Improvement of Evaporative Cooling System Efficiency in Greenhouses

Sirelkhatim K. Abbouda*, and Emad A. Almuhanna#

**Associate Professor, #Assistant Professor,*
Department of Agricultural Systems Engineering,
King Faisal University, Hofuf, Saudi Arabia.

Abstract - **An assisted evaporative cooling system is proposed and analyzed to get higher cooling efficiency in hot and arid environments such as Saudi Arabia. For this purpose, a two-stage evaporative cooling experimental setup consisting of a direct evaporative cooling and indirect evaporative cooling was designed, constructed, and tested.**

The obtained data showed that, the hourly average solar radiation flux incident outside and transmitted into the greenhouse was 555.7 and 298.7 W/m^2, respectively, consequently, the effective transmittance of the covering material was on the average 53.75%. The temperature and relative humidity of outdoor air, respectively, were 37.3ºC and 21.8%, dry and wet-bulb temperatures just leaving the cooling coil were 29.4ºC and 18.8ºC, respectively, and dry-bulb temperatures of air just leaving the direct evaporative cooling were 22.8ºC. The obtained results also revealed that, the overall effectiveness of the combining cooling system was more than 100%. Thus, this system environmentally clean and energy efficient system, which considered as an alternative to the mechanical, vapour compression systems. It can also conclude that, this combining cooling system can use in various climatic conditions as an environmentally clean and energy efficient system.

Keywords; *Cooling coil unit, direct evaporative cooling, and combining cooling system.*

1. Introduction

The weather of Saudi Arabia has a long summer season with high air temperature. Air-condition system has become more popular and even a necessity in life not only for human but also for animal and plants to create comfortable environment, and consumed a large amount of energy at the same time (Qun Chen *et al.*, 2010).

Evaporative cooling is one alternative to mechanical vapor compression for air conditioning applications. These systems usually require only a quarter of the electric power that mechanical vapor compression uses for air conditioning (Cerci, 2003). Therefore, such systems will help to reduce electricity requirements, and also contribute to reducing greenhouse gas emissions.

Conventional evaporative cooling system can decrease the process air temperature theoretically approaching its wet bulb temperature, and has been used as a low energy consuming device for various cooling and air conditioning applications in industrial, agricultural and residential sectors (Costelloea, and Finn, 2003), (Maheshwari *et al.*, 2001) for providing low temperature medium fluid (i.e. air, water, etc.).

Evaporative pad cooling is the most efficient method for greenhouses cooling under arid conditions (e.g., Saudi Arabia) (Al-Helal, 2001).

Controlling thermal environment in hot weather areas is very challenging. Removing excessive heat from the house requires using evaporative cooling pads, misting or fogging systems in conjunction with mechanical ventilation. In hot and dry climates such as the case in Saudi Arabia, evaporative cooling process is the most effective and economical technique of air conditioning (Alodan and Al-Faraj, 2005).

Still in order to improve the performance of the evaporative cooling units, extensive research has been conducted in analyzing the influences of such factors as moist air velocity, temperature and humidity (Muangnoi *et al.*, 2008), water velocity and temperature (Lemouari *et al.*2009), longitudinal heat conduction (Hettiarachchi *et al.*, 2007), heat and mass exchanging materials properties (Zhao *et al.*, 2008), and geometries (Sureshkumar *et al.*, 2008) on the efficiency of various traditional and novel evaporative coolers, including plate/tube type indirect evaporative cooler (Stoitchkov, and Dimitrov, 1998). Several active or passive evaporative cooling systems have been developed, including two-stage indirect/direct evaporative cooling (Jain, 2007) (Al-Juwayhel *et al.*, 2004). The general underlining principle in all these is to maximize the refrigerating effect in an evaporative cooling system.

Since, air temperature and humidity are the two major parameters affecting thermal comfort significantly, and only sensible load can be handled by an evaporative cooling system, conventional evaporative cooling system is suitable for dry and temperate climate where the humidity is low

(Costelloea, and Finn, 2003), (Heidarinejad *et al.*, 2009).

