THERMAL PERFORMANCE FOR GREENHOUSE HEATING BY USING EARTH-TUBE HEAT EXCHANGER DURING WINTER SEASON

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ABSTRACT

In this research work an attempt has been made to analysis the thermal performance of the earth-tube heat exchanger (ETHE) during winter season of 2012-2013 (December to March). The experimental work was executed in the experimental farm of Faculty of Agriculture, Suez Canal University, Ismailia Governorate, Egypt (Latitude angle of 30.62ºN, Longitude angle of 32.27ºE, and mean altitude above sea level of 5 m). The ETHE technique was used to utilize the stability of deep soil temperature for worming the indoor air of greenhouse cucumber during winter season, and reducing the indoor air temperature during the summer season. A computer simulation model has been developed and used based on MATLAB program to determine the depth at which the soil temperature is stabilized. The obtained data showed that, the depth at which the soil temperature is stabilized was achieved at 3 m deep. The overall thermal efficiency of the ETHE system during winter season (heating process) was 72.90 %. Due to the microclimatic conditions (air temperature and air relative humidity) were at and around the desired level, the growth rate, flowering rate, fruit set rate, and fresh yield of cucumber crop were at high rates and good quality. Data of the computer simulation model of the indoor air and soil temperatures were found to be very closest to that measured.

Key words: Greenhouses – Earth-tube heat exchanger – Simulation model – Soil temperature.

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NOMENCLATURE

Symbol	Quantity	*Units*	Symbol	Quantity	*Units*
A_c	the surface area of the cover	m^2	Q_v	the ventilation rate of floor surface area	$m^3/s.m^2$
A_f	the floor surface area	m^2	Q_{ven}	thermal heat loss from greenhouse air due to ventilation	Wm^{-2}
AIWP	annual irrigation water productivity	*$L.E/m^3$*	R_i	solar radiation flux incident inside the greenhouse	Wm^{-2}
AIWS	annual irrigation water supply	*m^3*		temperature	K
A_p	the plant surface area	m^2	T_{ai}	inlet air temperature of earth-tube heat exchanger	K
A_s	soil surface area	m^2	T_{ao}	outlet air temperature of earth-tube heat exchanger	K
C_{pa}	specific heat of dry air	$Jkg^{-1}k^{-1}$	T_c	cover surface temperature	$Wm^{-2}k^{-1}$
C_{pex}	the specific heat of air leaving greenhouse	$Jkg^{-1}k^{-1}$	T_{ex}	the temperature of exhaust air leaving greenhouse	ºC
C_{ps}	Greenhouse soil specific heat	$Jkg^{-1}K^{-1}$	T_f	equilibrium temperature	K
D	thickness of the soil layer	m	T_i	air temperature inside the greenhouse	K
E	the evapotranspiration coefficient	-	T_{inlet}	the temperature of air entering greenhouse	ºC
ETHE	Earth to Air Heat Exchanger	-	T_o	the outside air temperature	ºC
ETHE	Earth Tube Heat Exchanger	-	T_p	the plant surface temperature	K
F_{p-c}	shape factor between the plant and cover surface	-	T_s	sandy soil temperature	K
F_{s-c}	shape factor between the soil and cover surface	-	T_{sk}	the sky temperature	K
F_{s-p}	shape factor between soil and plant surface	-	T_{sub}	soil bulk temperature	K
h_{fg}	latent heat of vaporization of water	$kJkg^{-1}$	T_w	water temperature	K
h_i	convective heat transfer coefficient of the inside greenhouse	$Wm^{-2}k^{-1}$	U	the overall heat transfer coefficient	$W/m^2ºC$
h_o	convective heat transfer coefficient of the outside greenhouse cover		V	wind speed	ms^{-1}
h_p	convective heat transfer coefficient of the plant	$Wm^{-2}k^{-1}$	V_{ex}	the specific volume of air leaving greenhouse	m^3/kg_{air}
h_s	convective heat transfer coefficient between the greenhouse soil and indoor air	$Wm^{-2}k^{-1}$	VP_{air}	air vapour pressure	kPa
I	the solar radiation of floor area	W/m^2	VPD	vapour pressure deficit	kPa
IWUE	Irrigation water use efficiency	*kg/m^3*	VP_{sat}	saturation vapour pressure	kPa
k	Soil Thermal Conductivity	$Wm^{-1}K^{-1}$	W_{ac}	humidity ratio of air at the given cover temperature	$kg\ kg^{-1}$
$\dot{m}$	mass flow rate of air	$kg\ s^{-1}$	W_{ai}	humidity ratio of the greenhouse air	$kg\ kg^{-1}$
P_{wvs}	saturated vapour pressure	kPa	W_{ap}	humidity ratio of air at the given plant surface temperature	$kg\ kg^{-1}$
$Q_{(C-s)}$	convective heat transfer from the soil surface	Wm^{-2}	W_{as}	humidity ratio of air at the given soil surface temperature	$kg\ kg^{-1}$
$Q_{(Sh-s)}$	solar radiation absorbed by soil surface	Wm^{-2}	α	thermal diffusivity of soil	$m^2\ s^{-1}$
$Q_{C(c-i)}$	convective heat energy at inside cover surface	Wm^{-2}	α_p	leaf surface absorption	-
$Q_{C(c-o)}$	convective heat at outside cover surface	Wm^{-2}	α_s	soil surface absorption	-
Q_{cond}	conductive heat transfer from the soil	Wm^{-2}	γ	ventilation rate	m^3s^{-1}
Q_{conden}	heat flow due to condensation on the cover	Wm^{-2}	ε_c	greenhouse cover emissivity	-
Q_{earth}	heating potential obtained from the earth-tube heat exchanger	Wm^{-2}	ε_p	emissivity factor of the plant	-
Q_{evap}	latent heat from the soil to the inside air due to evaporation	Wm^{-2}	ε_s	soil surface emissivity	-
Q_{exc}	heat exchanging rate,	Watt	ζ_p	water covering ratio of the leaf surface	-
Q_G	solar heat gain	Wm^{-2}	ζ_s	water covering ratio of the soil surface	-
Q_{loss}	heat loss from the greenhouse element	Wm^{-2}	η	effectiveness of earth tube heat exchanger	%
$Q_{r(c-sk)}$	longwave radiant heat emitted from the cover to the ambient air	Wm^{-2}	ρ_a	density of the air	kgm^{-3}
$Q_{r(p-c)}$	radiant heat exchange between the plant and the cover	Wm^{-2}	ρ_s	The density of the sand soil	$kg\ m^{-3}$
$Q_{r(s-c)}$	radiant heat exchange between the soil and the cover	Wm^{-2}	σ	Stefan-Boltzmann constant	$Wm^{-2}K^{-4}$
$Q_{r(s-p)}$	radiant heat exchange between the soil and the plant	Wm^{-2}	τ_c	The effective transmissivity of the cover	
Q_{sub}	heat supplied to the greenhouse element	Wm^{-2}			

