Experimental Investigation of Greenhouse Microclimate Control using Phase Change Material

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Abstract— Greenhouses are used to create the appropriate environmental conditions such as temperature, relative humidity, lighting level and the concentration of carbon dioxide to grow many varieties of plants during off-season of the year and to achieve the greatest possible return per unit area. This paper deals with the design, manufacturing, installing, operating and field-testing a greenhouse to find the optimal environmental results inside the greenhouse. A greenhouse unit is built in the Solar Energy Department; National Research Centre, Egypt. In order to minimize the thermal load inside the greenhouse, two mechanisms are used. The first one is using a shading mechanism that is designed to be installed in the south facing wall containing a Phase Change Materials, PCM, (paraffin wax) filled in copper pipe with a considerable wide fins to enhance the heat transfer modes between the fins and the copper pipe. The second mechanism is to use evaporative cooling system. It is found that several parameters are affecting the system performance; like water temperature of the evaporative cooling system, inlet solar radiation, existence of PCM materials, airflow rates inside the greenhouse and effect of shading system. The best performance of the environmental conditions inside the greenhouse is to use PCM with shading system associated with pre-cooled water in the evaporative cooling system.

Keywords—Greenhouse, PCM, Thermal energy storage, Evaporative Cooling, Systems, Efficiency. Hydroponic system.

I. INTRODUCTION

The idea to use phase change materials (PCM) for storing thermal energy is to make use of the latent heat of the PCM, usually between the solid and the liquid state. Since a phase change involves a large amount of latent energy at small temperature changes, PCMs are used for temperature stabilization and storing heat with large energy densities in combination with rather small temperature changes. Mirahmad et al.[1] studied a comprehensive theoretical and experimental investigation on a Latent Heat Thermal Energy Storage (LHTES) system by using about 200 grams of PCM packed in aluminum sheets. They concluded that there is a feasible applications of a LHTES system for controlling the temperature swing in a greenhouse.

They studied the greenhouse numerically and compared the output results with their experimental values. They found that by using this passive coolant system, the internal temperature can be reduced for 10°C. Najjar. et al, [2] developed a mathematical model for the storage material for the greenhouse. The coupled models are solved using numerical methods and Java code program. The effect of different parameters on the inside greenhouse temperature is investigated. The temperature swing between maximum and minimum values during 24 h can be reduced by 3–5°C using the PCM storage. This can be improved further by enhancing the heat transfer between the PCM storage and the air inside the greenhouse. Bouadila. et al, [3] studied the thermal performance of a new solar air heater using a packed bed of spherical capsules with the latent heat storage system in east–west oriented greenhouse, the output data are analyzed and discussed. They found that the excess heat in the greenhouse was stored in the packed bed through the diurnal period and extracted at night. A comparative experimental study was conducted in two greenhouses installed in the Research and Technologies Centre of Energy (CRTEN) in Tunisia. Sirelkhatim K. A. et. al. [4] used evaporative cooling system. In their system, the water in a storage tank is cooled by means of circulating the water through the cooling pads throughout the nighttime. During the next daylight, the cold water in the storage tank used in the cooling coil unit as chilled fluid to decrease temperature of outdoor air (precooling). Then, the pre-cooled air with lower wet bulb temperature passed through the direct evaporative cooling system. Their system consists of three parts: (1) Greenhouse, (2) Cooling coil, and (3) Direct evaporative cooling. Helmy M. A. et al. [5] developed and constructed 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.
Several previous works studied the performance of the greenhouse plantation system with proper ventilation associated with evaporative air cooling and focused on the effective parameters lead to improve the greenhouse performance [6-10].

II. EXPERIMENTAL SETUP

The system consists of the greenhouse building and shading system, ventilation system, evaporative cooling system, hydroponic plantation system, and measuring devices. The system is designed to be in actual size to properly investigate its performance. The schematic diagram of the designed system from elevation and side orientation is shown in Fig. 1.

![Schematic diagram of the greenhouse from elevation and side orientation](image)

The greenhouse is designed to be manufactured using steel structure metal frame with dimensions of 3m X 4.5m X 1.6 m. All sidewalls are covered with transparent glass sheets, with the same dimensions and thickness of 4 mm, and well-sealed with silicone rubber to prevent any air leakage. The shading system is installed in the south facing wall which is exposed to the solar radiation that transmitted inside the greenhouse via glass sheets. The transmitted radiation causes thermal energy storage inside the greenhouse. In order to minimize the thermal energy that has bad effect on the plant growth inside the greenhouse, a shading system is installed in the south wall of the greenhouse.