Two principle methods of evaporative cooling are commonly used, the direct evaporative cooling (DEC) and the indirect evaporative cooling (IEC). DEC is the oldest, simplest, and the most widespread form of evaporative air conditioning

Direct evaporative cooling system adds moisture to the cool air, which also makes conditions more uncomfortable for humans as (air) humidity increases. On the other hand, an indirect evaporative cooling system provides only sensible cooling to the process air without any moisture addition. Therefore, it is more attractive than direct evaporative system. However, the cooling effectiveness is generally low, around 40–60% (Maheshwari *et al.*, 2001).

This is a major drawback of conventional evaporative cooling. To overcome this drawback, the enhancement of cooling effectiveness to provide much lower outlet air temperature is an interesting option for hot and humid climate conditions.

The underlying principle of DEC is the conversion of sensible heat to latent heat. Through a direct evaporative cooling system, hot outside air passes a porous wetted medium. Heat is absorbed by the water as it evaporates from the porous wetting medium, so the air leaves the system at a lower temperature. In fact, this is an adiabatic saturation process in which dry bulb temperature of the air reduces as its humidity increase (constant enthalpy). Some of the sensible heat of the air is transferred to the water and become latent heat by evaporating some of the water. The latent heat follows the water vapor and diffuses into the air. The minimum temperature that can be obtained is the wet bulb temperature of the entering air (Camargo *et al.*, 2005), (Heidarinejad, and Bozorgmehr, 2007–2008).

Direct evaporative cooling (DEC) involves no change in the heat content of the air/water vapor mixture. Rather, as water evaporates it takes away heat from the air thus reducing its temperature. These systems are based on the conversion of sensible heat into latent heat of evaporated water, with the water supplied mechanically. During the process, the total heat (enthalpy) of the air remains the same. It is known that one gram of water evaporated into 1 m^3 of air space reduces its temperature by about 2.5 C. The method of lowering the air temperature by evaporation of water is thus the most effective way of controlling the temperature and humidity inside a greenhouse.

Indirect evaporative cooling (IEC) where air is cooled via a heat exchanger – the temperature of air, whose moisture content consequently remains unchanged - can be classified in two types based on heat and mass transfer occurring in the heat exchangers (Zhao et al., 2008).

In heating, ventilation, and air conditioning (HVAC) systems, cooling coils unit (CCU) perform an essential function by exchanging the cooling load from the hot air to the chilled water loop by pushing airflow through the coil. In addition, cooling coil unit has utilized as pre-cooler systems to decrease temperature of hot air. Totally, utilization of cooling coils affects performance of HVAC systems increasingly (Jin Guang-Yu et al., 2006 ; Heidarinejad et al., 2010).

In this method, two streams of air are used; namely alternative wet and dry passages, which are separated from each other. Primary air is cooled in dry passages which is separated from wet passages where secondary air and water flow. Evaporation occurs in wet passages and heat is removed from primary air through impermeable separating wall and evaporates water into the secondary air. Therefore, heat and mass transfer due to evaporation in wet passages and heat removal in dry passages are simultaneous and practically inseparable. The air leaving the dry side of the cooler has a lower wet bulb temperature than the ambient. Consequently, it would be advantageous to extract a fraction of this cooled air and pass it through the wet side of the heat exchanger instead of using ambient air.

Depending on the climatic conditions and the application, combining indirect and direct evaporative coolers might be appropriate to increase the cooling capacity (Mazzei, and Palombo, 1999).

A two-stage air-conditioner combining indirect and direct processes is gaining popularity in places where the higher wet bulb temperatures (i.e. higher ambient humidity) does not permit sufficiently low indoor temperatures supplied from a simple direct air-conditioner.

In this research work, the water in a storage tank 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 (pre-cooling). Then, the pre-cooled air with lower wet-bulb temperature passed through the direct evaporative cooling system. The performance and feasibility of such cooling system have analyzed in this paper.

2. Materials and Methods

Reducing air temperature is one of the main problems facing greenhouse management during daylight time even in winter season such as in Saudi

Arabia. Ventilation is basically used to exchange air between inside and outside of the greenhouse as a means of air temperature, relative humidity, and carbon dioxide control. The experimental work was carried out in five successive days (from 21-25 July 2010). In this research work, the system consists of three parts: (1) Greenhouse, (2) Cooling coil, and (3) Direct evaporative cooling. Each part has described in the following subsections.

