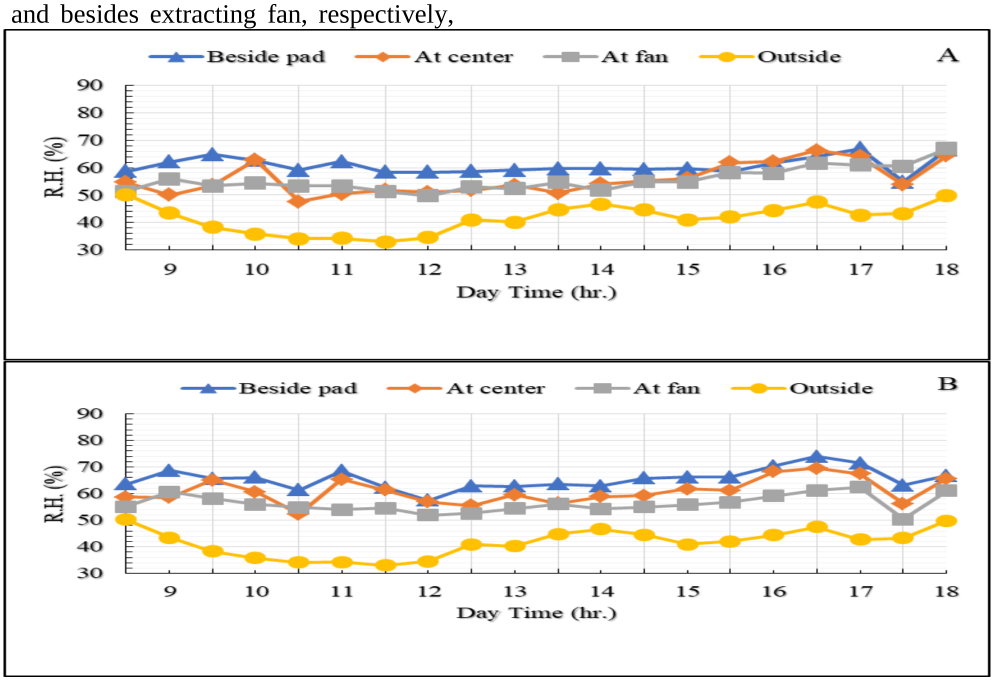


Fig. 13: Hourly relative humidity of air inside and outside greenhouse at different pad thickness with 4.5 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

Fig. 14 shows the effect of pad thickness (10, 15 and 20 cm) on hourly relative humidity of air inside greenhouse (besides pad cooling and besides extracting fan) and compared with hourly air relative humidity 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 relative humidity of air decreased gradually until it reached the peak at 12.00 PM and then increased during period from 9 AM to 6 PM. It could be seen that the minimum hourly relative humidity was 54.8, 57.4 and 58.6, 47.6, 52.3 and 56.7 and 49.8, 50.4 and 38.1% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness. While, the maximum hourly relative humidity was 66.9, 74 and, 81.4%, 66.3 and 69.5 and 75.7, 67 and 62.4, and 64.2% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness compared the maximum hourly relative humidity outside the greenhouse was 50.2%. 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 was 66.5, 64.4 and 67.0, 66.7 and 65.7 and 61, 68.7, 66.5 and 63.9% besides pad cooling, mid of greenhouse and besides extracting fan, respectively, for 10, 15 and 20 cm pad thickness at 6 PM.

The results also indicate that the relative humidity increases with increasing pad thickness, it could be seen that the relative humidity was 66.5 to 68.7, 64.4 to 66.5 and 63.9 to 67%, when the pad thickness increased from 10 to 20 cm, respectively, besides pad cooling, mid of greenhouse and besides extracting fan, respectively.



