Minufiya J. Agric. Res. Vol.36 No. 3:509-520 (2011) **"http://www.mujar.net"**

محاكاة رياضية لدرجات حرارة التربة تحت سطح الأرض

عبد الرحمن عثمان الغنام

هندسة النظم الزراعية، كلية العلوم الزراعية و الأغذية، جامعة الملك فيصل

المملكة العربية السعودية

الملخص العربي:

تم إجراء هذه الدراسة بمحطة الأبحاث والتدريب الزراعية التابعة لجامعة الملك فيصل في محافظة الإحساء، المملكة العربية السعودية . تهدف الدراسة إلى عمل محاكاة رياضية لدرجات الحرارة تحت سطح التربة عند أعماق مختلفة واستخدام نتائج المحاكاة لتقديم تصميم أمثل لنظام الأنابيب الأرضية تحت ظروف منطقة الأحساء. تم قياس درجة الحرارة للتربة في موقع الدراسة حيث تمت هذه القياسات على فترات مختلفة منها عام٢٠٠٤ م والأخرى لمدة أربعة أشهر متتالية عام ٢٠١٠ م على عمق ٣ م وذلك عن طريق تسجيل درجات الحرارة على كل عمق باستخدام أسلاك الازدواج الحراري. أ وضحت النتائج أن درجة حرارة التربة على عمق ١-٣ متر تحت سطح الأرض كانت في شكل منحنى جيبي نسبة لتباين درجات الحرارة خلال شهور السنة و أن درجة حرارة التربة على هذا العمق كانت شبه مستقرة خلال فصلي الصيف و الشتاء. وقد تراوحت درجات الحرارة خلال فصل الصيف بين٣٢ – ٣٥ درجة مئوية و بين ١٩-٢٠ درجة مئوية خلال فصل الشتاء. بمقارنة نتائج دراجات الحرارة الحقيقة والنظرية لعام ٢٠٠٤ متطابقة إلى حد كبير في أعماق التربة قيد الدراسة. وقد كانت مقدار الخطأ في المحاكاة ١-١.٥ درجة مئوية عن الحقيقية، وعلاوة على ذلك، فإن النموذج تنبأ باستمرار درجة حرارة التربة ٢٠١٠ (بمقدار خطأ ١.٧ درجة مئوية) من بداية يونيو إلى أواخر سبتمبر.

MATHEMATICAL SIMULATION OF SOIL SUBSURFACE TEMPERATURES

A. O. Ghannam
Agricultural Systems Engineering, College of Agricultural Sciences and Food, King Faisal University,

(Received: Apr. 7, 2011)

ABSTRACT: ***This study was conducted in the research and agricultural training of the King Faisal University in Al-Ahsa, Saudi Arabia. The study aims to conduct mathematical simulation of temperatures below the surface of the soil at different depths and use of simulation results to provide an optimal design of the piping system under the conditions of ground-Hassa region. Temperature of the soil subsurface in the study site was measured, at different depths of the year 2004 and another measurement were recorded for four consecutive months in 2010 at 3 m depth. Temperatures were recorded using thermocouples. The results indicated that the temperature of soil at a depth of 1-3 meters below the surface of the soil was a sinusoidal shape which fluctuates according to the rise and fall of the ambient temperatures throughout the months of the year. The temperature of the soil at the mentioned depths was almost stable during the summer and winter. The temperature ranged during the summer between 32-35°C and 19-20°C during the winter. Predicted and measured temperatures for the year 2004 agreed reasonably well at all soil depths under study. Predicted values were approximately within 1 to 1.5 ºC off the measured values; furthermore, the model consistently predicted the 2010 soil temperature (by as much as 1.7°C) from early June to late September.***

Key words: ***Mathematical simulation, soil temperatures, greenhouse, earth tubes, alternative energy.***

