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Design and Performance Testing of a Building Air Conditioning System using Geothermal Heat Exchangers

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Abstract

In many dry desert climates such as in Iraq, the summer season is long with a mean daily maximum temperature of (45ºC). Building air conditioning systems consume significant energy from total electricity generation. A passive air-cooling strategy is seen as a viable option to save energy for all hot and dry subtropical climatic zones. An earth pipe cooling technique is one of them which utilizes the earth's near constant underground temperature for cooling a space in a passive process without using any mechanical units, and thus saves energy in buildings with less or no environmental impact. This study aimed to design and energy performance estimation of a building integrated Cooling system using Geothermal. Ground temperature as well as the performance of the ground heat exchanger (31 m) with a depth (3 m) and diameter (6 in) were verified on a room with dimensions (3 × 3 × 5.5 m^3). The weather variables which are represented by solar intensity, ocean temperature and relative humidity which depend on the geographical location of the building, The effect of weather variables on the outlet air temperature. Operational variables which represented by the velocity of air flow (4, 5, 6 m/s), and its effect on the outlet air temperature and thermal performance. The study included a simulation of the cooling system that was designed by using MATLAB and ANSYS FLUENT. Theoretical results showed good compatibility with experimental results at the rate of difference (1.3%). The results showed that the daily temperature change is significant to a depth of (0.25 m), due to the impact of climatic conditions on the ground temperature, and the ground temperature at a depth of (3 m) is constant (21ºC) throughout the year. The results also showed that the outlet air temperature is increasing as the air speed ranged from (23-32ºC). Cooling effectiveness is increased by lower flow velocity as the maximum cooling effectiveness of the geothermal heat exchanger is (86.6 %) at air speed (4 m/s). The rate of difference between ambient temperature and room temperature due to the use of geothermal heat exchanger ranges between (10-16ºC). The results also showed that the outlet air temperature increases with increasing air speed and pipe diameter and decreases with increasing pipe length, pipe depth and pipe material conductivity.

1.1 Introduction

The global energy oil production is unstable and will diminish within a few years. Therefore, the energy prices are expected to rise and new energy systems are needed. In addition to this energy crisis the fossil fuels seem to be the main reason for climate change. There is a global political understanding that we need to replace fossil fuels by renewable energy systems in order to develop a stable and sustainable energy supply. Geothermal energy is one of renewable energy sources. It is a clean, renewable resource because the heat emanating from the interior of the earth is essentially limitless. The source of geothermal energy, the earth's heat, is available 24 hours a day, 365 days a year. Solar and wind energy sources, in contrast, are dependent upon a number of factors, including daily and seasonal fluctuations and weather variations. An earth tube is a long, underground metal or plastic pipe through which air is drawn. As air travels through the pipe, it gives up or receives some of its heat to/from the surrounding soil and enters the room as conditioned air during the cooling and heating period (Lee and Strand, 2008) [1]. An important factor that can influence the performance of geothermal heat exchangers is the soil type, Wasseem Morshed et al (2018) found that the best energy performances have been obtained for wet and heavy soil. As regards the material surrounding the buried tube, good contact between soil and tubes has to be ensured, by means of compacted clay or sand. These kinds of soil are also suitable for the correct tube installation. An important factor that can affect the performance of geothermal heat exchangers is the tube material type [2]. Noor Aziah and Aliyah Nur (2014) studied six pipes (polyethylene, polyvinyl chloride, steel, clay, concrete, and copper), burred at (1m) having length (25 m), diameter (50 mm), were verified. To evaluate the performance of different types of exchanger materials an Energy Plus simulation program was used. The results showed that the temperature drop ranges between (3-6) for air inside at a speed of (0.5 m/s), and the temperature ((36.46ºC), and although all the exchanges have slight differences between them, the polyethylene exchanger (PE) was Better to lower the temperature. In general, the results of many researchers in the past showed that the cooling tubes of different sizes of tubes work differently [3]. Another factor affecting the performance of geothermal heat exchangers is the diameter of the buried tube. (Kamal K. Agrawal et al (2018) studied the effect of four variables: the length, (30,40, 50, 60 m), diameter (0.1, 0.15, 0.2, 0.25 m), air velocity (2, 3, 4, 5 m/s), and temperatrue of inlet air (34.35, 38.35, 42.35, 46.35 ºC). shown that small pipes are thermally more efficient but cause greater pressure losses and require larger installations. A compromise has to be found between the cost of the installation and its thermal efficiency [4]. Another factor affecting the performance of geothermal heat exchangers is air velocity. Ascione et al. (2011) concluded that low speeds (about 8 m/s) of the airflow inside the tubes are preferable, as the pressure drops and fan electric energy requirements decrease [5]. Lee and Strand (2008) and Lee and Strand (2006) indicated that an earth tube with a lower air velocity will perform better since the air spends more time in the tube and thus in contact with the lower soil temperature. Another factor affecting the performance of geothermal heat exchangers is tube length [6] [7]. Ascione et al. (2011) studied the earth-to-air heat exchangers (EAHX) for Italian climates and found that the thermal exchange between the ground and the air crossing the tube increases with the length of the buried tubes. Values of about 10 m are unsatisfactory while significant advantages do not occur for lengths over 70 m. For the climates here considered, lengths of about 50 m were preferable, which optimize heat exchange and first costs [5]. (Ghosal) and (Tiwari) (2006) found that with the increase of the length of buried pipes from 30 m to 50 m, the temperatures of the air inside the greenhouse go on increasing in the winter period and decreasing during the summer period [8].