1.NTRODUCTION

Greenhouses are widely used to increase the productivity of the unit area and achieve optimal control over the environment inside the greenhouses where a suitable microclimate is provided and maintained **(Sethi and Sharma, 2007)**. Agricultural greenhouses have been proven a viable solution to world-wide increased demand for expanding production, facilitating out of season cultivation, protecting crops from unfavorable outdoor conditions, and allowing the growth of certain varieties in areas where it was not possible earlier **(Santamouris *et al.,* 1995)**. Heating of greenhouse is one of the most energy consuming activities during winter periods. Lack of heating has adverse effects on the yield, cultivation time, quality and quantity of the products in the greenhouse **(Shukla *et al.,* 2006)**. The use of low-cost and alternative heating system is therefore of primary importance for a greenhouse to provide optimum indoor conditions during winter months. Greenhouse heating can be obtained by active or passive methods of heating. For active heating in comparison to ground collector, warm water, warm air and an earth–air heat exchanger (EAHE). The passive heating technique in which heat is given to the greenhouses from the earth has become popular nowadays **(Ghosal *et al.,* 2005).** However, heating systems increase the capital and operational costs by 30 % and may be too expensive to use for most applications **(Tiwari, 2003)**. Due to high relative cost of energy, only a small number of greenhouse owners can afford to use auxiliary heating systems. It is well known that the temperature of the ground at a depth of about 2.5-3 m remains fairly constant and low around the year. The idea to dissipate the excess heat from a building to a natural sink like the ground is known from the ancient time. The most common technique to couple buildings and other structures with the ground is the use of underground air tunnels, known as earth-tube heat exchangers (ETHE) **(Mihalakakou, 1997)**. The ETHE are considered as an effective passive heating medium for buildings. It uses underground soil as a heat source and air as the heat transfer medium for space heating in winter. Earth to air heat exchangers consist of pipes which are buried in the soil while an air circulation system forces the air through the pipes and eventually mixes it with the indoor air of the building or the agricultural greenhouse. As a result, the air temperature at the outlet of the earth–air–pipes is much higher than that of the ambient. The outlet air from the earth–air–pipes can be directly used for space heating if its temperature is high enough **(Ascione *et al.,* 2011).** Heating of greenhouse using an earth–air heat exchanger has been studied by many others **(Pfafferott, 2003; Chen *et al.,* 2006)**. The main advantages of EAHE system are its simplicity, high cooling and pre-heating potential, low operational and maintenance costs. Plastic or aluminum buried pipes were used by **Santamouris *et al.* (1996)**. Greenhouses coupled with buried pipes have an average annual energy consumption for heating that is 30-60 % less than for a conventional greenhouse; the indoor temperatures are 3-10°C higher than the minimum outdoor temperature. **Kassem (1999)** studied the potential of using the deep soil as a renewable source of heating and cooling ambient air for protected agriculture. He found that the thermal performance of earth-tube heat exchanger was found to be directly proportional to temperature difference between the outlet and inlet airflow and inversely proportional to the temperature difference between tube surface and the inlet airflow. **Ghosal and Tiwari (2006)** developed a new thermal model for greenhouse heating with EAHE in New Delhi, India. The earth air heat exchanger, consisting of PVC pipes of 39 m length and 0.06m diameter. They found that, the greenhouse air temperature higher by 7-8^{o}C in the winter than those of the same greenhouse without EAHE. Also, the greenhouse air temperature increased in the winter with increasing pipe length, decreasing pipe diameter and decreasing mass flow rate of flowing air inside buried pipe. **Shukla *et al.* (2006)** studied a thermal model for heating of greenhouse by using different combinations of inner thermal curtain, an earth–air heat exchanger and geothermal heating. They found that an earth–air heat exchanger provided an alternative source for heating of greenhouse when geothermal energy is not available. **Tiwari *et al.* (2006)** studied the annual thermal performance of greenhouse with an earth- air heat exchanger. They found that the temperature of the greenhouse increased by 4^{o}C in winter, due to use of an EAHE. **Chel and Tiwari (2009)** developed a thermal model for a building integrated with earth to air heat exchanger (EAHE). They conducted a performance evaluation and life cycle cost analysis of EAHE. Experimental results showed that the room air temperature during winter was found to be 5-15^{o}C higher compared with ambient air temperature. A transient and implicit model based on computational fluid dynamics was developed by **Bansal *et al.* (2009)** to predict the thermal performance and heating capacity of earth–air–pipe heat exchanger systems. Effects of the operating parameters (i.e. the pipe material, air velocity) on the thermal performance of earth-air-pipe heat exchanger systems were studied. The 23.4 m long EAHE system discussed in this paper gave heating in the range of 4.1 - 4.8°C for the flow velocities of 2-5 m/s. Investigations on steel and PVC pipes have shown that performance of the EAHE system was not significantly affected by the material of the buried pipe. **Nayak and Tiwari (2010)** carried out a theoretical performance assessment of an integrated photovoltaic and earth–air heat exchanger greenhouse. The results indicated that the air temperature inside the greenhouse can be increased by around 7- 8°C during winter season when the system coupled with EAHE at night. **Ozgener and Ozgener (2010)** studied the heating performance of underground air tunnel UAT. A galvanized pipe of 56 cm in diameter 47 m in length was buried in the soil at about 3 m in depth, a galvanized pipe of 80 cm in diameter 15 m in length was connected to greenhouse. The experimental results indicate that this system can be used for greenhouse heating in the Mediterranean and Aegean regions of Turkey. The objective of this study is use earth-to-air heat exchanger as a method to overcome the reduction in the greenhouse air temperature within the cold nights of winter season.

2. Experimental Set-up

The experimental work was carried out in the experimental farm of Faculty of Agriculture, Suez Canal University, Ismailia Governorate, Egypt (Latitude angle of 30.62ºN, Longitude angle of 32.27ºE, and mean altitude above sea level of 5 m). It was executed during winter season of 2012-2013 (3rd of December to 30th of March) in order to investigate the possibility of using earth-to-air heat exchanger system for greenhouse heating. Two similar gable-even-span form greenhouses were designed, constructed, and operated during this research work. The first greenhouse with ETHE, the second greenhouse was considered as a control trial without any auxiliary heating systems The geometric characteristics of the gable-even-span greenhouse are as follows: eaves height 2.933 m, gable height 0.933 m, rafter angle 25º, total width 4.0 m, total length 6.0 m, floor surface area 24 m^2, and volume 60.00 m^3 as shown in **Figure (1)**. The greenhouse structural frame is formed of 25.4 mm hot dipped galvanized pipes (1 inch) with excellent anti-corrosion. The rafter length of the greenhouse gable is 2.207 m and gable height is 0.933 m, whilst the height of each vertical side wall is 2 m. The rafters were tilted at 25º to minimize the side effects of wind load on the roof of the greenhouse. At the same time it may be maximize the solar radiation flux incident on the inclined roof of the greenhouse. The two identical greenhouses (G1 and G2) were covered using double layer of UV polyethylene sheets of 150 μm thick in order to reduce the heat energy loss from the greenhouse particularly at nighttime. The two greenhouses were orientated in East-West direction, where the southern longitudinal direction faced into the sun's rays. The earth-tube heat exchanger was made from PVC pipes buried under the ground at 3 m in sandy soil. The gross dimensions of the earth-tube heat exchanger were 26 m long and 0.144 m inner diameter **(Figure 2)**. A portable blower of 335 W and flow rate of 1200 $m^3 h^{-1}$ has been fitted at the suction end of the pipe positioned in the center south side of the greenhouse. The mechanical analysis of the greenhouse soil was conducted according to the international pipette method **(Arnold *et al.*, 1986)** to determine the soil structures as presented in **Table (1)**. Experimental greenhouse trails plants were irrigated using drip irrigation system. The fertilizer was directly added to the soil and vegetative fertilization was also used to obtain a higher growth and production.

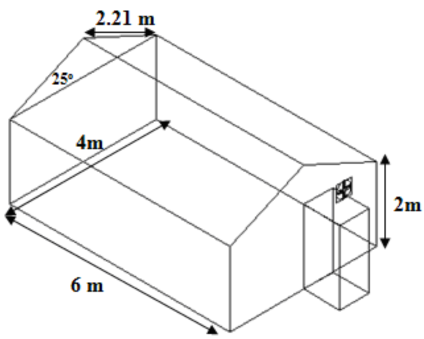


Figure (1): Schematic diagram of gable even-span greenhouse

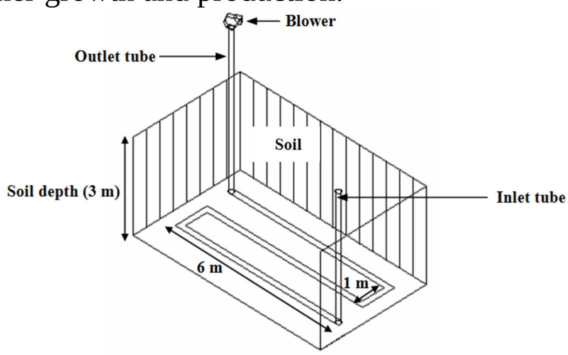


Figure (2): Diagram of the earth-tube heat exchanger

Table (1): Structure of the experimental soil

Soil structure %				Texture grade
Coarse sand	Fine sand	Silt	Clay	
68.93	26.04	3.81	1.22	Sandy

For the rest of this research, the greenhouse equipped with the earth-tube heat exchanger system and the control greenhouse are referred to as G1 and G2, respectively.