INTRODUCTION

Maintaining a comfortable temperature inside a greenhouse requires a significant amount of energy. Separate heating and cooling systems are often used to maintain the desired air temperature inside the greenhouse, and the energy required to operate these systems generally comes from electricity, fossil fuels, or biomass. Considering that 46% of sun’s energy is absorbed by the earth as shown in Figure 1. The other option is to use this abundant energy to heat and cool the greenhouse. In contrast to many other sources of heating and cooling energy which need to be transported over long distances, earth energy is available on-site, and in massive quantities. Because the soil transports heat slowly and has a high heat storage capacity, its temperature changes slowly depending on the depth of the measurement. As a consequence of this low thermal conductivity, the soil can transfer some heat from the cooling season to the heating season as presented in Figure 2. Heat absorbed by the earth during the summer effectively is used in the winter (NRCan, 2002). This yearly, continuous cycle between the air and

the soil temperature results in a thermal energy potential that can be utilized to help heat or cool a greenhouse.

Another thermal characteristic of the ground is that a few meters down the surface soil insulate the earth minimizing the amplitude of the variation in soil temperature in comparison with the temperature the ambient air above the ground. This thermal resistivity fluctuations further helps in shifting the heating or cooling load to the following season where it is needed. The earth is warmer than the ambient air in the winter and cooler than the ambient air in the summer. This warm earth and groundwater below the surface provides a free renewable source of energy that can easily provide enough energy year-round to heat and cool greenhouses.

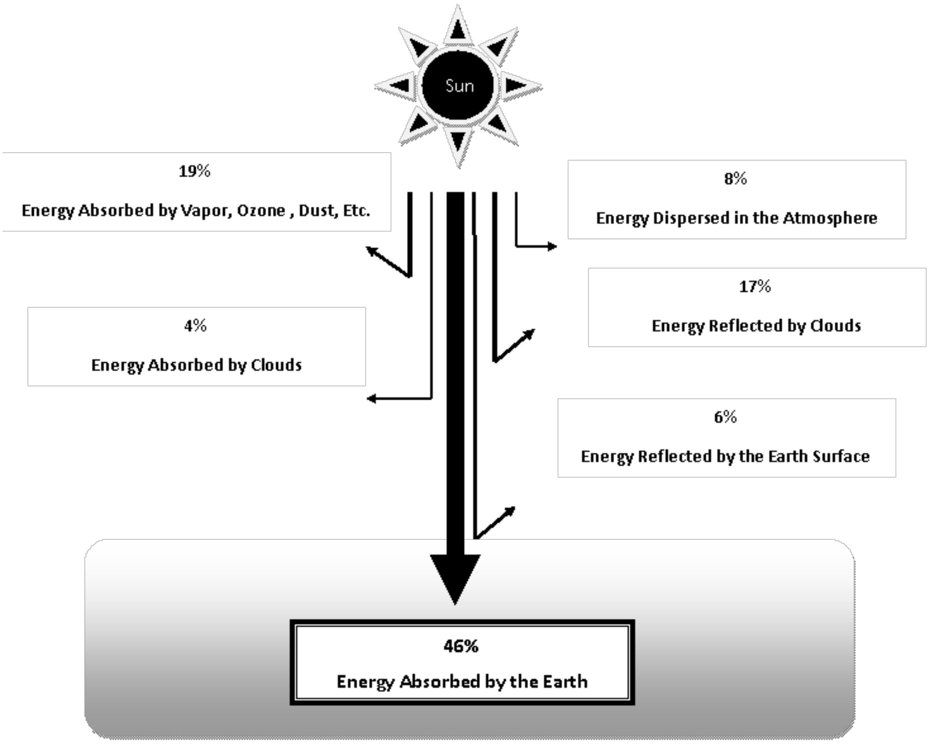

Figure (1): Source: Natural Resources Canada (NRCan),

Alahsa County is located in the south-east of the Kingdom of Saudi Arabia, where it extends approximately between the latitudes of 21/25° - 37/25° N and longitude 33/49° - 46/49° E. The Alahsa climate is almost continental with great extremes in temperatures, like most prevalent climates of the deserts in the kingdom. Climate of the Alahsa has long summer begins in April and lasts until November, and the temperature rise up to 44º C in July

and August, while in the winter it falls to about 15.5º C in January, and frost may be felt in the early morning hours.However, the average annual temperature of 26.5º C.