1.2 Mathematical Model

ANSYS and MATLAB software have been used to model the check and compare system with the tests results using Underground heat exchanger pipe, as shown in Figure (1).

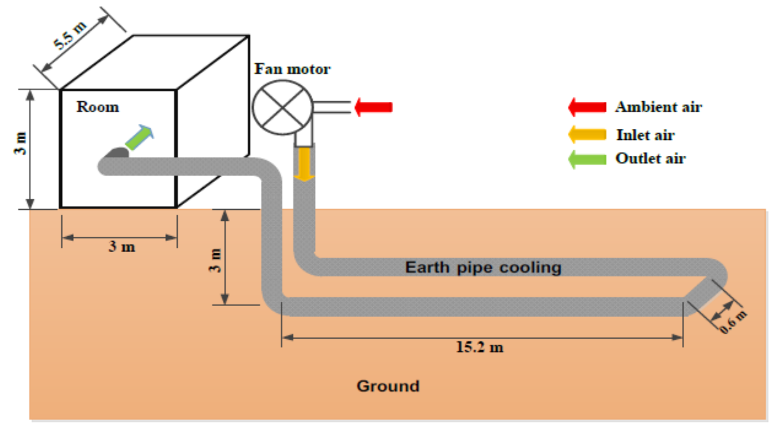


Figure. 1: Underground pipe system.

1.2.1 Theoretical model of the UGP Using MATLAB

Geothermal heat exchangers are long metal, plastic, or concrete tubes that are placed under the ground and connected to the air inlets of buildings. Its purpose is to provide some air conditioning or full air conditioning. In the present research, a type of Aluminium coated with diameter (6 in), length (31 m) and a distance (0.6 m) between the legs of the geothermal exchanger was used. where a mathematical model was employed as shown in Figure (2):

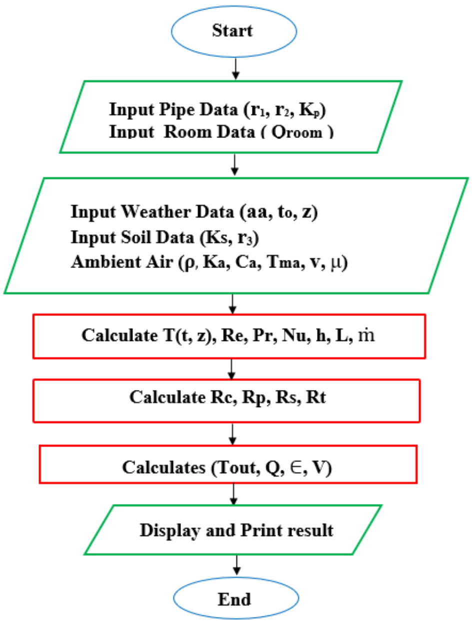


Figure. 2: Flowchart for MATLAB Model

1.2.2 Mathematical Model Assumptions

For simplicity's sake, we use the following hypotheses [43]:

1.The soil around the tubes is homogeneous, and the thermal conductivity of the soil is homogeneous for all layers of the ground.