3. Methodology and instrumentations

Meteorological station (Vantage Pro 2, Davis, USA) located above the roof of the Agricultural Engineering Department, was used to measure different macroclimate variables such as, the solar radiation flux incident on a horizontal surface, dry-bulb, wet-bulb, and dew-point air temperatures (ventilated thermistor), wind speed and its direction, air relative humidity and rainfall amounts. For the duration of the whole year of 2011, the temperature distribution in the earth at different depths of 0.0, 1.0, 2.0 and 3.0 m was measured and recorded to assess the specific depth of earth at which the relative temperature remains sufficiently high and low for effective heating and cooling modes performance, respectively. Eight thermocouples were vertically located in the earth at different depths starting at 0.0 m deep and continuing at 1.0 m intervals to a depth of 3.0 m (two thermocouples were used to measure each point). The two greenhouses soil temperatures were measured at four different depths of 0.0, 10.0, 20.0, and 30.0 cm using four thermocouples in each greenhouse. These depths represent the most root zone of cucumber crop (20-30 cm) as mentioned by **Hassan (2001)**. The inlet ambient air temperature was measured using two thermocouples. The outlet air temperature of the earth-tube heat exchanger was also measure using two thermocouples. Data included the measured indoor dry-bulb and wet-bulb temperatures were functioned to determine the indoor air relative humidity of the two greenhouses using a specific software computer program **(Sonntage and Borgnakke, 1988)**. These sensors were connected to a data-logger system (Lab-Jack logger, powered by USB cable, supply 4-5.25 volt, USA) to display, and record the data during the experimental period. Mono Crestline solar cell (75 mm x 75 mm, 0.5 volt, current of 800 mA, kemo, 139, Germany) was used to measure the global solar radiation. Formula was functioned to determine the solar radiation flux incident according to **Mujahid and Lamoud (1988)**. The Mono Crestline solar cell was calibrated with a Kipp pyranometer (Kipp and Zohne, Australia) under clear sky conditions. The short circuit reading obtained from the solar cell was measured using a digital multimeter (M3800, China) according to **Duffie and Beckman (1991)**. The solar cell and the Kipp pyranometer were placed in the same horizontal plane. One hundred readings were taken and recorded inside and outside the greenhouse. The effective transmissivity (τ_c) of the double layer of UV polyethylene sheet was determined using the following equation:

$$\tau_C = \frac{\textit{Solar radiation inside the greenhouse}}{\textit{Solar radiation outside the greenhouse}} \; x \; 100$$

The effective transmissivity of the double layer polyethylene sheet was 82 %. The thermal conductivity of the sandy soil was determined using the method of **Lewis (1990)**. From this method the average thermal conductivity of the sandy soil was found to be 0.97 W $m^{-1} K^{-1}$.

The specific heat (C_{ps}) of the sandy soil was determined in J kg^{-1} K^{-1} using locally made calorimeter device according to the following equation (**Klute, 1986)**. This method was applied on three different samples of sandy soil. The average specific heat was found to be 924 J kg^{-1} K^{-1}. The density of the sand soil (ρ_s) was deduced and determined using the method of paraffin wax **(Black, 1965)**. It was found to be 1442 kg m^{-3}. The thermal conductivity (k), density (ρ_s), and the specific heat of sandy soil were functioned to deduce the thermal diffusivity (α) using the following equation **(Incropera and Dewitt, 1996)**:

$$\alpha = \frac{k}{\rho_s \; C_{ps}}$$

The thermal diffusivity of the sandy soil which utilized in this research work was found to be 7.28 x 10^{-7} m^2 s^{-1}.

3.1 Effectiveness of earth-tube heat exchanger (ETHE)

The effectiveness of the earth-tube heat exchanger (η) was computed using the following two equations **(Al-Ajmi *et al*., 2006)**:

$$\eta = \frac{T_{ai} - T_{ao}}{T_{ai} - T_s} \, x100$$

The potential heating acquired from the earth-tube heat exchanger (Q_{exc}) can be calculated using the following equation **(Li *et al*., 2014)**:

$$Q_{exc} = \dot{m} \; C_{pa} \; (T_{ao} - T_{ai})$$

3.2 Experimental procedure and data analysis for cucumber crop

The effect of microclimatic conditions of the greenhouses on cucumber crop growth stages (vegetative growth, flowering, fruit set rate, and fresh yield) were estimated. The stem length of cucumber plants was measured every week from the transplanting date inside the two greenhouses. Flowering measurement was taken every day after four weeks of transplanting date. Fresh yield of cucumber crop were measured in kilogram twice every week during the harvesting period. Finally, the total fresh yield per square meter for each greenhouse during summer and winter crops were determined. Dry weight characteristic is a good indicator for growth of greenhouse protected cropping. Dry weight was also functioned to determine the total water consumption throughout the growing period of the greenhouse crops. **Aldrich and Bartok (1990)** reported that, each 28 grams of dry weight of greenhouse crop consume 7.5 litres of water during the complete growth. From the previous information, the amount of irrigation water in cubic meter (annual irrigation water supply, AIWS) during the growing period can be computed.

The annual irrigation water productivity (AIWP) is defined as the total value of crop production in L.E to the annual irrigation water supply in cubic meter. It can be computed as follows:

$$AIWP = \frac{Total\ value\ of\ crop\ production\ (L.E.)}{AIWS\ (m^3)}\ \text{L.E. m}^{-3}$$

The Irrigation water use efficiency (IWUE) is defined as the ratio of the marketable crop yield in kg to the annual irrigation water supply in cubic meter. It can be determined as follows:

$$\text{IWUE} = \frac{Marketable\ crop\ yield\ (kg)}{AIWS\ (m^3)}\ \text{kg m}^{-3}$$

3.3 Vapour pressure deficit (VPD)

Vapour pressure deficit (VPD) is the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated. VPD can be used to evaluate the disease threat, condensation potential, and irrigation needs of a greenhouse crop. The differences between the saturation vapour pressure and the actual air vapour pressure ($VP_{sat} - Vp_{air}$) is the mathematical definition of vapour pressure deficit (VPD). Higher vapour pressure deficit means that the air has a higher capacity of hold water, stimulating water vapour transfer (transpiration) into the air in this low humidity condition. Lower vapour pressure deficit, on the other hand, means the air is at or near saturation, so the air can not accept moisture from a leaf in this high humidity conditions **(Pringer and Ling, 2004)**.

4. Mathematical simulation model

4.1 Greenhouse energy balance

Environmental control of the greenhouse may be included the control of solar radiation, heat losses and gain, energy conservation, and humidity control. A greenhouse cover with high transmissivity for solar energy can produce temperatures that are higher than desired in the crop zone. Most surfaces within a greenhouse have high absorptivity for solar energy. **Figure (3)** shows energy exchange for a greenhouse during daylight when the sun's rays strike the surface at a right angle to the surface. Emissivity is the ratio of the total radiation emitted by a body to the total radiation emitted by a black body for the same time period **(Nelson, 2006)**.

Traditional cooling alternatives for greenhouses depend upon exhaust fans to remove excess heat energy. As outside air is brought into and then through the greenhouse, its energy level rises due to sensible heat gain from the canopy, ground and surrounding structure. The volume of air required to maintain a given temperature rise (T_{ex} - T_{inlet}), may be estimated using the following approximate energy balance **(ANSI/ASAE, 2003):**

$$(1 - E)\tau_c I A_f = U A_c (T_i - T_o) + \frac{Q_v A_f C_{pex}}{V_{ex}}(T_{ex} - T_{inlet})$$

A mathematical model of the greenhouse consisting of a set of algebraic equations was proposed. The equations were written for the five components of the greenhouse (cover, plant, earth-tube heat exchanger, indoor air and bare soil surface). The values of dimensions and material properties of the greenhouse have been substituted in these equations. The equations were solved using a computer program written in MATLAB **(MATrix LABortary, USA)** to predict the indoor air temperature, plant temperature, cover temperature and soil surface temperature. The output data of the computer model (predicted) were then compared with the experimental data (measured). Flow chart for solution of equations for the greenhouse model is given in **Figure (4)**.