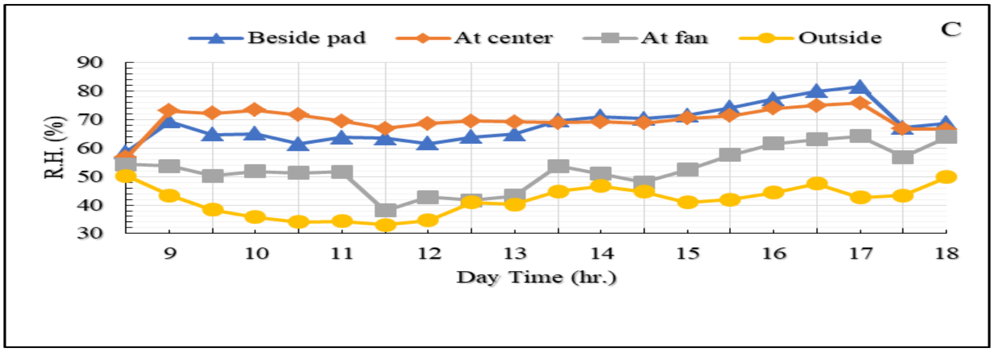
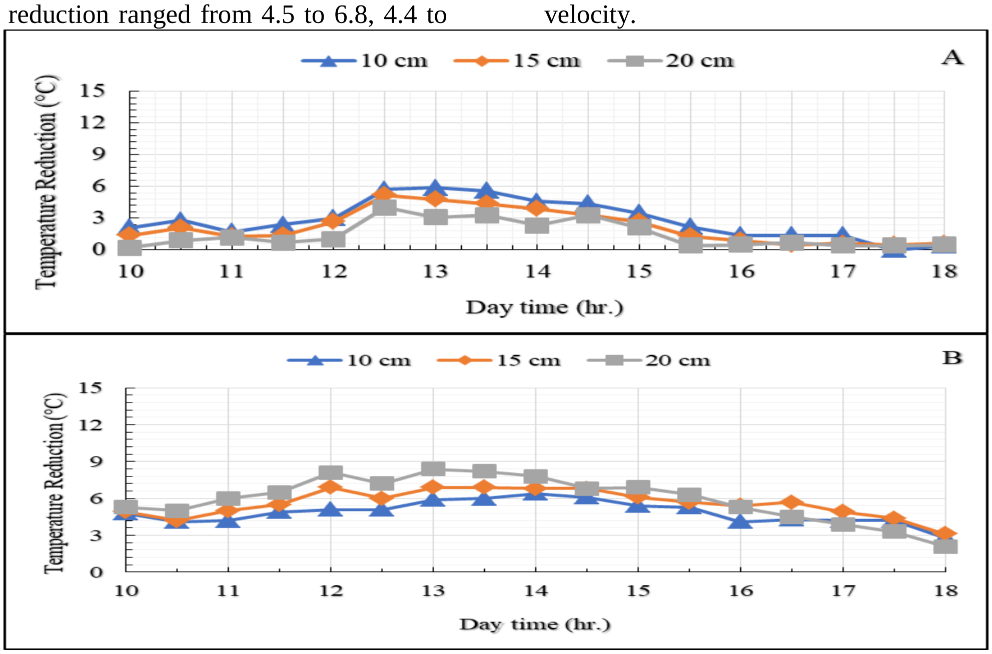


Fig. 14: Hourly relative humidity of air inside and outside greenhouse at different pad thickness with 6.0 m s^{-1} air velocity. A: 10 cm, B: 15 cm, C:20 cm

3.3. Temperature reduction (∆T):

Fig. 15 shows the effect of pad thickness (10, 15 and 20 cm) 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 at 12.00 PM and then decreased during period from 9 AM to 6 PM. It could be seen that the temperature reduction ranged from 0.4 to 4.0, 0.5 to 5.2 and 0.4 to 5.9 °C for 10, 15 and 20 cm pad thickness, respectively for 1.5 m s^{-1}. For 3.0 m s^{-1}, the temperature reduction ranged from 2.8 to 6.4, 3.1 to 6.9 and 2.1 to 8.4 °C for 10, 15 and 20 cm pad thickness, respectively. For 4.5 m s^{-1}, the temperature reduction ranged from 4.5 to 6.8, 4.4 to 8.6 and 5.7 to 9.6 °C for 10, 15 and 20 cm pad thickness, respectively. For 6.0 m s^{-1}, the temperature reduction ranged from 1.8 to 9.2, 2.1 to 10.4 and 4.2 to 11.6 °C for 10, 15 and 20 cm pad thickness, respectively.