2.The surface temperature of the Earth is roughly equal to the ambient air temperature, which equals the temperature of the incoming air.

3. The tube is a regular circular cross section.

1.2.3 Soil temperature model

This equation is developed from the work by Kusuda and Achenbach [2], It calculates the temperature around the pipe at different depths. They are arranged to fit this model to calculate temperatures at different times and depths.

$$T_{(t,z)} = T_{ms} + a_s * e^{-z*\sqrt{\frac{\pi}{365\alpha}}} * \cos(\frac{2\pi}{365}(t - t_\circ - \frac{z}{2}\sqrt{\frac{365}{\pi.\alpha_s}}) \quad (1)$$

Where:

T_{mean}: is the mean ground surface temperature, °C.

a_s: is the annual amplitude of the ground surface temperature, °C.

t: is the time in year (days) from starting date of year, number.

t_o: is the phase constant (days) since the beginning of the year of the minimum average ground surface temperature.

In this study it was decided to use Eq. 4.13 to predict the soil temperature after developing it for Iraqi conditions. For simplicity, the ground surface temperature is assumed to be equal the air temperature, which is an acceptable assumption for most design calculations as indicated by ASHRAE (2012), also the phase lag is assumed as the phase lag at the maximum air temperature according to Sharan and Jadhav (2002) and the annual amplitude of ground surface temperature is assumed to equal the annual amplitude of air temperature.

$$T_{(t,z)} = T_{ma} + a_a * e^{-z*\sqrt{\frac{\pi}{365\alpha}}} * \cos(\frac{2\pi}{365}(t - t_\circ - \frac{z}{2}\sqrt{\frac{365}{\pi.\alpha_a}})$$

1.2.4 Heat transfer between soil and UGP

Heat transfer between soil and air the exchange of heat between the soil and the air passing through a buried pipe is governed by the difference between the air and soil temperatures. The exchange induces a variation in the air temperature and at the same time that of the soil around the pipe (Deglin et al., 1999). The rate of heat transfer is to be calculated by dividing the overall temperature difference by the total thermal resistance as indicated by ASHRAE (2012):

$$q = \frac{(T_f - T_s)}{R_t} \quad (2)$$

1.2.5 Total Resistance

In order to calculate the heat transfer between the earth tube and the surrounding soil, the overall thermal resistance (Rt) should be determined using the following three thermal resistance values (Lee and Strand, 2008).

$$R_t = R_c + R_p + R_s \quad (3)$$

1.2.6 Air Resistance

Thermal resistance due to convection heat transfer between the air in the pipe and the pipe inner surface ($\boldsymbol{Rc}$) calculation, Thermal resistance Rc in Eq. 3 is calculated by the following Eq. according to Al-Ajmi et al. (2006); Ascione et al. (2011); Lee and Strand (2008) and Lee and Strand (2006):

$$Rc = 1 / 2\pi r_1 hc \quad (4)$$

1.2.7 Pipe wall Resistance

Thermal resistance due to conduction heat transfer between the pipe inner and outer surface ($\boldsymbol{Rp}$) calculation: Thermal resistance (Rp) is calculated by the following equation according to Al-Ajmi et al. (2006); Ascione et al. (2011); Lee and Strand (2008) and Lee and Strand (2006):

$$Rp = 1/2\pi\ kp \ln [\ _1 + r_2 / r_1] \quad (5)$$

1.2.8 Soil Resistance

Thermal resistance due to conduction heat transfer between the pipe outer surface and the undisturbed soil ($\boldsymbol{Rs}$) calculation: Thermal resistance due to conduction heat transfer between the pipe outer surface and the undisturbed soil (Rs) is calculated by the following Eq. according to Al-Ajmi et al. (2006); Ascione et al. (2011); Lee and Strand (2008) and Lee and Strand (2006):

$$Rs = 1/\ 2\pi k_s \ln [\ _1 + r_2 + r_3 / r_1 + r_2] \quad (6)$$

1.2.9 heat transfer

is the convective heat transfer coefficient at the inner pipe surface, the convection heat transfer coefficient (hc), inside the pipe is calculated using the following equation according to Al-Ajmi et al. (2006); ASHRAE (2009) and Maerefat and Haghighi (2010):

$$hc = Nu.ka/2r_1 \quad (7)$$

1.2.10 Nu, Reynolds, Pr

To calculate the convective coefficient, it is necessary to know the characteristics of the flow using dimensionless numbers: Nusselt number, Reynolds number and Prandtl Number. Nusselt number is calculated by the following equation for turbulent flow of air and Re number is higher than or equal to 10000 according to ASHRAE (2009):