(1) Greenhouse

An experimental gable-even-span greenhouse model has designed, constructed, and installed at the Agricultural and Veterinary Research Station of King Faisal University (latitude 25.4ºN, longitude 49.6ºE, and altitude 142 m above the sea level). The geometric characteristics of the gable-even-span model are as follows: eaves height 1.20 m, gable height 0.30 m, span angle 31º, width 1.0 m, length 2.0 m, floor surface area 2.0 m^2, and volume 2.1 m^3. (1). The greenhouse structural frame is formed from wooden plates (5×5 cm). The experimental greenhouse is covered with single polyethylene sheet (PE, UV) 200µm thick. It was orientated in East-West direction, where the southern longitudinal direction faced into the sun's rays. A 60% shading black net has used to cover the roof of the green house. One extracting fan (single direct driven, 30 cm diameter, and 900 m^3/h discharge) was located on the leeward side of the greenhouse and the cooling pads on the side toward the prevailing wind.

(2) Cooling coil unit (CCU)

Based on the conversion of sensible heat into latent heat by means of evaporation of water supplied directly into the cross-fluted cellulose cooling pads, the collected water in the sump was allows equal to the dew point temperature of the entering air. Thus, the cold water supplied through the cooling coil during the experimental period as revealed in Fig. (1). The cooling coil consists of heat exchanger and water supplied lines installed 20 cm before the direct evaporative cooling system. The heat exchanger is made of 116 finned aluminum tubes arranged in vertical four rows. The gross dimensions of cooling coil are: 73 cm high, 60 cm wide, and 10 cm thick. A sensible cooling process only existed when the outer surface temperature of the coil is equal to the dew point temperature of the outdoor air. A sensible cooling process can indicate by a horizontal line (from point 1 to point 2) towards the saturation curve on the psychrometric chart as shown in Fig. (2). In other words, the humidity ratio is always constant (Wang, 2001).

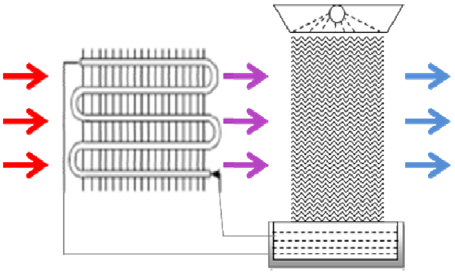

Figure (1): Schematic diagram of combining cooling system included cooling coil unit (CCU) and direct evaporative cooling system (DEC).

(3) Direct Evaporative Cooling System (DEC)

The direct evaporative cooling system (DEC) is based on the process of heat absorption during the evaporation of water supplied. It is mainly consisted of cooling pad and extracting fan. A cross-fluted cellulose pad has mounted in a vertical fashion on the side toward the prevailing wind 20 cm after the cooling coil unit (CCU). A cross-fluted cellulose pad having gross dimensions of 73 cm high, 60 cm wide, and 10 cm thick. A polyvinyl chloride pipe (12.5 cm diameter) has suspended directly above the cooling pad. Holes were drilled (1 mm diameter) in a line about 2 cm apart along the top side, and the end of this pipe was capped. A baffle has 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 coil and cooling pad by the water pump. In the direct evaporative cooling system, the transformation of heat and mass between air and water causes decrease in the air-dry-bulb temperature and increase in its humidity, while the enthalpy is basically constant in a perfect process. The minimum temperature that can attain is the wet-bulb temperature of the incoming air (point 3) as revealed in Fig. (2). Wet pad equips a water surface in which the air has humidified and the pad is wetted by dripping water.

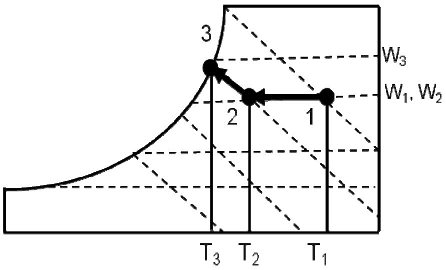

Figure (2): Schematic diagram of two-stage cooling process included cooling coil unit and direct evaporative cooling system.