The results also indicate that the temperature reduction increases with increasing pad thickness. It could be seen that, the temperature reduction increased from 4.0 to 5.9, 6.4 to 8.4, 6.8 to 9.6 and 9.2 to 11.6 °C when the pad thickness increased from 10 to 20 cm, 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 11.3 °C was found with 20 cm pad thickness and 6.0 cm s^{-1}air velocity.



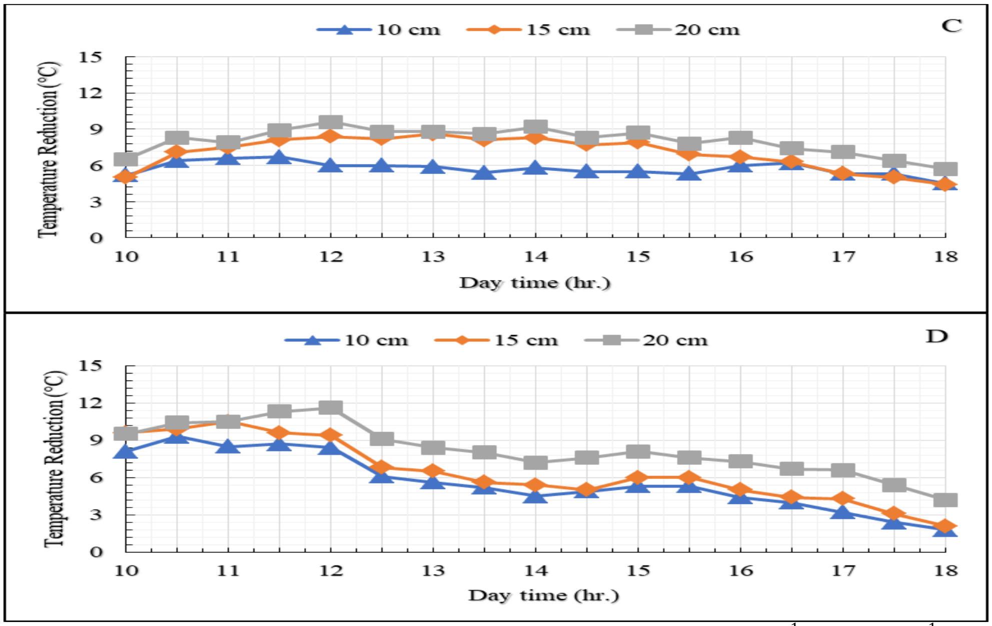
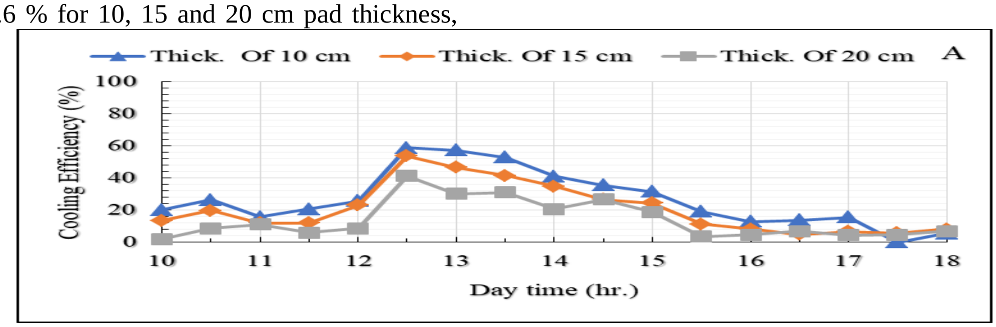


Fig. 14: Temperature reduction for different pad thicknesses. A: 1.5 m s^{-1}, B: 3.0 m s^{-1}, C: 4.5 m s^{-1}, D: 6.0 m s^{-1}

3.4. Cooling Efficiency:

Fig. 15 shows the effect of pad thickness (10, 15 and 20 cm) 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 at 12:30 PM and then decreased during period from 9 AM to 6 PM. It could be seen that the cooling efficiency ranged from 3.8 to 45.5, 5.4 to 59.1 and 5.03 to 64.8 % for 10, 15 and 20 cm pad thickness, respectively for 1.5 m s^{-1}. For 3.0 m s^{-1}, the cooling efficiency ranged from 36.5 to 58, 38.5 to 64.6 and 28.6 to 73.6 % for 10, 15 and 20 cm pad thickness, respectively. For 4.5 m s^{-1}, the cooling efficiency ranged from 49.1 to 67.5, 55.7 to 79.2 and 72.2 to 88.6 % for 10, 15 and 20 cm pad thickness, respectively. For 6.0 m s^{-1}, the cooling efficiency ranged from 25.7 to 77.6, 29.96 to 87.76 and 59.91 to 97.9 % for 10, 15 and 20 cm pad thickness, respectively.