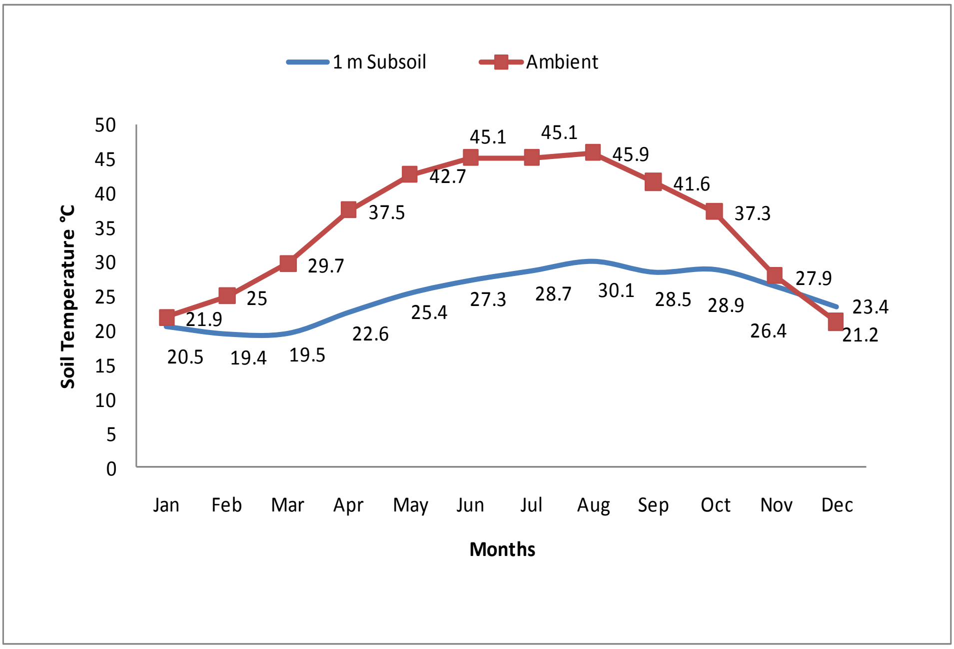

Figure (2): Soil subsurface temperature at various depths.

The method for sizing the ground heat exchanger (ETHE) requires knowledge of the minimum and maximum ground temperature at the ETHE depth. The ground temperature variation with time and depth is worth the research due to its importance in engineering design. These designs include but not limited to; the extension of drinking water manifolds systems and sanitation, irrigation systems, electrical cables and roads and pavements and other areas of agriculture and engineering. The variation of the average daily and annual temperature with depth forms a sinusoidal curve and could therefore be modeled using sine function. It is known that there might be an error of 2°C in estimating these models to the actual average temperature of the soil (Hillel, 1982 Marshall and Holmes1988). A survey of temperature simulation of soil subsurface mathematical models was conducted. Most of the mathematical models are identical in the fundamental equations in the ambient and soil subsurface temperatures which are basically a sinusoidal shape curve which differs only in the constants of these equations depending on soil type or moisture content. Kusuda and Bean (1983), Moreland *et al*, (1980) and Labs (1989), Vose and Swank (1991), have

developed mathematical models to estimate the temperature of the soil based on the heat conduction in soils that are often assumed to have homogeneous textures.

Alajmi *et. al* (2006) also developed a mathematical model to simulate subsurface soil temperatures in a location that is within similar environmental conditions and depths. The model was used to simulate the cooling of a residential house in the State of Kuwait. Results showed that the system was able to reduce the temperature by 2.8° C in mid-July. During his modeling he simulated the subsurface temperature of the soil at depth of 3m. He used the mathematical model that developed by (Hillel, 1982) and the amount of error in the prediction was ± 1º C.

MATERIALS AND METHODS

The main objective of the research was to make a thorough study and data analysis for the site subsoil temperature variation that will include a real measurement and a prediction. This study will be used as a base to design Earth Tube Heat Exchangers (ETHE) in a closed system under the climate of the of Alhasa (Figure 3). The ETHE was used to heat the greenhouse during cold winter nights and cool it on hot summer days. Air was withdrawn from the exit of the greenhouse then pushed through the pipes under the ground and enters again from the other side to the greenhouse. During this process there is heat exchange between air and walls of the pipe so as to reduce the temperature of the air during the summer or raise it during the winter.