Energy balance equations for various components of the greenhouse combined with the earth-tube heat exchanger can be written based on the following assumptions:

- Analysis based on quasi-steady state condition.

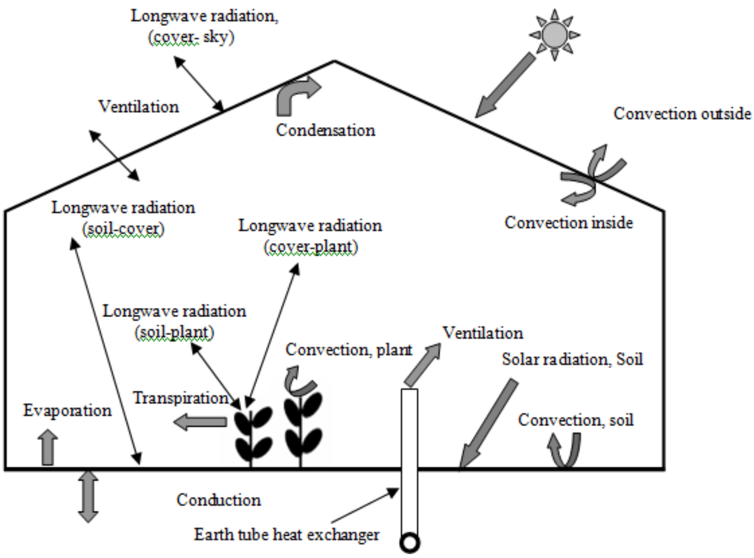


Figure (3): Schematic diagram of the heat energy balance occurring on the greenhouse

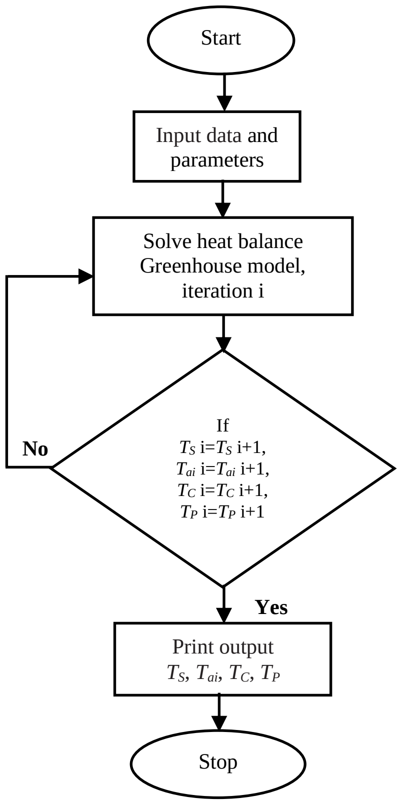


Figure (4): Flow chart of the greenhouse mode

- Temperatures of shading cloth and greenhouse cover are all the same.
- Heat conduction through the bottom layer of the ground is one-dimensional.
- Flow of air is uniform along the length of the buried pipes.
- The pipes are uniform circular cross-section.
- The soil surrounding the pipe is homogenous and has constant thermal conductivity.

4.2 Energy balance on greenhouse cover

Greenhouse cover is exposed to solar radiation and exchange thermal radiation with the plants, soil, and sky. Convective heat transfer takes place from the cover to the outside depending on wind speed. Condensation could also be detected on the cover depending upon the saturated humidity ratios at both the cover surface and inside air. An energy balance equation can be written for the greenhouse cover as follows **(Ibrahim, 1999)**:

$$Q_{C(c-o)} + Q_{C(c-i)} + Q_{r(s-c)} + Q_{r(c-sk)} + Q_{r(p-c)} + Q_{Conden} = 0$$

The convection heat transfer from the outside cover surface was determined as follows **(Norton, 1992)**:

$$Q_{C(c-o)} = h_o\,(T_c - T_o)$$

The rate of heat transfer by the greenhouse covering sheet convection is highly dependent on wind speed. The relationship between the wind speed and the convection heat transfer coefficient (h_{out}) is given by **Mc Adams (1954)** as:

$$h_o = 1.98\,(V^{0.8})$$

The convective heat loss from the inside cover surface to ambient air was computed by the following equation **(Hollman, 2010)**:

$$Q_{C(c-i)} = h_i\,(T_c - T_i) \quad , \quad h_{ins} = 4.36\,\,(T_i - T_c)^{0.25}$$

The thermal radiant heat exchange between the cover and the soil was determined using the following equation **(El-Sheikh, 2001)**:

$$Q_{r(s-c)} = F_{s-c}\,\sigma\,\frac{A_s}{A_c}\,(T_s^4 - T_c^4) \qquad , \qquad F_{s-c} = \frac{1}{\frac{1}{\varepsilon_s} + \frac{A_s}{A_c}(\frac{1}{\varepsilon_c} - 1)}$$

The longwave radiant heat emitted from the cover to the ambient air can be estimated as follows **(Taha, 2003)**:

$$Q_{r(c-sk)} = \varepsilon_c\,\sigma\,(T_c^4 - T_{sk}^4)$$

The sky temperature can be calculated from the following equation **(Pieters *et al.*, 1994)**: $T_{sk} = 0.0552\,(T_{ao})^{1.5}$

The thermal radiant heat exchange between the plant and the cover was determined using the following equation **(El-Sheikh, 2001)**:

$$Q_{r(p-c)} = F_{p-c}\,\sigma \frac{A_p}{A_c}(T_p^4 - T_c^4)\;, \qquad F_{p-c} = \frac{1}{\frac{1}{\varepsilon_p} + \frac{A_p}{A_c}(\frac{1}{\varepsilon_c} - 1)}$$

Condensation may occur if the humidity ratio of the greenhouse air is greater than that of the saturated air at the temperature of the cover. The heat flow due to condensation on the cover can is expressed as follows **(Garzoli, 1985)**:

$$Q_{conden} = \frac{h_{ins}}{C_{pa}}\,h_{\text{fg}}\,(W_{ai} - W_{ac})$$

Humidity ratio was determined using the following equations **(Lewis, 1990)**:

$$W_{ai} = \frac{18P_{wv}}{29\,(P_a - P_{wv})}\;, \qquad W_{ac} = \frac{18P_{wvs}}{29\,(P_a - P_{wvs})}\;, \qquad P_{wv} = 0.61078\exp\left(\frac{17.2693882\,T}{T + 237.3}\right)$$

4.3 Energy balance of greenhouse soil

An energy balance equation for the bare soil surface can be written as follows:

$$Q_{(Sh-s)} + Q_{(C-s)} + Q_{r(c-s)} + Q_{r(s-p)} + Q_{cond} + Q_{evap} = 0$$

The solar radiation absorbed by the soil surface can be determined as follows:

$$Q_{(Sh-s)} = (1 - E)\alpha_s R_i$$

The convective heat transfer from the soil surface can be computed as follows:

$$Q_{(C-s)} = h_s\,(T_s - T_i)\;, \qquad h_s = 2.5\,(T_s - T_i)^{0.25}$$

The thermal radiant heat exchange between the soil and the plant was determined using the following equation:

$$Q_{r(s-p)} = F_{s-p}\,\frac{A_s}{A_p}(T_s^4 - T_p^4)\;, \qquad F_{s-p} = \frac{1}{\frac{1}{\varepsilon_s} + \frac{A_s}{A_p}(\frac{1}{\varepsilon_p} - 1)}$$

