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Performance Analysis of Geothermal Heat Pump with Helical Ground Heat Exchanger in Syria

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Abstract - GSHP (Ground Source Heat Pump) system is a highly sophisticated technology for cooling and heating buildings worldwide. Unfortunately, this technology is not available here in Syria, however it is time to start thinking about applicable ways that enable us to make use of the advantages of this promising technology here is Syria because of its high performance. Aiming for this exact purpose, an experiment was installed at the Faculty of Mechanical and Electrical Engineering, Damascus University in Syria. First, to evaluate the optimal parameters of the GSHE (ground source heat exchanger), the performance of a helical GSHE was analyzed experimentally and analytically. The heat pump cycle (Carnot cycle) was analyzed, also dryness factor, subcooling, coefficient of performance, response of GSHE were analyzed.

The findings of this experimental study, will be used to evaluate the COPhp (coefficient of performance of the heat pump) which are ranged between 2.3-4.7. The results showed that the use of the ground source heat pump is appropriated for cooling buildings in Syria, which has hot climate, as a substitutional solution of traditional air-cooled heat pump.

Index Terms: Geothermal energy. Ground source heat pump. Helical heat exchanger- experimental study.

I. INTRODUCTION

Air conditioning systems maintain a comfortable temperature for humans inside air-conditioned buildings, and this requires consuming of energy that is powered by electricity or fossil fuels. The Earth absorbs 46% of the solar energy that falls on the atmosphere, and this enormous energy can be used to cover the needs of air conditioning systems [1]. Heat pumps are nowadays widely used for heating and air conditioning buildings. These machines rely on the reverse Carnot cycle

principle to extract heat from one place and transfer it to another place with the help of an external power source

(mostly electricity). GSHP (Ground Source Heat Pump) are defined as ground source heat pumps and provide heating of

buildings and water heating by extracting the necessary heat from the ground and providing cooling in the opposite process [2]. The earth is characterized by a lower temperature in summer and a higher temperature in winter compared to the temperature of the outside air for both the surface and deep layers. The surface layers isolate the deeper layers from the outside air, which causes the temperature of these layers to remain constant. (all year round) [3] As a result of these advantages, electrical consumption decreases and the efficiency of geothermal pump systems increases compared to conventional systems. Either horizontal or vertical heat exchangers are usually used in ground source heat pump systems, and vertical exchangers have a set of advantages as they require small areas of land compared to horizontal ground source heat pump systems [4]. The relatively large drilling depths lead to a relative stability in the temperature of the ground and thus stability in the work of the system, as well as the use of a relatively small number of pipes compared to other ground source heat pump systems [5]. (use a name instead of the pronoun) disadvantage is the high foundation cost due to the high cost of drilling, as the drilling depths reach 80 meters. As for the horizontal exchangers, their advantages are: the low cost of the foundation cost compared to the vertical systems due to the low cost of drilling and the simplicity of design and implementation [6]. The disadvantages are: the need for large areas of land and fluctuations in the performance of the system unit as a result of the fluctuation of the ground temperature at low depths due to rainfalls and the change in the ambient temperature in addition to the lower coefficient of performance

II. Helical Geothermal Exchanger:

Helical GSHE is classified as horizontal heat exchanger. The use of this type leads to a greater reduction in the required area, as the required length of the trench is reduced by 80-70% of the required length for the trench of the single tube exchanger, but the required length of the tubes increases by twice as well [3]

The advantages of dual performance horizontal geothermal pump systems are ordered as follows [7]:

1- The set-up cost is low compared to the vertical systems due to the low cost of drilling.

2- The simplicity of installation and design.
3- Possibility to access to the exchanger and the ability to monitor the topsoil.

The disadvantages of dual-performance horizontal geothermal pump systems are set as follows [7]:

1- requires large areas of land.
2- Fluctuations in the performance of the heat pump unit as a result of the fluctuation of the ground temperature at low depths due to precipitation and change in the ambient temperature.
3- The power required for the circulation pump is slightly higher.
4- Lower system coefficient of performance (COP)

III. Experimental Unit [8]

The experimental unit consist of a geothermal helical exchanger. It was linked to a ground source heat pump circuit, which is used to conditioning a room throughout the year.