The results also indicate that the cooling efficiency increases with increasing pad thickness. It could be seen that, the cooling efficiency increased from 45.5 to 64.8, 58 to 73.6, 67.5 to 88.6 and 77.6 to 97.9 % when the pad thickness increased from 10 to 20 cm, 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 97.9% 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)**.



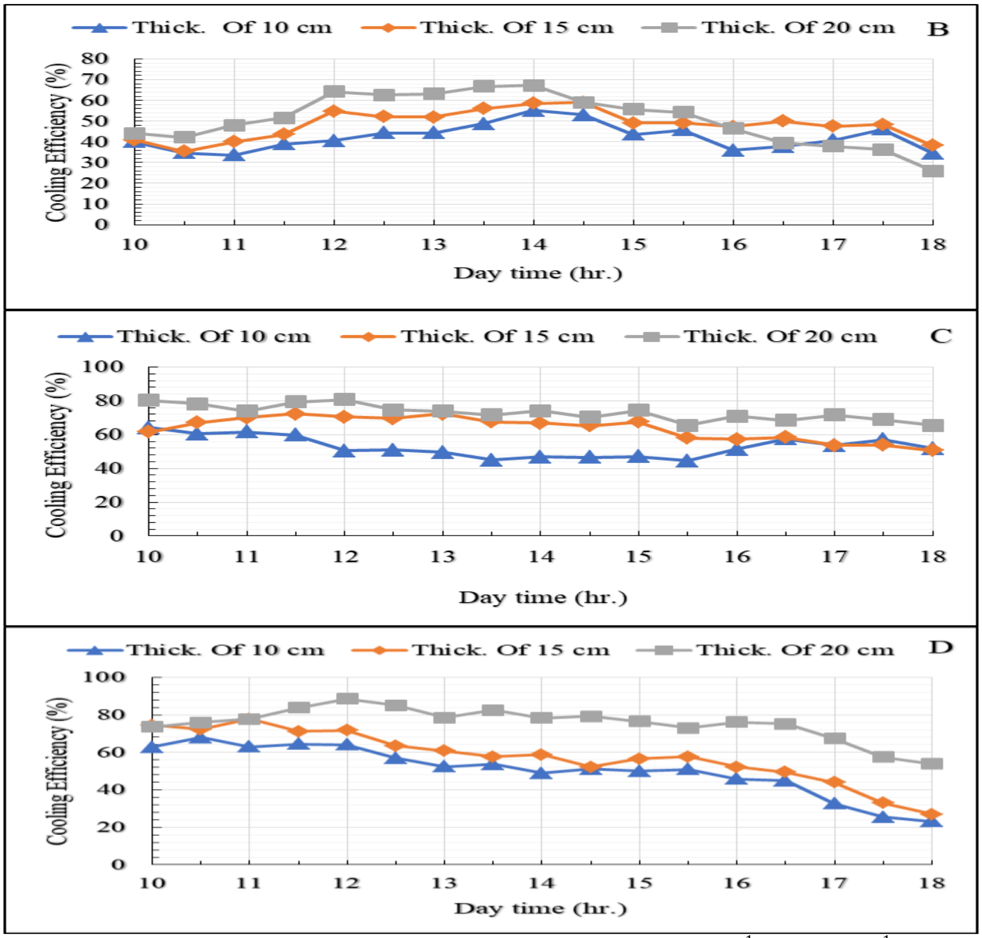


Fig. 15: Cooling efficiency for different pad thicknesses. A: 1.5 m s^{-1}, B: 3.0 m s^{-1}, C: 4.5 m s^{-1}, D: 6.0 m s^{-1}