The cooling effectiveness (η) of the cooling coil unit (CCU) and the direct evaporative cooling system (DEC) can compute by determining the mean degree of cooling ($T_{ao} - T_{ai}$) and the wt-bulb depression ($T_{ao} - T_{wb}$) using the following equation (ASHRAE, 2005):-

$$\eta = \frac{T_{ao} - T_{ai}}{T_{ao} - T_{wb}} \times 100 \qquad (1)$$

Where, T_{ao} and T_{ai}, respectively, are the outlet and inlet dry-bulb temperatures of the air stream, and, T_{wb}, is the outlet wet-bulb temperature of the air.

Measurements and Data Acquisition

Sensors were employed to measure temperature, solar radiation, air volumetric flowrate and relative humidity of outside air.

Five thermistors sensors were distributed in the system (1) before cooling pads (2) water tank, (3) between pads and heat exchanger, (4, 5) inside greenhouse at 20, 180 cm from cooling system. Sensors were connected to MM900 Logger - ELE International, Leighton Buzzard, Bedfordshire, LU7 4WG, UK. Ambient Air temperature and relative humidity outside greenhouse model were measured using 12-bit Temperature/RH Smart Sensor (S-THB-M002). The temperature and relative humidity sensors were placed in multi-plate radiation shields (Hobo-RS3 Solar Radiation Shield) to protect them from error-producing solar radiation and precipitation. These shields rely on a combination of plate geometry, material and natural ventilation to provide effective shielding. The solar radiation (W/m^2) was measured using Hobo Silicon Pyranometer, with a measurement range of 0 to 1280 W/m^2 over a spectral range of 300 to 1100 nm. Data were collected at each 30 s by a data logger (HOBO data logger- U30 - NRC) and averaged over a time of 1 hr. Testo 435-2, (Testo Inc. 40 White Lake Road Sparta, N.J. 07871 – USA) multi-function instrument equipped with hot wire anemometer probe was employed to measure the air velocity and temperature.

3. Results and Discussion

The optimization of air temperature in greenhouses is of particular importance in relation to plant growth, development, and productivity. In order to acachieve optimum microclimatic conditions, it is necessary to cool the greenhouses, particularly in hot and humid climates. Evaoprative cooling is anenvironmentally friendly and energy efficient method for cooling greenhouses in hot and dry regions. The effectiveness of combining cooling system (CCU and DEC) was investigated in particular for the hottest days during the summer (21-25 July 2010) in Saudi Arabia. The intensity of solar, air temperature, and air relative humidity inside the greenhouse model were compared with that data outside as an important measure of the effectiveness of the combining cooling system.

The data measured and recorded for a period of five days at Al-Ahssa, Saudi Arabia, used to evaluate the combining cooling system (CCU and DEC). Actual solar radiation recoded outside (R_o) and inside the greenhouse model (R_i) ranged from near zero to about 1000 W/m^2. The lowest values recoreded during the experimental period were in the range between 25 and 100 W/m^2, which occurred just after sunrise and prior to sunset due to the solar altitude angle and the sky cover. The actual solar radiation recoded inside the greenhouse model was lower than that outside, due to the reflectance, absorptance, and transmittance factors of the greenhouse covering material. The hourly averages solar radiation recorded outside and inside the greenhouse model were 555.7 and 298.7 W/m^2, consequently, the effective transmittance of the covering material was on the average 53.75% as revealed in Fig. (3). To determine the solar radiation flux incident on a horizontal surface inside the greenhouse model (R_i), all the data recorded **.** during the experimental period was plotted as a function of the solar radiation outside (R_o) as demnostrated in Fig. (5). Regression analysis revealed a highly significant linear relationship (r = 0.997 ; P = 0.001) between these parameters. The regression equation for the best fit was:

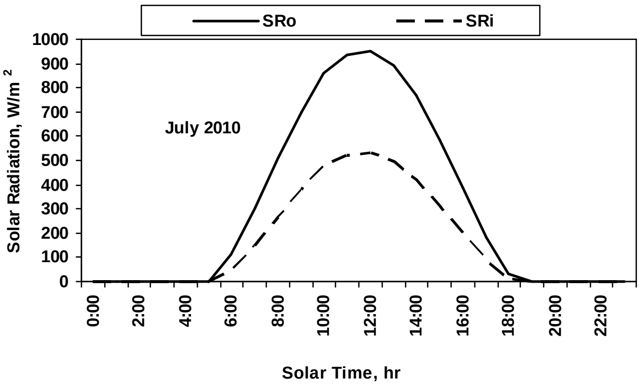

Figure (3): Solar radiation flux incident on a horizontal surface inside and outside the greenhouse model as a function of solar time

$$SR_i = 0.5478\,(SR_o) \qquad (2)$$

The regression analysis also indicated that, the solar radiation flux incident inside the greenhouse model could express as:

$$SR_i = \tau\ (SR_O) \qquad (3)$$

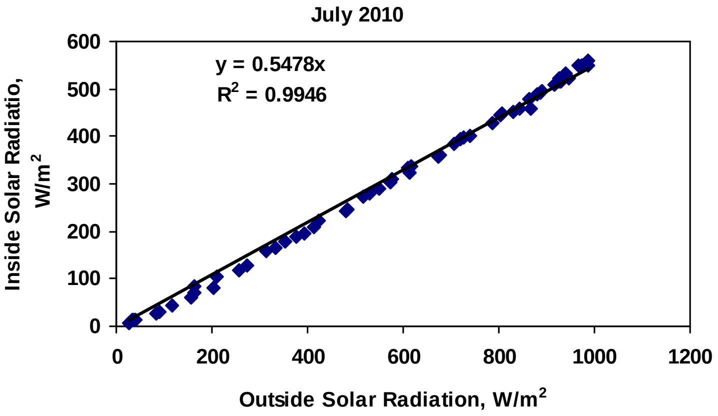

Figure (4): Solar radiation recorded inside the greenhouse model against solar radiation outside.

Regression equation is definitely the numerical expression of the above equation. The slope is almost equal to the effective transmittance of the polyethylene and the shading black net covers (**τ**).

Since, air temperature and relative humidity are the two major parameters affecting thermal comfort significantly, and only sensible load can be handled by an evaporative cooling system, conventional evaporative cooling system is suitable for dry and temperature climate where the relative humidity is low. The air temperature just leaving the cooling coil unit (CCU) varied between 23.1 and 36.0ºC, wheares the outside air temperature ranged from 25.9 to 47.8ºC. The hourly average air temperatures recoded outside and behind the cooling coil at and around noon (critical period) were 45.5 and 35.1ºC, respectively. Accordingly, the compiled data revealed that, the cooling coil unit was an effective method for cooling air as the air temperature after passed through the CCU was lowered 10.1ºC at that period. Based on a combining cooling system (CCU and DEC) the hourly average air temperature inside the greenhouse model was lowered 15.6ºC blow the outside air temperature. The air temperature difference between the outside and inside varied from hour to another and during the experimental period due to effectiveness of the combined cooling system. During the critical period at and around noon this difference reached to 20.1ºC as shown in Fig. (5). The air temperature just leaving the cooling coil unit ($T_{a,exch}$) was plotted against the air temperature outside the greenhouse model (T_{ao}) to examin their relationship under Al-Ahssa city condition (Fig. 6). Regression analysis revealed a highly significant linear relationship (r = 0.959 ; p = 0.001) between these parameters. The regrssion equation for the best fit was:

$$\mathbf{T_{a,exch.} = 2.7734 + 0.7136\,(T_{ao})} \qquad \mathbf{(4)}$$

For the duration of the experimental period the hourly average wet-bulb depression of the outside air was 17.1ºC. According to test results, using of cooling coil unit can be provided mean degree of cooling on the average of 8.1ºC, consequently, the effectiveness of the CCU system was 47.4%. The air just leaving the cooling coil unit was continuously passed through the direct evaporative cooling system in order to reduce the air temperature and at the same time increase the air relative humidity to achieve the desired level of microclimatic conditions for different plants. The hourly averages wet-bulb depression of the air just leaving the cooling coil unit (CCU) and the mean degree of cooling achieved by the direct evaporative cooling system (DEC), respectively, were 10.2ºC and 7.7ºC. Consequently, the hourly average effectiveness of the direct evaporative cooling system was 75.12%. A compiled information from many reasearchers (Nelson, 1996 ; Arbel et al., 1999 ; Kittas et al., 2003 ; Sethi and Sharma, 2007) reported that, the air temperature inside the greenhouse without cooling system are frequently between 11 – 20ºC higher those outside in spite of open ventilators.