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \quad \text{for heating} \quad (8)$$

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.3} \quad \text{for cooling} \quad (9)$$

Reynolds number in Eqs. 8 and 9 characterizes the mode of the flow according to ASHRAE (2009):

$$Re = \rho_a v.D\mu a \quad (10)$$

Prandtl number in Eqs. 4.21 and 4.22 characterize the relationship between the viscosity and the thermal diffusivity of the fluid according to ASHRAE (2009):

$$Pr = c_a \mu_a\, k_a \quad (11)$$

1.2.11 length of ETAHE

Using the previous calculation, the total length of the ETAHE is to be calculated from the following:

$$l = q.Rt\,(Tf - Ts) = \dot{m}\, c(Tf - Tout).Rt\,(Tf - Ts)\ \dot{m} = \rho_a * v * A_p \quad (12)$$

1.2.12 Air flow rate Air flow rate

is to be calculated by the following Eq.:

$$\dot{m} = \rho_a A_p v = 2\pi \rho_a r_1\, v \quad (13)$$

1.2.12 Fan power

The fan energy consumed in blowing air through a pipe is additional energy expenditure in the ETAHE system. The fan air power is given by Al-Ajmi et al. (2006):

$$Pf = \Delta P A_p\, v\, \eta_{fan} \quad (14)$$

The pressure drop in a smooth pipe is given by ASHRAE (2009) and Paepe and Janssens (2003):

$$\Delta P = f\ l\ \rho_a\ v^{2} /\ 2\,D \quad (15)$$

$$f = 64\, Re \quad \text{if } Re < 2300 \quad (16)$$

$$f = (1.82 \log Re - 1.64)^{-2} \quad \text{if } Re \geq 2300 \quad (17)$$

1.2.13 Outlet fluid temperature

Outlet fluid temperature from the earth pipe in the earth to air heat exchanger, air is the only heat transporting fluid. The heat released or absorbed by the air is flowing through the tube to the surrounding soil. If the contact of the tube wall with the earth is considered to be perfect and the conductivity of the soil is taken to be very high compared to the surface resistance, then the wall temperature at the inside of the tube can be assumed to be constant and equal to ground temperature. The total heat transferred to the air when flowing through a buried pipe can be written as (ASHRAE, 2011 and Paepe and Janssens, 2003):

$$Tout = T_s + (T_f - T_s)\exp - l/Rt\dot{m}\, c_a \quad (18)$$

$$\Delta Tm = (T_i - T_{out}) / \text{Log}\,[(T_i - T_{out})/(T_{out} - T_s) \quad (19)$$

$$Q = \dot{m}\, c(T_f - T_{out}) = l.\Delta Tm\, Rt \quad (20)$$

1.2.14 Efficiency of ETAHE

The effectiveness of earth to air heat exchanger can be defined as:

$$\eta ETAHE = (T_{out} - T_f)\,(T_s - T_f) \quad (21)$$

Table 1: input data for MATLAB software

T_{ma}	22ºC	K_a	**0.02669W/m.ºC**
A_a	24ºC	ρ_a	**1.109Kg/m^3**
T	135	μ_a	**1.941*10^{-5} Kg/m.s**
t_o	28	C_a	**1007J/Kg.m**
Pipe Data		**Soil Data**	
r_1	0.0762m	K_s	**0.78W/m.ºC**
r_2	0.0015m	ρ_s	**1935Kg/m^3**
r_3	0.0777m	α_s	**0.037M^2/day**
L	31m		
K_p	205W/m.ºC		

Table 2: Physical Properties of the study area [6]