Picture (1): the depth of drilling into the study for the development of underground pipes

This study was conducted at different times of the years 2003 and 2004 at the depths (5 cm, 10 cm, 20 cm, 50 cm, and 100 cm) and in another four consecutive months at a depth of 3 m in the moths of June-July-August-

September 2010 as depicted in picture 1 and by recording temperatures at each depth using thermocouples.

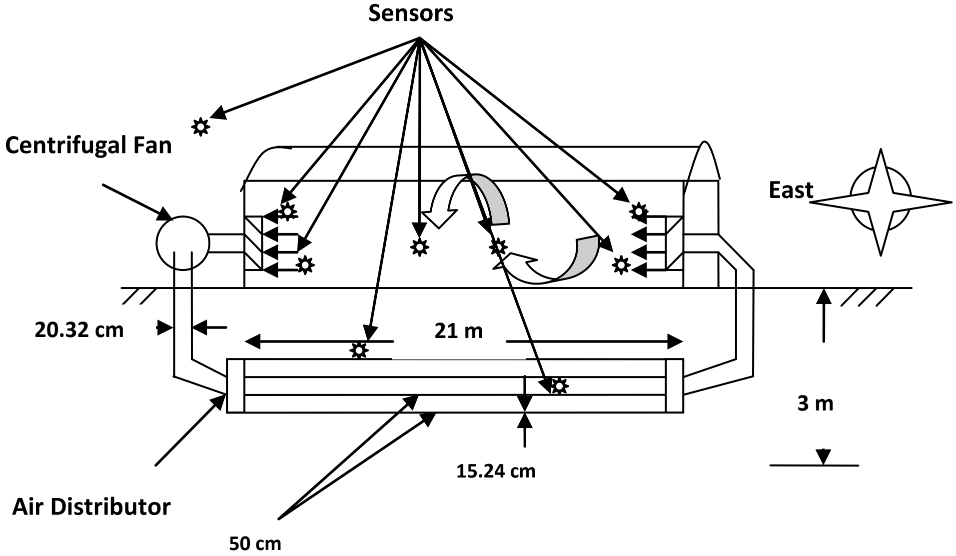

Figure (3): Diagram of the greenhouse with Earth Tube Heat Exchangers (ETHE) in a closed system.

Mathematical model

The design of the Earth Tube Heat Exchangers (ETHE) in a closed loop system is primarily concerned with identifying the lengths of heat exchanger which is mainly dependent on upper and lower soil subsurface temperatures at the depth where the heat exchanger is placed. The mathematical model used was developed Kusuda and Bean (1983), Moreland *et al.* (1980) and Labs (1989) to simulate soil subsurface temperature at various depths as follow:

$$T(z,t) = T_m - T_s * e^{\left(-z\left(\frac{\pi}{8760}\alpha\right)^{0.5}\right)} \cos\left[\frac{2\pi}{8766}\left(t - t_o - \frac{z}{2}\left(\frac{8760}{\pi x}\right)^{0.5}\right)\right]$$

Where:

T = undisturbed soil temperature (°C) at depth z (m) and time t (hours)
t = time of the year (hours)

z = depth below ground (m)
Tm = mean annual ground temperature ¼ mean annual ambient air temperature,° C.
Ts = ambient air temperature, ° C
α = thermal diffusivity of the soil (m2/h).
t_0 = phase constant, hours (time to occurrence of minimum surface temperature since start of year, in hours)

RESULTS AND DISCUSSION

As mentioned by Alajmi *et. al* (2006), the prediction accuracy of the undisturbed soil temperature is very sensitive to the values of the input parameters. Figure (4) shows the mean experimental soil subsurface temperature at the depths (0.05 m, 0.1 m, 0.2 m, 0.5 m, 1 m) with the fluctuation in temperature during the months of the year, which is an evident that the soil subsurface temperature almost stable at various depths during summer and winter. Soil subsurface temperature during summer ranged between 26 - 30.6ºC during which the summer ambient temperature reached up to 45ºC and more. Regarding the winter temperature it was between 21-23ºC while the temperature of outside air was close to 28 ºC.