The conductive heat transfer from the soil can be expressed as follows:

$$Q_{cond} = k\,(T_s - T_{sub})\,/\,d$$

The latent heat from the soil to the inside air due to evaporation is given by the following equation:

$$Q_{evap} = \frac{h_s}{C_{pa}} h_{fg} \zeta_s (W_{ai} - W_{as})$$

4.4 Energy balance of plant

An energy balance equation can be written for the plant as follows:

$$Q_{abs} + Q_{(C-p)} + Q_{r(c-p)} + Q_{r(s-p)} + Q_{Trans} = 0$$

The solar radiation at the plant can be determined as follows:

$$Q_{abs} = \alpha_p R_i$$

The convective heat transfer from the plant surface can be computed as follows:-

$$Q_{C-p} = h_p (T_p - T_i) \quad , \quad h_p = 2.5 (T_p - T_i)^{0.25}$$

The latent heat from the plant to the inside air due to transpiration is given by the following equation:-

$$Q_{Trans} = \frac{h_p}{C_{pa}} h_{fg} \zeta_p (W_{ai} - W_{ap})$$

4.5 Energy balance of indoor air

An energy balance equation can be written for the indoor air of greenhouse as follows:

$$Q_G + Q_{(C-c)} + Q_{(C-s)} + Q_{(C-p)} + Q_{ven} + Q_{earth} = 0$$

The solar gain can be estimated by the following equation:-

$$Q_G = A_f R_i$$

The heat flow from inside to outside due to ventilation through ventilations openings can be calculated by using the following formula:

$$Q_{ven} = \rho_a \gamma c_{pa} (T_i - T_o)$$

The heating potential obtained from the earth-tube heat exchanger was calculated as the following expression: **(Ghosal and Tiwari, 2006; Al-Ajmi *et al*., 2006; Li. *et al*., 2014)**

$$Q_{supply} = \dot{m} C_{pa} (T_i - T_{ao})$$

5. RESULTS AND DISCUSSIONS

5.1 Deep Soil as an Energy Source

For the duration of the whole year the temperature gradients in the earth at different depths of 1.0, 2.0 and 3 m and the maximum and the minimum ambient air temperatures were examined, measured and recorded to assess the specific depth of earth at which the relative temperature remains sufficiently high or low for effective cooling or heating modes performance, respectively. The obtained data for winter season is summarized and listed in **Table (2)**. From table, the 3 m peripheral deep soil temperature on average remained constant at 21.7^{o}C during the four months period of winter season. This deep soil temperature on January was 21.2^{o}C and on March it was 22.1^{o}C. This was a change of 0.9^{o}C for that period; sequentially there were some little variation in the earth temperature for the 3 m deep soil throughout the winter months. Also, the monthly average daily thermal potential difference between the 3 m deep soil temperature and average minimum temperature was 11.5^{o}C.

Table (2): Monthly average daily maximum and minimum ambient air temperatures and peripheral deep soil temperature at different depths for the winter months of 2012-2013

Month	Ambient air temperature, ^{o}C			Deep soil temperature at different depths, m		
	Maximum	Minimum	Mean	1	2	3
December	23.6	11.6	16.4	19.2	21.4	21.9
January	23.0	8.0	14.2	17.0	19.8	21.2
February	26.1	10.1	17.3	18.5	20.9	21.6
March	27.2	11.3	18.4	21.1	21.7	22.1
Mean	**25.0**	**10.2**	**16.6**	**19.0**	**20.8**	**21.7**

5.2. Effectiveness and heat exchange

The monthly average daily inlet airflow temperature, outlet airflow temperature, peripheral deep soil temperature at 3 m deep, thermal efficiency and heat exchange rate of the earth-tube heat exchanger are summarized and listed in **Table (3)**. It obviously indicates that, the thermal efficiency and heat exchange rate of earth-tube heat exchanger system was continuously variable during the whole period of heating mode depending upon the temperature difference between outlet and inlet earth-tube airflow and temperature difference between peripheral deep soil temperature and inlet earth-tube airflow. It reveals that, the monthly average daily overall thermal efficiency for December, January, February, and March months, respectively, were 71.9 %, 77.0 %, 72.4 %, and 70.2 % that gave an average overall thermal efficiency of 72.9 %. It evidently shows that, the greatest value of heat energy exchange rate (3.341 kWh) occurred on January month when the monthly average daily inlet airflow temperature was quite low (10.3ºC). Whereas, the lowest magnitude of heat energy exchange rate (2.307 kWh) was achieved on March month with an inlet airflow temperature of 13.8ºC. It also reveals that, the seasonal average daily heat energy exchange rate throughout the heating mode was 2.734 kWh.

Table (3): Monthly average daily inlet airflow temperature (T_{ai}), outlet airflow (T_{ao}), soil temperature at 3 m deep (T_s), overall thermal efficiency (η_h) and heat exchange rate (Q_{exc}) throughout the winter season of 2012-2013

Month	T_{ai} , ºC	T_{ao} , ºC	T_s , ºC	η_h, %	Q_{exc} , kWh/day
December	12.6	19.3	21.9	71.9	2.665
January	10.3	18.7	21.2	77.0	3.341
February	12.5	19.1	21.6	72.4	2.625
March	13.8	19.6	22.1	70.2	2.307
Mean	**12.3**	**19.2**	**21.7**	**72.9**	**2.734**

The relationship between seasonal average hourly thermal efficiency of the earth-tube heat exchanger and time of the day is illustrated in **Figure (5).** Also, the seasonal average hourly thermal energy exchange of the earth-tube heat exchanger which related to the inlet and outlet airflow temperature is illustrated together in **Figure (6)**. This figure shows that an inverse relationship between the energy exchange rate and the inlet air flow temperature.

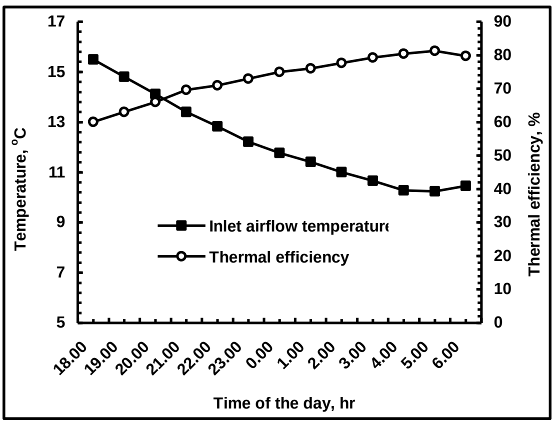


Figure (5): Hourly average thermal efficiency of earth-tube heat exchanger related to the inlet airflow temperature for winter season of 2012-2013

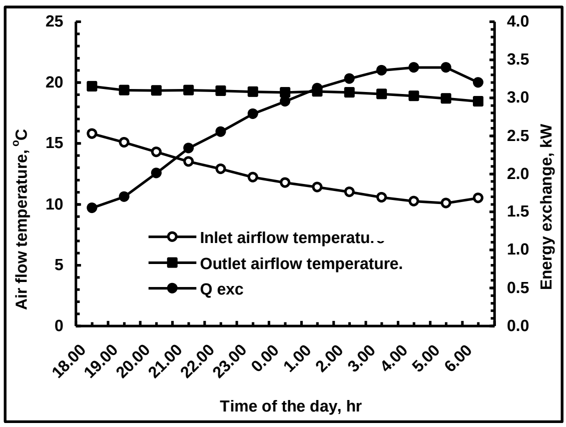


Figure (6): Seasonal average heat energy exchange rate related to the inlet and outlet airflow temperatures during winter season of 20122013

5.3. Effect of earth-tube heat exchanger system on microclimatic conditions of cucumber growth, development and productivity

The seasonal average hourly exterior and interior air temperature for the two greenhouses (G1 and G2) around 24 hours is shown in **Figure (7)**. It evidently shows that, the nightly average outdoor air temperature, the outlet airflow temperature of the earth-tube heat exchanger system, and the indoor air temperatures for the two greenhouses (G1 and G2) during the heating period, respectively, were 12.3, 19.1, 16.7, and 11.9ºC. It also reveals that, the nightly average indoor air temperature of the greenhouse (G1) was higher than that of the control greenhouse (G2) by 4.8ºC (40.34 %) owing to the heat energy gained from the earth-tube heat exchanger system. For the duration of the heating period, the earth-tube heat exchanger system was provided a heating effect of 6.8ºC.