Properties		Soil
Compaction Characteristic (Modified Method)	Optimum dry unit weight (kN/m3)	17.83
	Optimum moisture content %	13
Atterberg limits	Liquid limit (L.L)%	28
	Plastic limit (P.L)%	N.P
M.I.T Classification	Sand	81
	Gravel	17
	Fines	2
Minimum dry unit weight, (γmin) kN/m³		11.21
Maximum dry unit weight, (γmax) kN/m³		16.75
Field unit weight, (γf) kN/m³		13.73
Unified Soil Classification		SP
Coefficient of uniformity (CU)		0.86
Coefficient of curvature (CC)		6.63
Relative density, (Dr) %		55.5
Moisture content, (ω)%		1.86
Specific gravity, (Gs)		2.58

Table 3: Chemical Properties of the study area [6]

Sample Symbol	Soil
PH value	8.01
Gypsum content %	42
Total sulphate content (T.D.S.)%	46

2.2 Analytical modelling of UGP Using ANSYS

Using ANSYS FLUINT 15.0 software for the simulation and purpose of the cooling system, where a mathematical model was employed as shown in Figure (3), the simulation data for ANSYS software for the purpose of finding the results shows in Table 4.

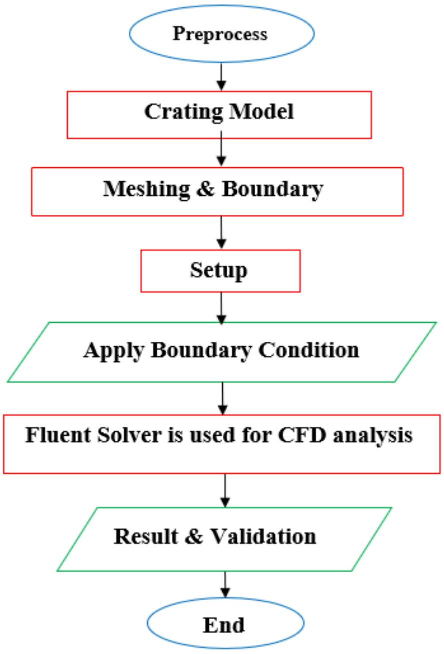
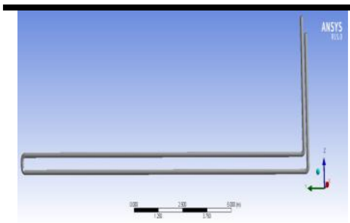
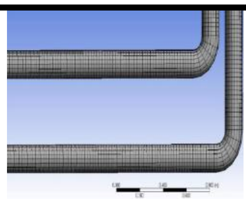


Figure. 3: Flowchart for Ansys Model

Table 4: Simulation data required for ANSYS software

Design modeler	Mesh	Boundary Condition
	 Nodes : 193831 Elements: 130251 Transition: Slow Smoothing: Fine	Pipe :Stationary walls Inlet :Velocity inlet with time varying profile Outlet :Pressure outlet

3.0 Methodology

This aspect displays the designs and tests that have been performed.

3.1 Materials and Equipment's

The main objective of this research is to establish a cooling system based on the principle of heat exchange by taking advantage of the earth's temperature. The specifications of the used aluminum pipe and operating conditions are explained. The designed cooling system consists of a test room, an underground heat exchanger pipe, where a trench was made 16 meters, 3.25 meters deep, 1 meter wide, and 10 cm Thickness layer of soft sand is put in place to increase the conductivity between the thermal exchanger and the surrounding soil as shown in Figure 4. An aluminum pipe of 15.2 cm in diameter and 31 meters in diameter was placed inside, temperature sensors were installed and the hole was sanded.

Figure .4: trench ditch.

3.2 Experimental study

All the system data such as, design and work parameters are recorded using three sensors: temperature, solar meter and humidity sensors. All the tests are carried out in summer season (May - July months) with different parameters. The temperatures of air which enters and exits from the underground heat exchanger pipe, soil, test room, ambient air was recorded by thermocouples. The circulated flow rate of air was measured by using anemometer. Experiments have been repeated several times to ensure accuracy of reading and measurement. as shown in Figure 5:

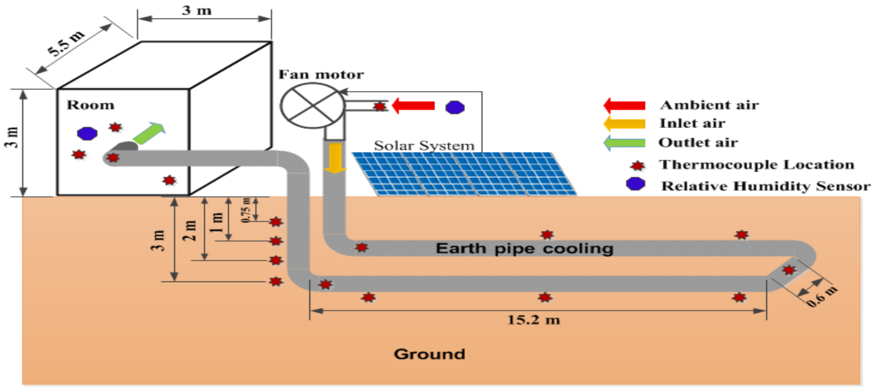


Figure .5: system of Underground pipe and solar chimney.

3.3 Site of Test

All tests were conducted in Tikrit/Iraq city (34. 35°N, 43.37°E), with a diverse climate, hot and dry in summer and spring (May - July months) where the maximum temperature of ambient up to 44^{0}C. with annual average ambient temperature of 33 °C. The other metrological data (maximum and minimum temperature, Sunshine period, solar intensity) are measured and presented in Table 5.

Table 5: Metrological data that measured for Tikrit

Month	Mean solar intensity (w/m^2)	Mean sunshine period (hours)	Mean temp. (Max) ^{0}C	Mean temp. (Min) ^{0}C
May	710	9.7	34	23
June	770	11.6	44	28
July	795	11.3	46	32

4.0 Experimental setup

The study was carried out on a test room made of a compressed Sandwich Panel material (5.5 x 3 x 3) m^3. The test room connected with the Underground heat exchanger pipe.

4.1 Design of Underground Heat Exchanger Pipe

Underground heat exchanger pipe made of Aluminum material U-shaped available in local markets with dimensions (length of 31 m and 15.2 cm diameter), 0.6 m the distance between two line as shown in Figure 6. Use aluminum because available in domestic markets, low cost, high conductivity, corrosion resistance, and good physical properties as shown in Table 2. The tests were conducted during May to July months in the research area of Tikrit / Iraq and recorded readings per hour. The sensors used to measure the temperature inside the soil, solar Chimney and test room. The relative humidity sensor fixed inside and outside the test room.

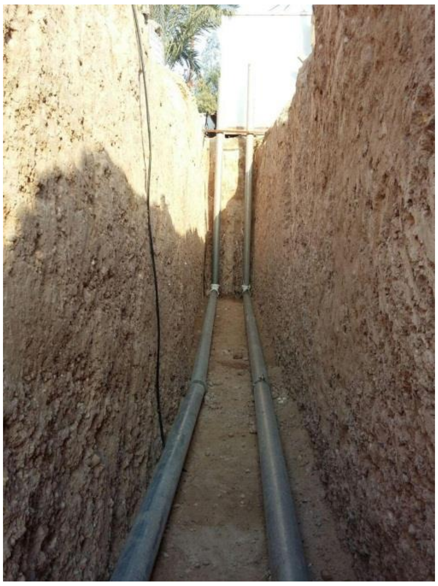


Figure .6: Underground heat exchanger pipe.

Table 6: Physical properties of Aluminum [1]

Thermal conductivity (W/cm)	Tensile resistance (Kg/mm^2)	Density at 20 ºC (g/cm^3)	Flexibility factor (Kg/mm^2)	Fusion point (ºC)
2.18	6.3	2.7	7250	660.1

4.2 Measuring the temperature of the earth

Knowledge of earth temperatures and the factors that determine soil temperature as well as an understanding of how temperatures vary with time and depth is essential to determine the appropriate depth of the geothermal heat exchanger. As the test was performed using (6) thermocouples to measure the soil temperature at different depths (0.25, 0.5, 0.75, 1, 1.5, 2, 3 m).

4.3 Test Room

The test room is manufactured of compressed Sandwich Panel with thickness 15 cm, dimensions $5.5 \times 3 \times 3$ m^3, the room contains a door in dimensions 2×1 m^2, and contains windows in dimensions 1×1 m^2, and it's connected to the underground heat exchange pipe from the bottom of the wall of the room. as shown in Figure (7).

Figure .7: Test room.

4.4 Solar system

The solar system was used for the purpose of equipping the system with electricity continuously in case of power outages, the parts of the system shown in Figure (8).