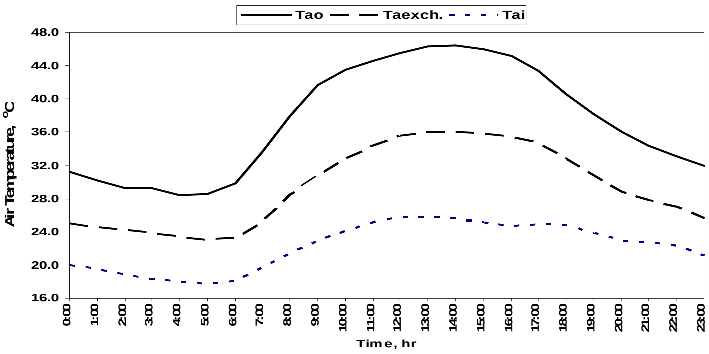

Figure (5): Cyclic changes in air temperatures outside, after passed through the cooling coil unit (CCU), and just leaving the direct evaporative cooling system (DEC).

The obtained results showed that, the hourly average effectiveness of the combining cooling system (CCU and DEC) during the daylight (13 hrs) was 102.8%, since it achieved mean degree of cooling (air temperature depression) of 21.9ºC at that time. Therefore, significant thermal comfort can be acieved during hot summer by combining cooling system with a great reduction of cooling load. The majorty of protected cropping can be grown well under microclimatic conditions of 25 – 28ºC air temperatures and 60 – 65% air relative humidity **(Nelson, 1996).** During the daylight time, the air temperature inside the greenhouse model not exeeded 25ºC and air relative humidity in the range between 60 – 70% by using the combining cooling system.

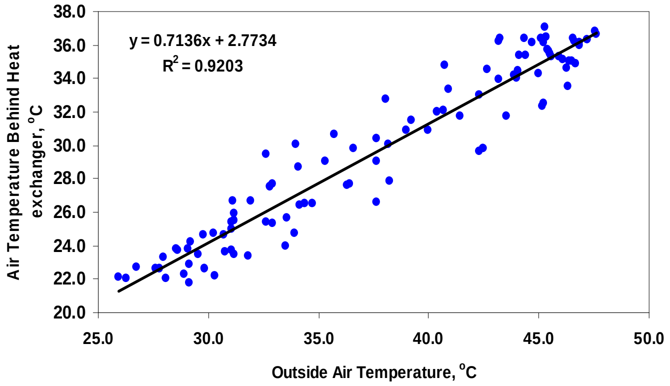

Figure (6): Air temperatures just leaving the cooling coil unit (CCU) versus air temperature outside the greenhouse model

4. Conclusion

From this study, the following conclusion can draw as:

(1) The hourly averages solar radiation recorded outside and inside the greenhouse model were 555.7 and 298.7 W/m^2, consequently, the effective transmittance of the covering material was on the average 53.75%.

(2) The hourly average air temperatures recoded outside and just leaving the cooling coil unit (CCU) during daylight time were 42.7 and 33.3°C, respectively, consequently the cooling coil unit was lowered the outside air temperature by 9.4°C. Wheares, this cooling system lowered the outside air temperaure at night time by 6.1°C.

(3) Based on a combining cooling system (CCU and DEC) the hourly average air temperature inside the greenhouse model was lowered by 19.1°C and 9.0°C blow the outside air temperatures during daylight and at night times, respectively.

(4) It was observed that, the cooling coil unit (CCU) can be provided mean degree of cooling on the average of 8.1°C, consequently, the effectiveness of the CCU system was 47.4%. While, the hourly average effectiveness of the direct evaporative cooling system (DEC) was 75.12%.

(5) This combining cooling system can be used in variuos climatic conditions as an environmentally clean and energy efficient system.

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