Average soil temperature for the greenhouse (G1) and greenhouse (G2) were averaged in **Table (4)**. It was found that, the presence of the earth-tube heat exchanger increased the average soil temperature as a result to the earth-tube heat exchanger increased the greenhouse inside air temperature above that for the control greenhouse.

Table (4): Monthly average soil temperatures for the two greenhouses (G1 and G2) under different soil depths

Month	**Soil temperature under the greenhouse with earth-tube heat exchanger, °C**				**Soil temperature under the control greenhouse, °C**			
	Soil surface	**10 cm depth**	**20 cm depth**	**30 cm depth**	**Soil surface**	**10 cm depth**	**20 cm depth**	**30 cm depth**
December	19.5	19.7	20.6	21.5	18.9	19.1	19.2	21.1
January	18.1	18.2	18.5	19.2	17.2	17.1	17.2	17.9
February	18.5	18.8	19.1	19.6	17.5	17.7	17.9	18.2
March	21.0	20.2	20.3	20.8	19.7	18.8	18.9	19.5
Mean	19.3	19.2	19.6	20.3	18.3	18.2	18.3	19.2

The hourly average vapour pressure deficit (VPD) inside the two greenhouses (G1 and G2) was plotted in **Figure (8).** It evidently reveals that, the vapour pressure deficit of the air surrounding the cucumber plants decreased gradually with time from 1.466 kPa (G1) and 1.194 kPa (G2) at 18.00 hour until they reached the minimum values (0.896 and 0.166 kPa, respectively) at 6.00 hour, as the indoor air temperature decreased, and the air relative humidity increased. Four the duration of the heating season, the hourly average vapour pressure deficit (VPD) occurred inside the two greenhouses (G1 and G2) at nighttime, respectively, was o.969 and 0.343 kPa.

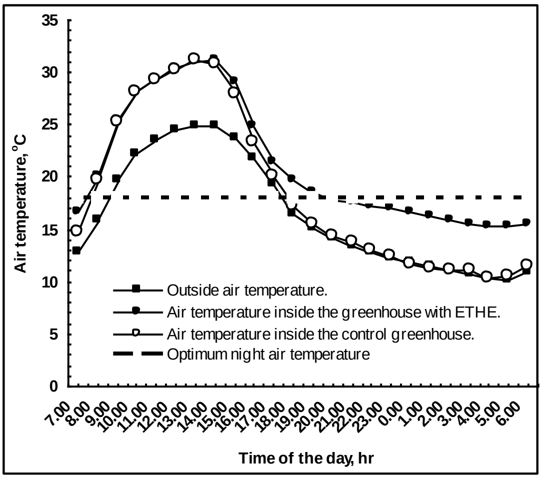


Figure (7): Changes in indoor and outdoor air temperatures for the two greenhouses as a function of time during the heating period.

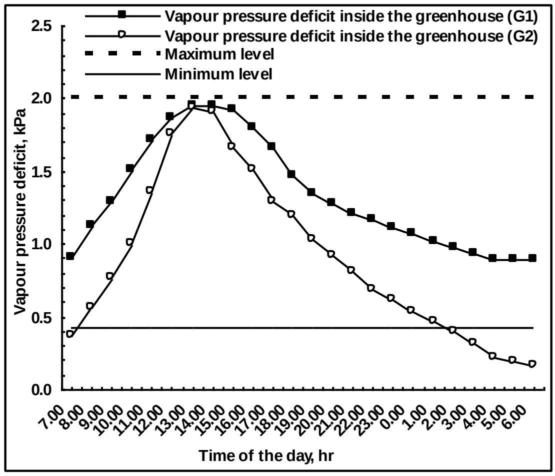


Figure (8): Variations in vapour pressure deficit inside the two greenhouses (G1 and G2) during the heating period

5.4. Effect of Earth-tube Heat Exchanger System on Microclimatic Conditions of Cucumber Growth, Development and Productivity

The stem length of cucumber plants varied during the growth stage (17 weeks) in each greenhouse. The weekly averages stem length of cucumber plants for the two greenhouses (G1 and G2) were 12.26 and 9.98 cm/week, respectively. The maximum lengths of the cucumber plants inside the two greenhouses, respectively, were 208.4 and 169.6 cm as shown in **Figure (9)**. The average numbers of flowerage inside the two greenhouses (G1 and G2) after 65 days from the transplanting of cucumber plants, respectively, were of 11.14 and 7.52 flower/plant**.** Duo to all the previous reasons, the total fresh yield of cucumber crop for the two greenhouses (G1 and G2), respectively, was 227.2 and 160.5 kg as revealed in **Figure (10)**. This means the earth-tube heat exchanger increased the greenhouse crop production by 41.6 % above that for the control greenhouse. After the final harvesting operation, five samples of cucumber plants were randomly taken from each greenhouse for determining the wet and dry matter weights. The average dry weight of cucumber plants for the two greenhouses (G1 and G2) was 83.32 and 65.85 g/plant. Dry weight was functioned to determine the water consumption during the long growth period.

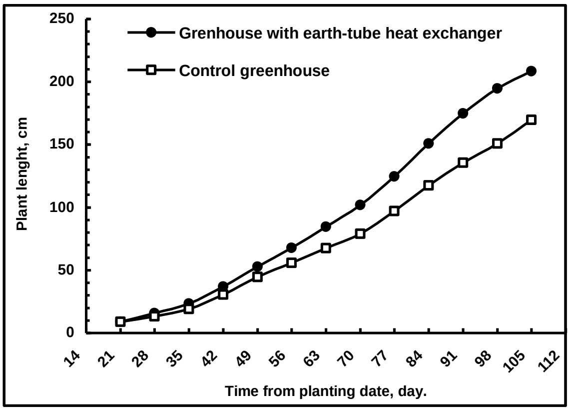


Figure (9): Stem length of cucumber plants for the two greenhouses (G1 and G2) during the winter season of 2012 - 2013.

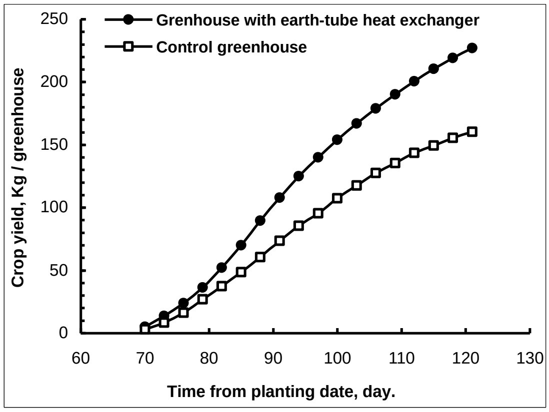


Figure (10): Fresh yield of cucumber crop for the two greenhouses (G1 and G2)

Accordingly, the annual irrigation water supply to each plant inside the two greenhouses (G1 and G2), respectively, was 22.318 and 17.638 litres/plant. Consequentially, the annual irrigation water supply (AIWS) during the winter crop for the two greenhouses (G1 and G2) was 2.143 and 1.693 m^3, respectively. The irrigation water-use efficiency (IWUE) for the greenhouses (G1 and G2), respectively, was 106.020 and 94.802 kg/m^3. The annual irrigation water productivity (AIWP) for the two greenhouses (G1 and G2) was 530.1 and 474.0 $L.E/m^3$, respectively. From the previous obtained results, the irrigation water-use efficiency and the annual irrigation water productivity for the greenhouse (G1) which equipped with earth-tube heat exchanger system was greater by 11.84 % than that for the greenhouse (G2) which was used as a control greenhouse.

5.5. Model Evaluation

The equations were solved using the computer program written in Matlab software (Mathworks, MA, USA). The simulation results which obtained from this model are considered “blind”, since they have not been yet compared with that measured within the greenhouse. The comparison between measured and simulated results is very important in order to check out how far the simulated results from the measured ones. The calculations have been done for the four months for December, January, February and March.