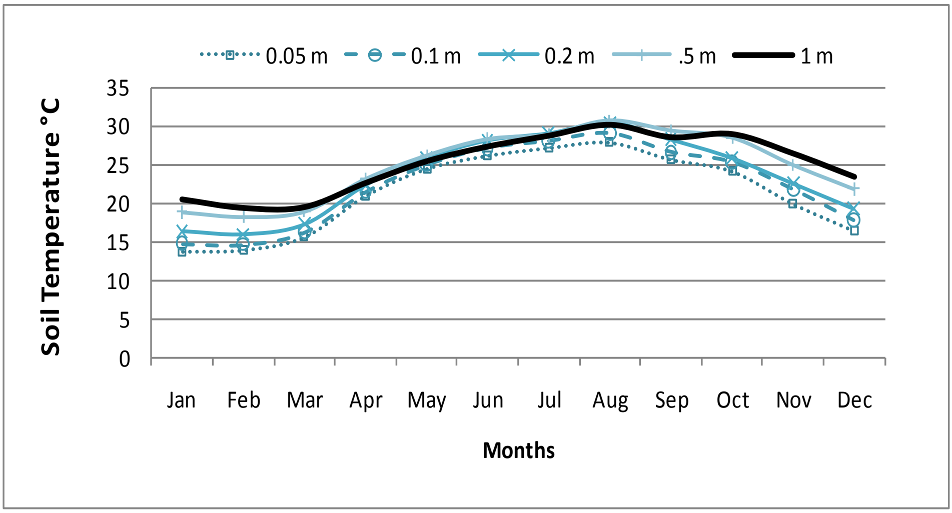

Figure (4): Actual soil subsurface temperature at various depths in 2003

In contrast, the mathematical model has achieved a good matching prediction to the actual temperatures in the depths under study as depicted Figure (5).

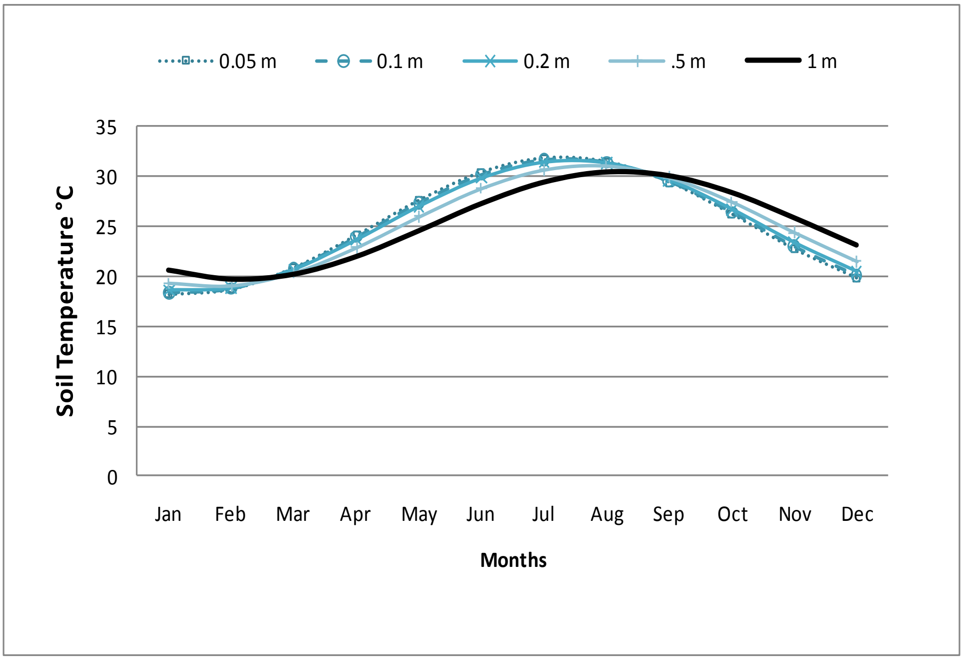

Figure (5): Prediction of soil temperature at various depths

The results of the Standard Error between actual temperatures and prediction are small, which indicates the extent of proximity between them. Furthermore it indicates that standard error decreases as the depth in the soil increase.