The heat exchanger consists of PEX pipes with a nominal diameter of 32 mm. The test set for thermal response behavior is a (Soil/water)-air heat pump.

FIG. 1. VIEW OF THE GHE BURIED IN 3 M DEPTH

III.I. Experimental Unit Description

The experimental unit shown in Fig 2 consists of 3 main elements.

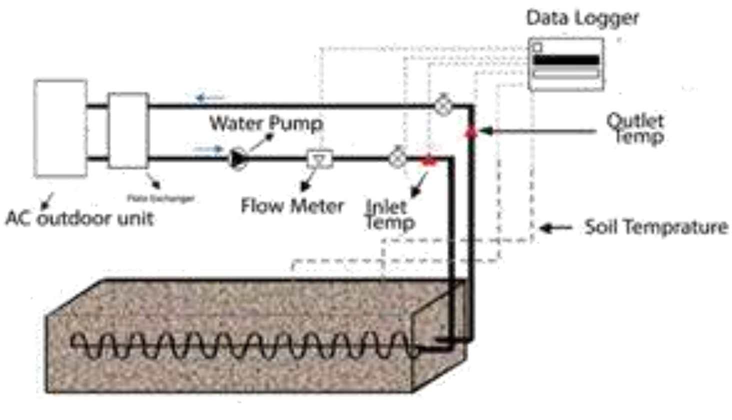

FIG. 2. SCHEMATIC DIAGRAM OF EXPERIMENTAL UNIT

1- Split air conditioner

Split Split air conditiner with an actual capacity of 0.9 tons. Working refrigerants is R22, the air condenser and the fan were uninstalled and replaced with ground source heat exchanger, pump and plate exchanger.

2- Plate heat exchanger

Water – Freon Plate heat exchanger used for heat exchange between the refrigerant, Freon R22, which is located in the inner part of the air conditioner and the compressor, as well, and between the water heading to the soil passing through the pex tubes that form the geothermal exchanger

3- Ground source heat exchanger

GSHE are usually made of HDPE high-density polyurethane pipes, but pex pipes, diameter 32 mm, were used to experiment another type of pipes, and the HDPE available in the local market are of medium quality. The tubes above the soil were insulated with Armaflex insulation to reduce heat waste.

Here are the design equations of the Helical GSHE

When dealing with internal flow, it is important to determine the region of the extent of entry, which depends on the type of flow, whether it is laminar or turbulent, by calculating the Reynolds number according to the following relationship

$$Re = \frac{D \times V \times \rho}{\mu}$$

Whereas:

D: pipe diameter [m]

V: fluid velocity[m/s]

ρ : fluid density [kg/m^3]

μ : viscosity [N.S/m^2]

Nusselt and Brandl numbers, the dimensionless numbers that express heat transfer by forced convection, are calculated from the following equation [16,17]:

$$Pr = \frac{\mu \times C_p}{k}$$

C_p : specific heat [j/kg.°C]

k : conduction heat transfer coefficient [W/m.°C]

fluid flow:

$$m = \frac{Q}{C_p \ \times \Delta t}$$

Q :heat flow [W]

Δt :temperature difference [°C]

fluid velocity:

$$V = \frac{m \times \rho}{A}$$

A :cross area[m^2]

To calculate Nusselt number in a circular section pipe, Nusselt equations are applied and then verify the conditions corresponding to the case of the studied exchanger, taking into account that the flow is turbulent in the studied exchanger

Detus Buetler's equations:

$$Nu_o = 0.023 \ Re^{0.8} Pr^{0.4} \quad for: t_{wall} > t_{fluid}$$

$$Nu_o = 0.02 \ Re^{0.8} Pr^{0.3} \quad for: t_{wall} < t_{fluid}$$

$$For: \begin{cases} 0.7 < Pr < 120 \\ 10{,}000 < Re < 160{,}000 \\ L/D \;\; > 10\ (50?) \end{cases}$$

Nu_o :Nusselt number

t_{wall} :temperature of the pipe wall[ºC]

t_{fluid}: temperature of the fluid [ºC]