3.5 Cooling Capacity:

Fig. 16 shows the effect of pad thickness (10, 15 and 20 cm) 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 at 12:30 PM 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, 2.7 to 28.0 and 2.2 to 31.8 kW for 10, 15 and 20 cm pad thickness, respectively for 1.5 m s^{-1}. For 3.0 m s^{-1}, the cooling capacity ranged from 30.2 to 69.0, 33.4 to 74.4 and 22.6 to 90.6 kW for 10, 15 and 20 cm pad thickness, respectively. For 4.5 m s^{-1}, the cooling efficiency ranged from 72.8 to 110, 71.2 to 139.1 and 92.2 to 155.3 kW for 10, 15 and 20 cm pad thickness, respectively. For 6.0 m s^{-1}, the cooling efficiency ranged from38.8 to 198.4, 45.3 to 224.3 and 90.6 to 250.1 kW for 10, 15 and 20 cm pad thickness, respectively.

The results also indicate that the cooling capacity increases with increasing pad thickness. It could be seen that, the cooling capacity increased from 21.6 to 31.8, 69.0 to 90.6, 110 to 155.3 and 198.4 to 250.1 kW when the pad thickness increased from 10 to 20 cm, 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 250.1kW was found with 20 cm pad thickness and 6.0 cm s^{-1}air velocity. These results agreed with those obtained by **Khater (2014)** who found the cooling capacity increases with increasing the air velocity.