Figure (6) shows a sample of the comparison between the actual and predicted average temperatures at a depth of (1m) for two consecutive years are 2003 - 2004. The figure also shows the compatibility between the two curves is almost exact.

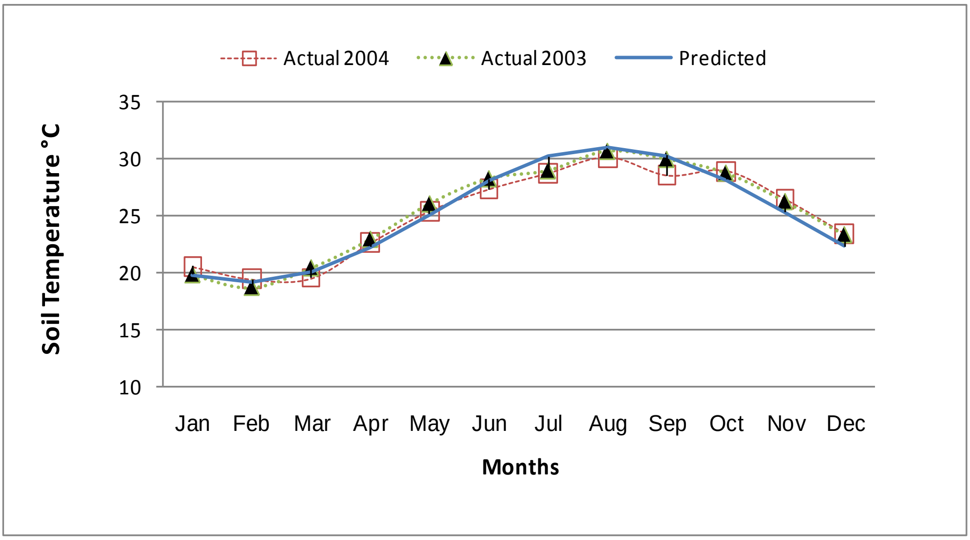

Figure (6): The actual and predicted of temperatures of the soil at a depth (1m) for the years 2003 and 2004.

Predicted and measured temperatures for the year 2003 agreed reasonably well at all soil depths (Figure 6). Predicted values were usually within ±1 to ±1.5 ºC of the measured values for depths of 0.5 and 1 meter; whereas error starts to increase as it moves closer to surface. Table 1 shows the Error in prediction for different depths. The highest prediction error was 5.3 ºC at depth 0.05 m. In other words, as the depth increase, error decreases. This also confirmed in the calculation of the standard error and Standard Deviation in table (2). Predictions at the 1m and 0.5 m soil depth were in general agreement with measured values; errors ranged from ±.1 °C above to ±1.9 °C off the measured values. Most predictions (95 percent) were within ±1 °C off the measured values (Table 1). Consistent with heat-flow theory, predicted soil temperatures at 0.10 m closely paralleled with measured with larger temperature fluctuations. However, measured data showed a steady soil temperature during the period. Although the model adequately predicted soil temperature at 0.10 m January through November, temperatures were consistently was overestimated thereafter. Sixty-seven percent of the predicted soil temperatures at 0.20 m were 1 to 1.5 °C off the measured values (Table 1). Furthermore, the model consistently predicted the 2010 soil temperature (by as much as ±1.7 °C) for depth of 3m from early June to late September (Figure 5).

Table (1): Error in prediction for different depths

Depth (m)					
MNTH	**0.05 m**	**0.1 m**	**0.2 m**	**.5 m**	**1 m**
Jan	**4.558214**	**3.665899**	**2.288866**	**0.50779**	**0.1061**
Feb	**4.863146**	**4.178152**	**2.921828**	**0.852667**	**0.307293**
Mar	**5.305226**	**4.623535**	**3.476335**	**1.458412**	**0.698174**
Apr	**3.22728**	**2.570178**	**1.370456**	**-0.21339**	**-0.64674**
May	**3.189761**	**2.498182**	**1.224035**	**-0.12149**	**-0.88476**
Jun	**4.290474**	**3.114337**	**1.763254**	**0.628469**	**-0.08344**
Jul	**4.699659**	**3.684859**	**2.448318**	**1.893903**	**0.653354**
Aug	**3.650134**	**2.426583**	**0.966219**	**0.488747**	**0.268855**
Sep	**3.832973**	**2.906808**	**1.438349**	**0.610118**	**1.498461**
Oct	**2.173772**	**1.125755**	**0.914926**	**-0.93488**	**-0.56132**
Nov	**2.895702**	**1.186231**	**0.857686**	**-0.50916**	**-0.578**
Dec	**3.505018**	**2.284448**	**1.241399**	**-0.31169**	**-0.29584**