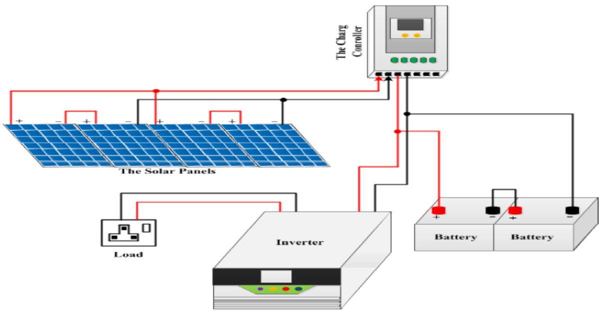
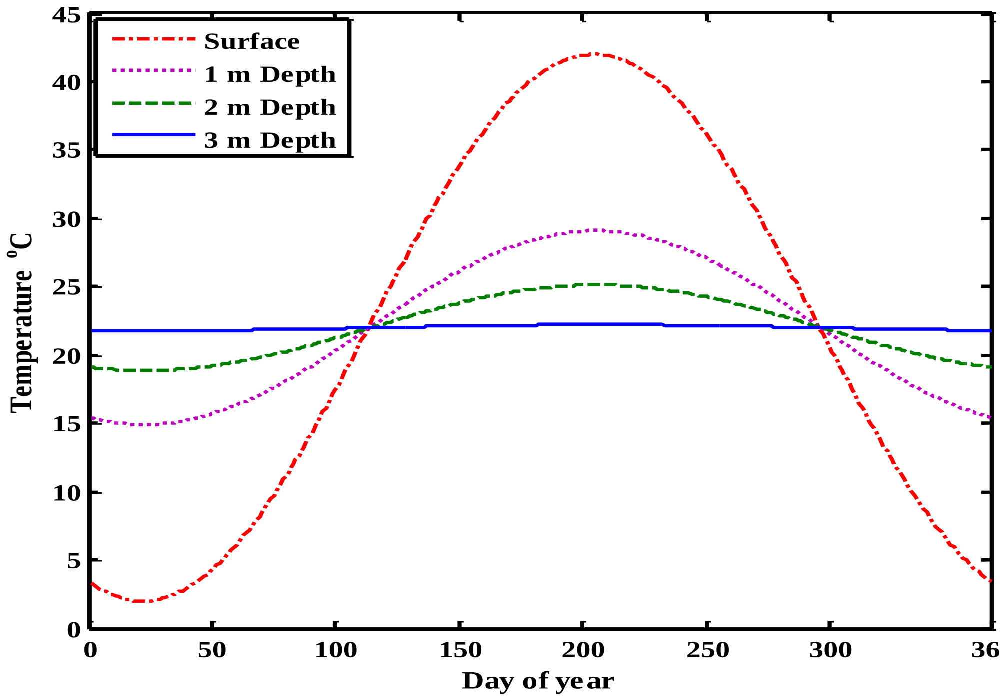


Figure .8: Solar system.

Figure .8 show the predicted soil temperatures at different soil depths for the whole year. It could be seen that the temperature fluctuations decreased with soil depth illustrates the amplitude of soil temperature at various depths. It could be seen that with increasing depth under the soil surface the amplitude of temperatures decreased. At a depth of 2 to 3 meters, the maximum Earth temperature occurs about 6 months after the average maximum surface temperature in summer and at a depth of about 3 meters, the temperature is insensitive to any surface changes. Thus, a depth of 3 m is the preferable depth to installation an earth tube for geothermal energy system.



Data in Table 5.1 and Figs. 5- a, b, and c show the comparison between the predicted and measured soil temperatures at different depths (2, 3, and 4 m). It could be seen that the measured soil temperature ranged from 24 to 26°C at 1 m depth, 23 to 24 °C at 1 m depth, and for the depth of 3 m, the temperature is be constant at 21ºC depth. The mean difference between the Earth's temperature at depth (m2) and the temperature at depth (m3) is equal to (ºC3). we notice that the change in the Earth's temperature at depths (m3and 2, 1) is stable and the decrease in the earth's temperature with the increase in depth, and the reason for this is due to the influence of weather conditions decreasing with increasing depth