It is made from five copper tubes, each tube with diameter of 0.5 inch and 3.5 m length is associated with a wide copper fin to maximize the heat transfer surface area and the copper tubes are filled with the PCM. When the transmitted solar radiation entered the greenhouse, the fin and tube system provides two functions, the first one is to make shading inside the greenhouse area from the thermally harmful south direction while the daylight can be transmitted through the greenhouse side walls. The second function is to absorb the thermal energy through the fins and this heat is transferred to the copper tube wall and consequently transferred into the PCM material. The thermal energy is used to melt the PCM and change its state from solid one to liquid state. By this way the harmful thermal energy is absorbed by the PCM system and the environmental conditions inside the greenhouse is improved. A photographic view of the metal frame and glass cover sheets of the greenhouse is illustrated in Figs. 2a and 2b. It is prepared with access metallic door for inlet and outlet purposes. Based on the greenhouse area and internal volume, the ventilation system is designed to have two exhaust fans installed in the Eastern wall of the greenhouse. Each fan has a capacity of 1500 CFM. The evaporative cooling system consists of pad with a size of 1 m x 1 m that made from a high density corrugated cartons as one of the best water absorbing materials, water tank, circulating pump, atomizer, and connecting pipes.

III. HYDROPONIC CULTURE SYSTEM

A hydroponic system is designed and installed inside the greenhouse.

![Photographic view of the metal frame and glass cover sheets of the greenhouse](image)
This system called Nutrient Film Technique (NFT) system where the plants have their roots growing in shallow stream recirculated water; this water consists of all the necessary elements required for plants growth.

Four simple constructive NFT gullies 3 meter length, 30 cm wide, 6 cm height and 1% slop were used. White-black polyethylene with 200 micron thickness 90 cm wide were used to form the gullies. To construct channels, the polyethylene sheets were laid in, where the white side lowermost and the black side uppermost, on the prepared surface. A rectangular polystyrene frame (30 cm wide, 6 cm height and 3m long were lead on the prepared table surface, The sides of the sheet were raised and turned around the frame and stapled together at one edge of the frame, plant hole were done at the distance of 50 cm apart for tomato transplants. A plastic tank with capacity 80 L, was used, this was sufficient volume to prevent rapid changes in nutrient concentration.

The tanks were placed under the table under the gullies. Solution was circulated by submersible pump from catchments thank to flow pipe to introduced nutrient solution at the top of gullies and return back to the catchments thank by gravity. Nutrient solution analysis of 

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\begin{align*}
\text{N} &= 60 \text{ ppm;} \\
\text{P} &= 30 \text{ ppm dm}^{-3} ; \\
\text{K}^+ &= 280 \text{ ppm;} \\
\text{Ca}^{+2} &= 26 \text{ ppm;} \\
\text{Mg}^{+2} &= 11; \\
\text{Fe} &= 6 \text{ ppm;} \\
\text{Mo} &= 0.3 \text{ ppm;} \\
\text{Cu} &= 0.5 \text{ ppm;} \\
\text{Zn} &= 2 \text{ ppm}.
\end{align*}
\]

was used.

Electrical conductivity of the solution tank was adjusted 2-2.5 dS/m (EC), and PH was kept at 6-6.5. The schematic diagram of the hydroponic system is shown in Fig. 3. With proper ventilation inside the greenhouse, the tomato tissues started to grow gradually, passing through the growing of stems and leaves until reached the final stage of producing the tomato plant as shown in Figs. 4-6.
I. RESULTS AND DISCUSSIONS

Several experiments have been run to experimentally investigate the system performance. To make proper performance evaluation, suggested three cases are applied. The first one is to use evaporative cooling with normal water temperature and PCM shading. The second case is to use evaporative cooling with cooled water (using cooling water temperature outlet from a vapor compression system that has an evaporator immersed in the water tank) and PCM shading. The third case is to use evaporative cooling with cooled water without shading. The Relative Humidity (RH %) variation inside and outside the greenhouse in the first case is shown in Fig. 7.

The dry bulb temperature and wet bulb temperature variation inside and outside the greenhouse in the first case is shown in Fig. 8. It is clear that there is a considerable reduction in temperature inside the greenhouse from 5-7 °C. It is clear that due to using evaporative cooling system, the inside RH% has higher values than that of the outside case.

The PCM temperature variation throughout the first case experiment and the temperature distribution inside the greenhouse in different levels compared to the ambient temperature is shown in Fig. 9.
It is clear that the PCM temperature is increased gradually until it reached its maximum value around noon period and then started to decrease until the end of the day which is comply with the solar radiation variation throughout the day. Absorbing the thermal energy by the PCM material makes a reduction in the thermal load inside the greenhouse and consequently reduces its inside air temperature. The air temperatures inside the greenhouse are very close to each other which mean the ventilation system is properly designed.