Table (2): Standard Error and Standard Deviation for different depths

Depth (m)						
	2003					**2010**
MNTH	**0.05 m**	**0.1 m**	**0.2 m**	**.5 m**	**1 m**	**3 m**
STDE	**0.95**	**1.10**	**0.82**	**0.86**	**0.71**	**0.39**
STDEV	**5.41**	**5.23**	**5.01**	**4.40**	**3.83**	**1.87**

In order to validate the accuracy of the model, another temperature prediction was conducted during the summer 2010 during which some extreme changes in climatic had happened. Figure (7) shows the actual and predicted values of temperatures of the soil at a depth (3m) for the year 2010. The resulting error in the prediction of the soil temperature was within the acceptable limit but it can be attributed to the following: (1) soil compressibility and soil moisture content difference at each depth which leads to the difference in heat transfer coefficient while in the model the heat transfer coefficient was constant for all the depths. (2) The soil characteristics at these depths may be quite heterogeneous at different depths. In general, a result shows that the current mathematical model is quite sufficient, and was able to describe the actual data within the acceptable range of error. This is enough evidence that mathematical modeling is an easy and inexpensive way to estimate the soil subsurface temperature. It can also help in the optimal design of underground pipe systems and other engineering and agricultural designs under the conditions of the Kingdom of Saudi Arabia.

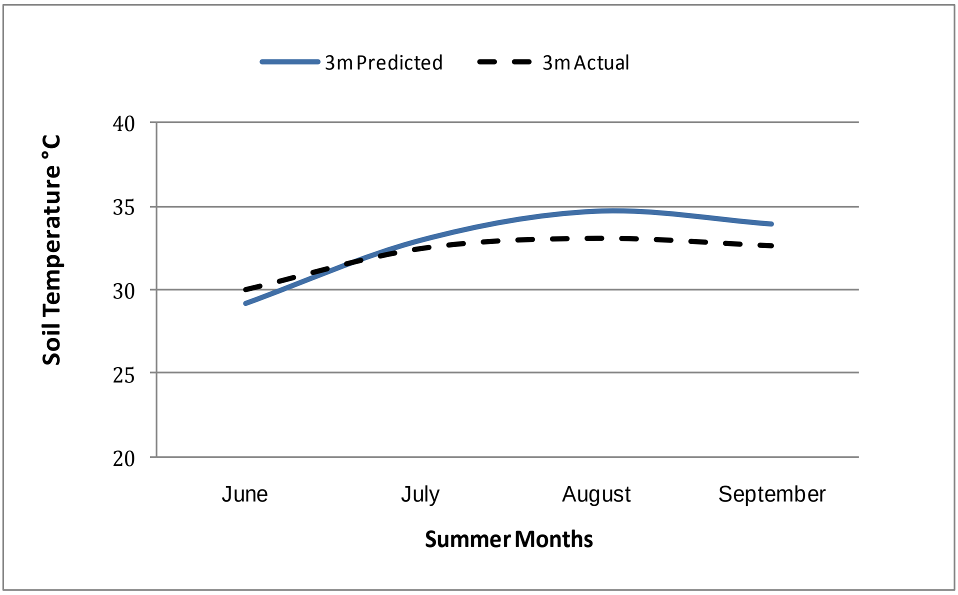

Figure (7): The actual and predicted of temperatures of the soil at a depth (3m) for the year 2010.