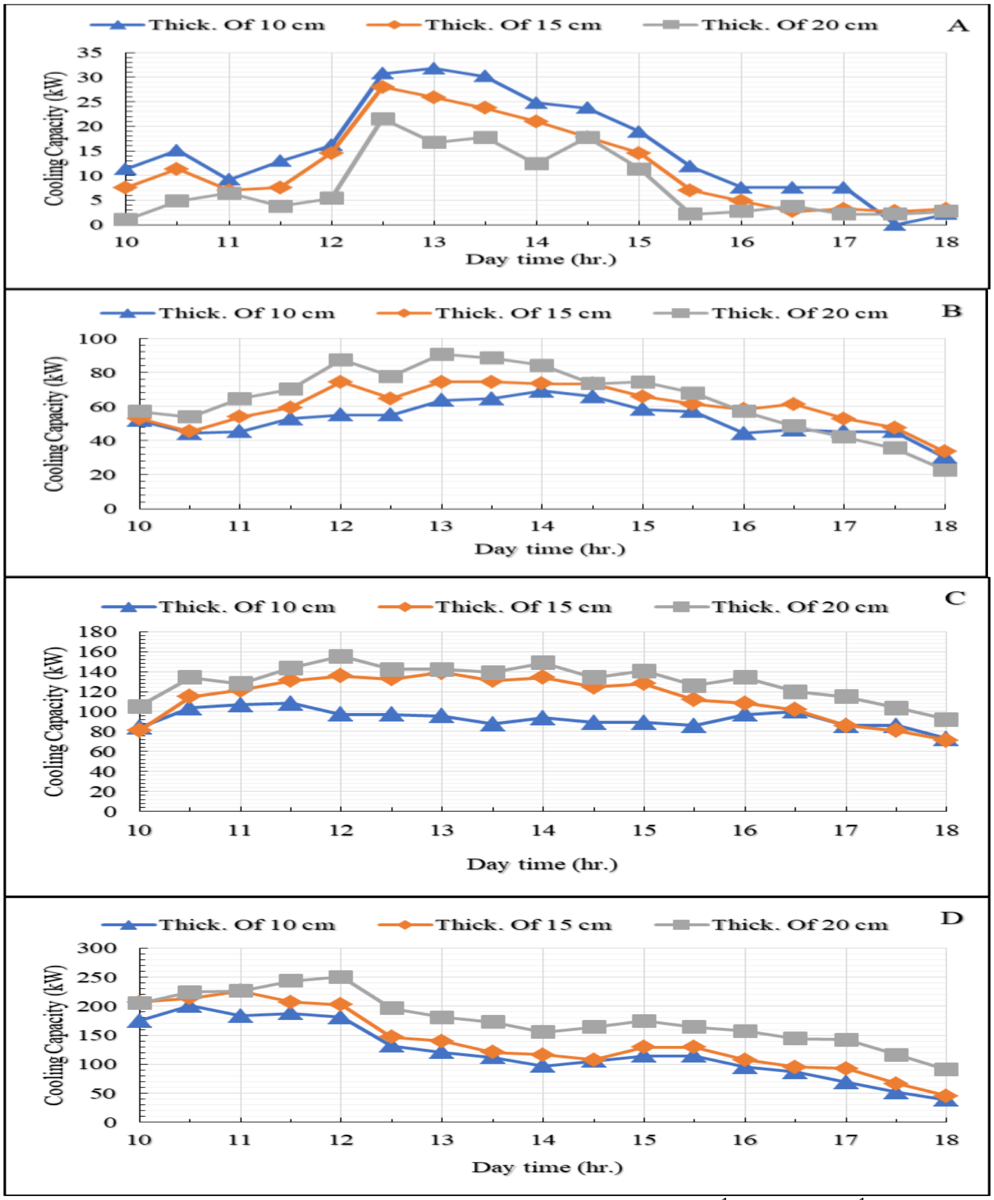


Fig. 16: Cooling capacity for different pad thicknesses. A: 1.5 m s^{-1}, B: 3.0 m s^{-1}, C: 4.5 m s^{-1}, D: 6.0 m s^{-1}

Conclusion

The experiment was carried out to study the effect of pad thickness (10, 15 and 20 cm) 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 at 12.00 PM 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 at 12.00 PM and then increased during period from 9 AM to 6 PM.
- The temperature reduction increased from 4.0 to 5.9, 6.4 to 8.4, 6.8 to 9.6 and 9.2 to 11.6 °C when the pad thickness increased from 10 to 20 cm, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity. The highest value of temperature reduction was 11.6 °C was found with 20 cm pad thickness and 6.0 cm s^{-1}air velocity.
- The cooling efficiency increased from 45.5 to 64.8, 58 to 73.6, 67.5 to 88.6 and 77.6 to 97.9 % when the pad thickness increased from 10 to 20 cm, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity.

- The cooling capacity increased 21.6 to 31.8, 69.0 to 90.6, 110 to 155.3 and 198.4 to 250.1 kW when the pad thickness increased from 10 to 20 cm, respectively for 1.5, 3.0, 4.5 and 6.0 m s^{-1} air velocity.

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تأثير سمك 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 السكمية والبيوت المحمية – كلية الزراعة بمشتهر – جامعة بنها – محافظة القليوبية لدراسة تأثير سمك الوسادة (10 و15 و20 سم) وسرعة الهواء (1.5 و3.0 و4.5 و6.0 م ثانية$^{-1}$) . وكانت أهم النتائج المتحصل عليها كما يلى: زادت درجة الحرارة تتدريجيا حتى وصلت الى اعلى قيمة لها الساعة الثانية ظهرا ثم انخفضت على مدار اليوم من الساعة التاسعة صباحا حتى الساعة السادسة مساءا. انخفضت الرطوبة النسبية تتدريجيا حتى وصلت الى اقل قيمة لها الساعة الثانية عشر ظهرا ثم زادت على مدار اليوم من الساعة التاسعة صباحا حتى الساعة السادسة مساءا. زاد الانخفاض فى درجات الحرارة من 4.0 الى 5.9 ومن 6.4 الى 8.4 ومن 6.8 الى 9.6 ومن 9.2 الى 11.6 °م بزيادة سمك الوسادة من 10 الى 20 سم على الترتيب لكل من سرعة الهواء 1.5 و3.0 و4.5 و6.0 م ثانية$^{-1}$. كانت اعلى قيمة للانخفاض فى درجة الحرارة 11.6 °م عند سمك وسائد 20 سم وسرعة هواء 6.0 م ثانية$^{-1}$. زادت كفاءة التبريد من 45.5 الى 64.8 ومن 58 الى 73.6 ومن67.5 الى 88.6 ومن 77.6 الى 97.9% بزيادة سمك الوسادة من 10 الى 20 سم على الترتيب لكل من سرعة الهواء 1.5 و3.0 و4.5 و6.0 م ثانية$^{-1}$. كانت اعلى قيمة لسعة التبريد 250.1 كيلو وات عند سمك وسائد 20 سم وسرعة هواء 6.0 م ثانية $^{-1}$.

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