Based on the experimental data, the hourly system efficiency is calculated and presented in Fig. 10. The Relative Humidity (RH %) variation inside and outside the greenhouse in the second case is shown in Fig. 11. It is clear that due to using evaporative cooling system with cooled water circulation, the inside RH% has higher values than that of the outside case. The dry bulb temperature and wet bulb temperature variation inside and outside the greenhouse in the second case is shown in Fig. 12. It is clear that there is a better reduction in temperature (than the first case) inside the greenhouse about 9 °C.
The PCM temperature variation throughout the second case experiment and the temperature distribution inside the greenhouse in different levels compared to the ambient temperature are shown in Fig. 13. It is clear that the PCM temperature is increased gradually until it reached its maximum value around noon period and then started to decrease until the end of the day which is comply with the solar radiation variation throughout the day. The air temperatures inside the greenhouse are very close to each other, which, mean the ventilation system is properly designed. The hourly system efficiency of the second case is calculated and presented in Fig. 14 The third case represents the utilization of evaporative cooling system with cooled water without shading. The Relative Humidity (RH %) variation inside and outside the greenhouse in the third case is shown in Fig. 15.

The dry bulb temperature and wet bulb temperature variation inside and outside the greenhouse in the third case is shown in Fig. 16. The temperature distribution inside the greenhouse in different levels throughout the third case experiment compared to the ambient temperature is shown in Fig. 17. The air temperatures inside the greenhouse are very close to each other which, mean the ventilation system is properly designed. The hourly system efficiency of the second case is calculated and presented in Fig. 18.

![Fig. 13 Temperature variation inside the greenhouse in the second case](image)

![Fig. 14 The efficiency of evaporative cooling in greenhouse for the second case](image)

![Fig. 15 Relative humidity variation inside and outside the greenhouse in the third case](image)

![Fig. 16 Dry bulb temperature and wet bulb temperature variation inside and outside the greenhouse in the third case](image)
The PCM temperature variation throughout the second case experiment and the temperature distribution inside the greenhouse in different levels compared to the ambient temperature are shown in Fig. 13. It is clear that the PCM temperature is increased gradually until it reached its maximum value around noon period and then started to decrease until the end of the day which is comply with the solar radiation variation throughout the day. The air temperatures inside the greenhouse are very close to each other, which, mean the ventilation system is properly designed. The hourly system efficiency of the second case is calculated and presented in Fig. 14. The third case represents the utilization of evaporative cooling system with cooled water without shading. The Relative Humidity (RH %) variation inside and outside the greenhouse in the third case is shown in Fig. 15.

The dry bulb temperature and wet bulb temperature variation inside and outside the greenhouse in the third case is shown in Fig. 16. The temperature distribution inside the greenhouse in different levels throughout the third case experiment compared to the ambient temperature is shown in Fig. 17. The air temperatures inside the greenhouse are very close to each other which, mean the ventilation system is properly designed. The hourly system efficiency of the second case is calculated and presented in Fig. 18.
The system performance is investigated by presenting a comparison between the temperature distributions inside the greenhouse for the studied three cases as illustrated in Fig. 19.

It is clear that using PCM and shading system contributes for a reduction in the thermal load inside the greenhouse and consequently reduces its inside air temperature as the PCM absorbed the thermal energy coming from the solar radiation. On the other hand, using evaporative cooling associated with a ventilation system contributes also for a further reduction of air temperature inside the greenhouse using pre-cooled water in the evaporative cooling system improved the cooling temperature environment inside the greenhouse solar greenhouse. It is obtained from Figs. 19 and 20 that the best performance of the environmental conditions inside the greenhouse is to use PCM with shading system associated with pre-cooled water in the evaporative cooling system.

V. CONCLUSIONS

The greenhouses are used to create the appropriate environmental conditions such as temperature, relative humidity, lighting level and the concentration of carbon dioxide to grow of many varieties of plants during any season of the year and to achieve the greatest possible return per unit area. The studied system consists of the greenhouse building and shading system, ventilation system, evaporative cooling system, hydroponic plantation system, and measuring devices.
Fig. 20 Comparison between the hourly efficiency of evaporative cooling in greenhouse for three studied cases

It is found that the best performance of the environmental conditions inside the greenhouse is to use PCM with shading system associated with pre-cooled water in the evaporative cooling system. The evaporative cooling efficiency increases by using cold water and using PCM shading. The temperature difference between ambient temperature and air temperature inside the greenhouse is 9°C when PCM with shading system associated with pre-cooled water in the evaporative cooling system and ranged from 3-5°C without using PCM and shading system, and using without using pre-cooled water in the evaporative cooling system.

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