5.5.1. Air temperature

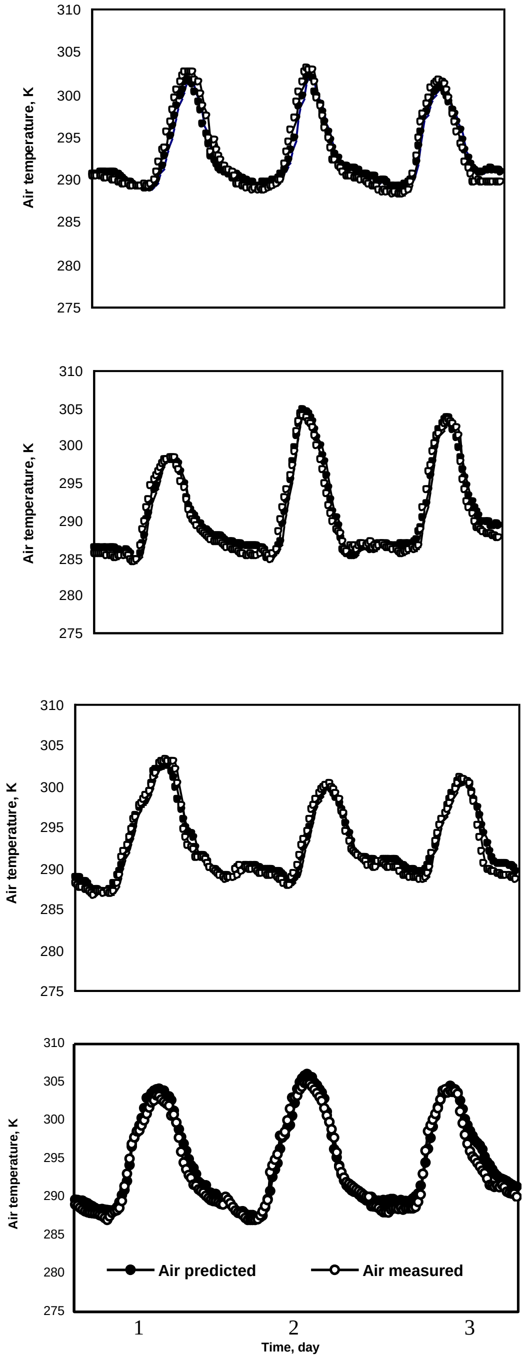
To investigate the model’s ability to predict and describe greenhouse microclimatic conditions during different times, simulations were compared with that measured and recorded during three consecutive days for each month as follows: 19, 20 and 21 December 2012, 11, 12 and 13 January, 12, 13 and 14 February, 5, 6 and 7 March 2013. **Figure (11)** present the measured and predicted air temperatures inside the greenhouse with earth-tube heat exchanger against simulation period assuming that the state of cover and plant temperatures equal to the simulated values obtained from the model during the simulation periods. The measured air temperature inside the greenhouse with earth-tube heat exchanger was plotted versus the predicted temperature from simulation model shown in **Figure (12).** The closeness of predicted and experimental values has been presented with root mean square of percent. High correlation coefficient between the predicted and measured values of air temperature inside the greenhouse was observed. It was found as 0.961, 0.968, 0.969 and 0.966 for the December, January, February and March, respectively. This shows that the thermal model given by MatLab is in fair agreement with the experimental work for composite climate of Ismailia, Egypt.

5.5.2. Soil surface temperature

The simplest mathematical representation of the fluctuating thermal regime in the soil profile is assuming that at all soil depths, the temperature oscillates as a pure harmonic (sinusoidal) function of time around an average value. At each succeeding depth, the peak temperature is dampened and shifted progressively over time. **Figure (13)** show the measured and predicted soil surface temperature for three successive days. A good agreement can be observed between the simulated soil surface temperature and that measured. Sometimes, there are little differences between measured and predicted soil surface temperature profiles occurred. The coefficient determination of soil surface temperature between predicted and measured values was 0.972, 0.978, 0.958 and 0.967 for the month of December, January, February and March, respectively as shown in **Figure (14)**.

CONCLUSION

- The 3 m deep soil temperature on average remained constant during the four months period of winter season.
- The monthly average daily overall thermal efficiency for December, January, February and March months were 71.9, 77.0, 72.4 and 70.2 % respectively that gave an average overall thermal efficiency of 72.9 %.
- The average monthly thermal energy exchange of an earth-tube heat exchanger were found as 2.7, 3.3, 2.6 and 2.3 kW for December, January, February and March months, respectively that gave an average of 2.7kW.



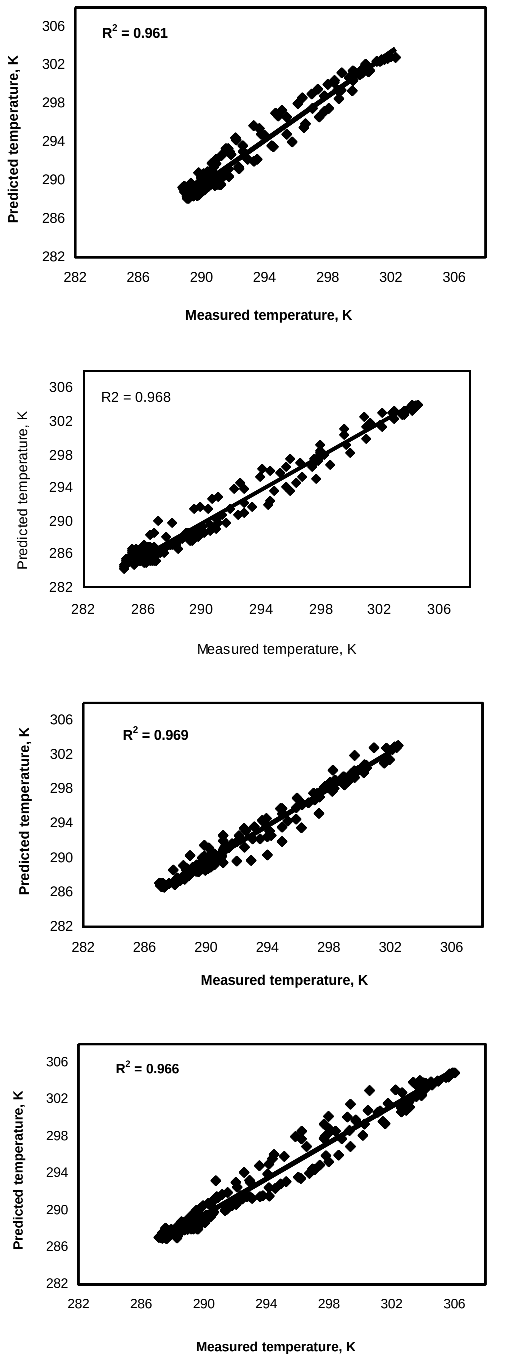
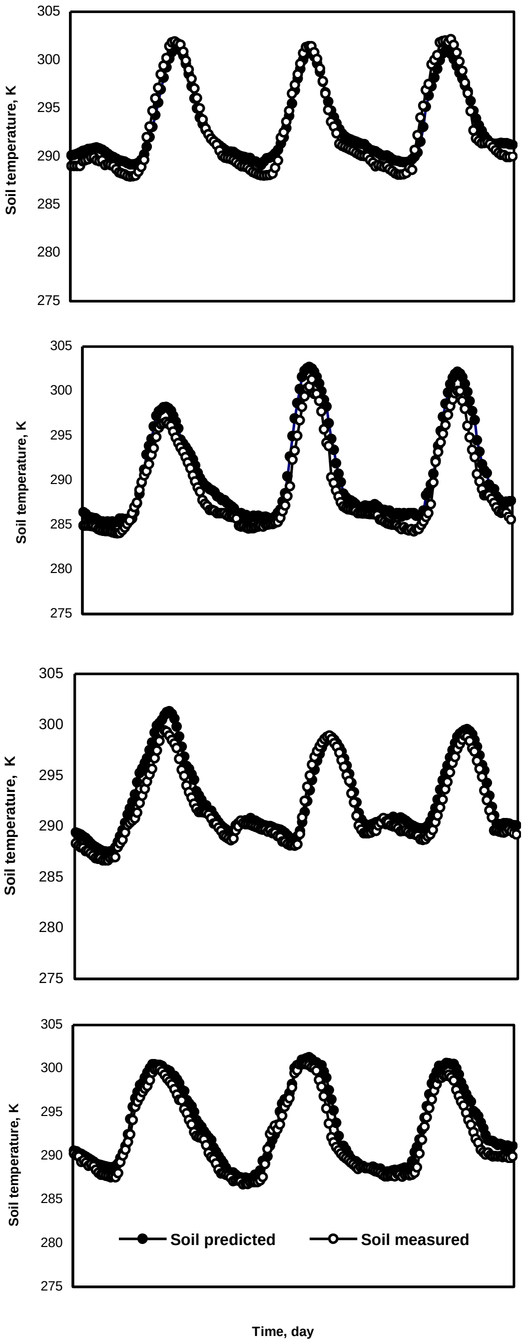