CONCLUSION

In this paper, an algorithm for the simulation of Subsurface soil Temperature is described, and validated against an actual field data. The results of the simulation was also investigated and analyzed and the following conclusions can be made based on the data presented above:

As a result of the validation against the actual data, the subsurface soil temperature model showed a good agreement with the actual data. Thus it can be suitably used to predict the thermal performance of subsurface soil temperature at the depth indicated.

The availability of a subsurface soil temperature model is an important step forward when attempting to determine whether or not the soil and depth for certain location is suitable to apply any engineering study. In the case of the ETHE it so important to for the design of the system concerning the length, diameter, number of lines needed, and the fan power required.

REFERENCES

Al-Ajmia, F., D. L. Loveday, V. Hanby (2006). The cooling potential of earth-air heat exchangers for domestic Buildings in a desert climate, Building and Environment 41:235-244. Electrical energy, (25th ed.) State of Kuwait, 2000.

Hillel, D. (1982). Introduction to soil physics. Academic Press, San Diego, CA.

James M. Vose and Wayne T. Swank (1991) A Soil Temperature Model for Closed Canopied Forest Stands, Coweeta Hydrologic Laboratory, Otto, NC 28763. April 1991.

Kusuda T., W. (1983). Bean Annual variation of temperature field and heat transfer under heated ground surface, slab-on grade floor heat loss calculation. Building Science Services 156, Gaithersburg, MD: National Bureau of Standards.

Labs K. In and J. Cook (1989). Passive cooling. Cambridge Massachusetts, London, England: MIT Press..

Marshall, T. J. and J. W. Holmes (1988). Soil Physics. 2nd ed. Cambridge Univ. Press, New York.

Moreland FL, F, Higgs, J. Shih (1980). Earth-covered buildings. Proceeding of conference in Fort Worth, Texas, US, May 1978, Washington, DC: DOE,

NRCan (2002). Residential Earth Energy Systems: A Buyer’s Guide, Natural Resources Canada’s Renewable and Electrical Energy Division, ISBN 0-662-30980-4, Cat. No. M92-236/2001E, Ottawa, ON, Canada, 41 pages.

محاكاة رياضية لدرجات حرارة التربة تحت سطح الأرض

عبد الرحمن عثمان الغنام

هندسة النظم الزراعية، كلية العلوم الزراعية و الأغذية، جامعة الملك فيصل
المملكة العربية السعودية

الملخص العربي:

تم إجراء هذه الدراسة بمحطة الأبحاث والتدريب الزراعية التابعة لجامعة الملك فيصل في محافظة الإحساء، المملكة العربية السعودية . تهدف الدراسة إلى عمل محاكاة رياضية لدرجات الحرارة تحت سطح التربة عند أعماق مختلفة واستخدام نتائج المحاكاة لتقديم تصميم أمثل لنظام الأنابيب الأرضية تحت ظروف منطقة الأحساء. تم قياس درجة الحرارة للتربة في موقع الدراسة حيث تمت هذه القياسات على فترات مختلفة منها عام٢٠٠٤ م والأخرى لمدة أربعة أشهر متتالية عام ٢٠١٠ م على عمق ٣ م وذلك عن طريق تسجيل درجات الحرارة على كل عمق باستخدام أسلاك الازدواج الحراري. أ وضحت النتائج أن درجة حرارة التربة على عمق ١-٣ متر تحت سطح الأرض كانت في شكل منحنى جيبي نسبة لتباين درجات الحرارة خلال شهور السنة و أن درجة حرارة التربة على هذا العمق كانت شبه مستقرة خلال فصلي الصيف و الشتاء. وقد تراوحت درجات الحرارة خلال فصل الصيف بين٣٢ – ٣٥ درجة مئوية و بين ١٩-٢٠ درجة مئوية خلال فصل الشتاء. بمقارنة نتائج دراجات الحرارة الحقيقة والنظرية لعام ٢٠٠٤ متطابقة إلى حد كبير في أعماق التربة قيد الدراسة. وقد كانت مقدار الخطأ في المحاكاة ١-١.٥ درجة مئوية عن الحقيقية، وعلاوة على ذلك، فإن النموذج تنبأ باستمرار درجة حرارة التربة ٢٠١٠ (بمقدار خطأ ١.٧ درجة مئوية) من بداية يونيو إلى أواخر سبتمبر.