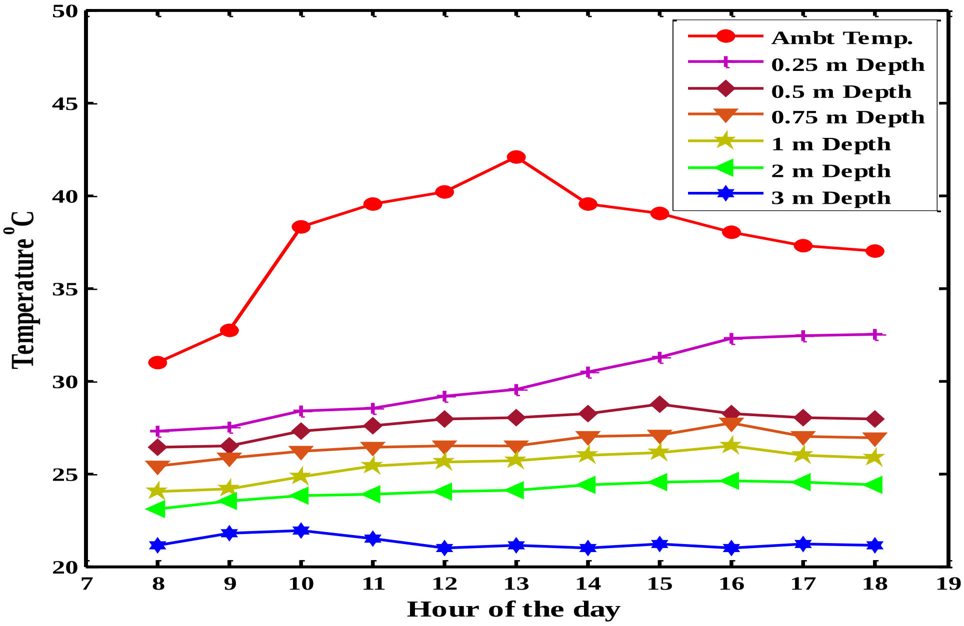


Figure (9) shows the distribution of air temperatures inside the geothermal heat exchanger at an air flow (Q= 459.67). As it becomes evident that the air temperature decreases from (43 ºC) at the start of the geothermal heat exchanger to (28 ºC) at the end of the geothermal heat exchanger, and we also notice that the temperature of the outgoing air increases with the increase in air velocity due to the lack of sufficient time for heat exchange.

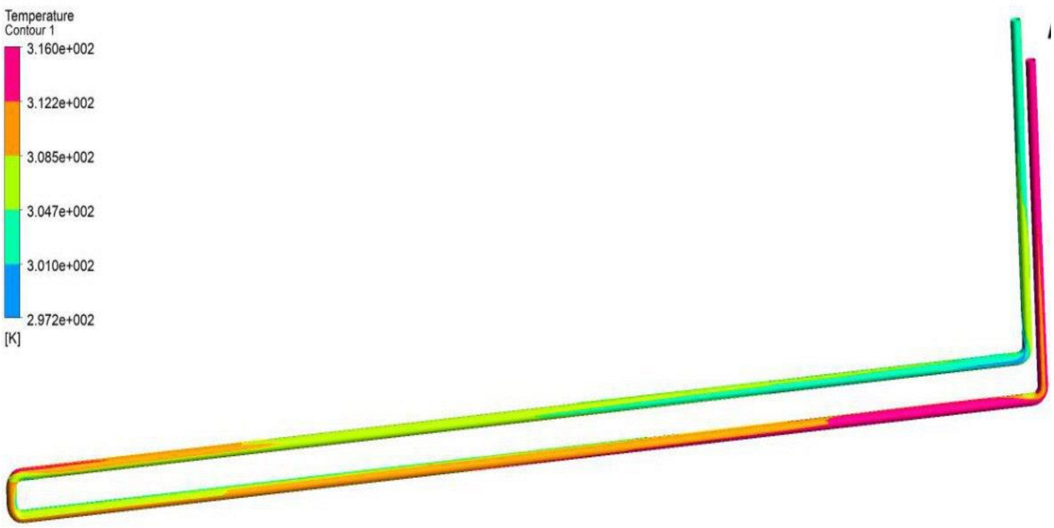


Fig (9) shows the distribution of air temperatures inside the geothermal heat exchanger at an air flow (Q= 459.67).

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