Figure (11): Validation of the measure and predicated indoor air temperatures for the greenhouse (G1) during daylight and at night for three successive days of (a) December, (b) January, (c) February, and (d) March.

Figure (12): Predicted and measured values for the indoor air temperatures of the greenhouse (G1) during (a) December (b) January (c) February, and (d) March



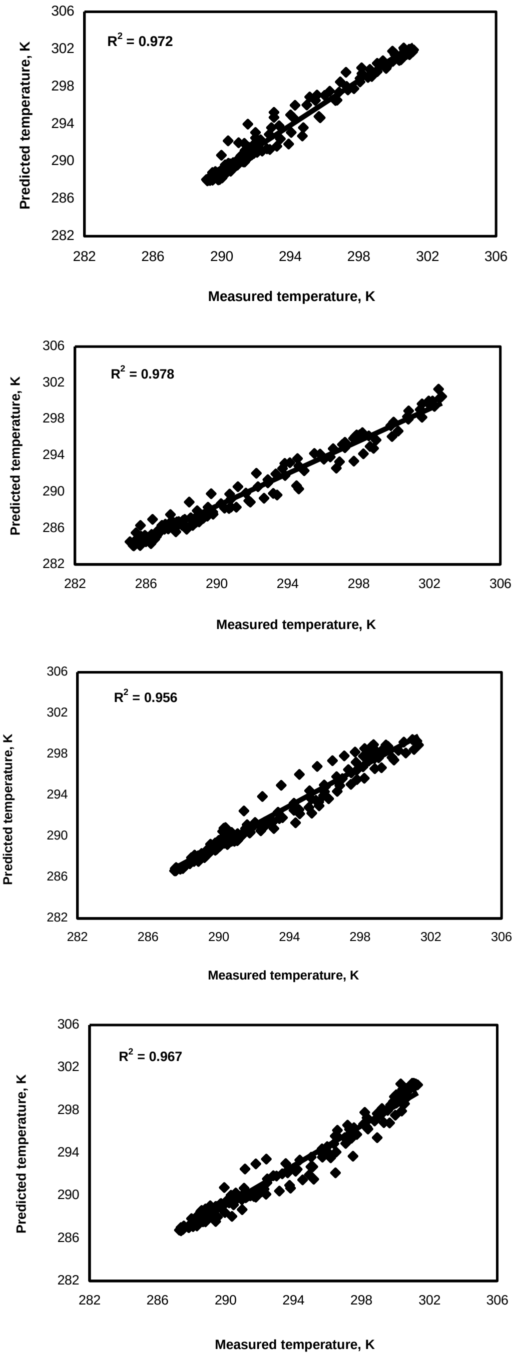


Figure (13): Validation of the measure and predicated soil temperatures for the greenhouse (G1) during daylight and at night for three successive days of (a) December, (b) January, (c) February, and (d) March.

Figure (14): Predicted and measured values for the soil temperatures of the greenhouse (G1) during cooling mode; (a) June, (b) July, and (c) August, R^2 coefficient of determination.

- Average air temperature under the greenhouse containing ETHE was increased above the control greenhouse.
- The output values obtained by simulation model are very close to the measured values.

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الملخص العربى

السلوك الحرارى لتدفئة البيوت المحمية باستخدام مبادل الهواء التحت أرضى خلال موسم الشتاء

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الهدف الرئيسى لهذا البحث هو استخدام مبادل الهواء التحت أرضى لتوفير الظروف المثلى لنمو محصول الخيار داخل البيوت المحمية أثناء فترات اليل خلال موسم الشتاء. استخدمت للتجارب صوبتين من البلاستيك على شكل الجمالون المتناظر الجوانب بمساحة ارضية ٢٤ م٢. الصوبة الاولى (ج١) متصلة بنظام مبادل الهواء التحت أرضى و المشيدة بمزرعة كلية الزراعة جامعه قناة السويس, الإسماعيلية, مصر. الصوبة الثانية (ج٢) صوبة مقارنة. التجارب نفذت خلال الفترة من ٣ ديسمبر ٢٠١٢ و حتى ٣٠ مارس ٢٠١٣. تم تصميم نموذج محاكاة رياضى على برنامج الماتلاب للتنبؤ بدرجة حرارة الهواء الداخلى و كذلك حرارة سطح التربة للصوبة أثناء فترة التجارب. وقد توصلت الدراسة إلي درجة حرارة ثبات التربة وجدت على عمق ٣ متر خلال بمقدار٢١,٧مº وتظل ثابتة عند و حول هذه القيمة خلال شهور الشتاء. المتوسط الشهري اليومى للكفاءة الحرارية الكلية لنظام مبادل الهواء التحت أرضى خلال شهور ديسمبر و يناير و فبراير و مارس وجدت ٧١,٧ ، ٧٧,٠، ٧٢,٤، ٧٠,٢ % على الترتيب. المتوسط الشهرى اليومى لكل ساعة لمعدل التبادل الحراري لنظام مبادل الهواء التحت ارضى وجدت ٢,٦٧، ٣,٣٤، ٢,٦٣، ٢,٣١ كيلو وات/ساعة لشهور ديسمبر و يناير و فبراير و مارس على الترتيب. المتوسط الموسمي لكل ساعة لحرارة الهواء الداخلية للصوبتين (ج١و ج٢) وجدت ١٦,٧ ، ١٢,٦مº على الترتيب. و بالتالى فإن نظام مبادل الهواء التحت أرضي أدى الى زيادة حرارة الهواء الداخلى بمقدار ٤,١مº عن صوبة المقارنة (ج٢). مبادل الهواء التحت أرضي أدى الى زيادة متوسط درجة حرارة التربة عن صوبة المقارنة. المتوسط الاسبوعى لطول ساق النباتات تحت الصوبتين (ج١و ج٢) وجدت ١٢,٢٦ و ٩,٩٨ سم/اسبوع, على الترتيب و بالتالى فإن نظام مبادل الهواء التحت أرضي أدى الى زيادة متوسط النمو الخضرى بمقدار ٢٢,٩ % مقارنة بصوبة المقارنة. كمية محصول الخيار الكلى للصوبتين (ج١و ج٢) على الترتيب وجد ٢٢٧,٢ و ١٦٠,٥ كيلو جرام. وبالتالى نظام مبادل الهواء التحت أرضي حقق زيادة فى كمية المحصول بمقدار ٤١,٦ %.معامل الإرتباط بين النتائج المتحصل عليها من نموذج المحاكاة و النتائج المقاسة لحرارة الهواء الداخلى وجد ٠,٩٦١، ٠,٩٦٨، ٠,٩٦٩، ٠,٩٦٦ لشهور ديسمبر و يناير و فبراير و مارس على الترتيب. بينما وجد ٠,٩٧٢، ٠,٩٧٨. ٠,٩٥٨، ٠,٩٦٧ لحرارة التربة لنفس الشهور على الترتيب.

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