Or:

$$Nu_o = \frac{\left(\frac{f}{8}\right)(Re - 1000)\ Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)}$$

$$where \quad f = (0.790 \ln Re - 1.64)^{-2}$$

$$For: \begin{cases} 0.5 < Pr < 2000 \\ 3000 < Re < 5 \times 10^6 \end{cases}$$

Or:

$$Nu_o = \frac{\left(\frac{f}{8}\right)(Re - 1000)\ Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)}\left[1 + \left(\frac{D}{L}\right)^{\frac{2}{3}}\right]$$

$$where \quad f = (0.790 \ln Re - 1.64)^{-2}$$

$$For: \begin{cases} Pr > 0.7 \\ Re > 2300 \end{cases}$$

where f is the roughness of the inner surface

Then temperature correction equation is applied to calculate the convective heat transfer coefficient:

$$h = h_o\left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

$$h_o = \frac{Nu_0 \times K}{D}$$

Whereas:

μ_b : water viscosity [N.S/m^2]

μ_w : pipe viscosity [N.S/m^2]

h : Convection heat transfer factor [W/m^2.ºC]

The heat transfer coefficient by conduction through a pipe or soil is given by:

$$h_{p\ Or\ S} = 2k/(d_i \times \ln\left(\frac{d_o}{d_i}\right))$$

Thus, the overall heat transfer coefficient by convection and conduction is:

$$U = \frac{1}{h + h_p + h_S}$$

The heat exchange area is:

$$A = \frac{Q}{U \times \Delta t}$$

Exchanger pipe length:

$$L = \frac{A}{\pi \times d_i}$$

pressure drop of the exchanger

$$\Delta p = \frac{0.6 \times L \times f \times V^2}{d_i}$$

The hydraulic power required for pump is

$$P = \frac{\Delta p \times \dot{V}}{\eta}$$

the volume of the roll is calculated from the equation

$$V_{turn} = \frac{\pi \times D_{turn}^2 \times X}{2}$$

D_{turn}: the diameter of the turn [m]

X: distance between 2 turns which must be 0.6[m] at least to avoid heat overlap between the turns

The number of turns

$$N = L/Per$$

Per: perimeter of the turn

The volume of the exchanger

$$V_{HX} = N \times V_{turn}$$

The extra length factor or the so-called safety factor is used to express the effect of secondary bending and flow on the heat transfer of the tube-helical exchanger and thus correcting the length of the tubular exchanger by multiplying it by the correction factor given in the equation [11]:

$$F_{helical} = 1 + 3.6\left(1 - \frac{r_i}{R_c}\right)\left(\frac{r_i}{R_c}\right)^{0.8}$$

r_i : radios of exchanger pipe

R_c: diameter of exchanger turn

The range of application of this correction factor is relative to the Reynolds number

$$2 \times 10^4 < Re < 1.5 \times 10\text{^}5$$

$$5 < \frac{R_c}{r_i} < 8$$

Table 1

Design Properties of used GSHE

PARAMETER	VALUE
EXCHANGED HEAT [W]	3150
INNER DIAMETER [MM]	32
TURN DIAMETER [M]	1.5
DISTANCES BETWEEN TURNS [M]	0.6
TOTAL LENGTH OF PIPE [M]	60
NUM. OF TURNS	8.6
PUMP CAPACITY [W]	121
PRESSURE DROPS [PA]	839
EXCHANGER VOLUME [M^3]	9.1

A coated with epoxy metal pipes, 120 m length, were used as fins to increase heat transfer to soil and the conductivity of the soil

FIG. 3. VIEW OF THE GSHE WITH METAL FINS

There are also some supplementary components such as: water pump 0.5 HP, expansion tank 25 L and gate valves.

III.II. Measurement devices and instrument

1- Flow meter

Used to measure water flow in the GSHE

2- Thermo cable

PT100 thermo cable to measure the temperature of Freon and water at the inlet and outlet of the plate exchanger, soil temperature, and the temperatures along the GSHE in five positions. The sensor is connected with Digital temperature converter (DTC) and data logger (HMI screen) to store the data.

3- Temperature and humidity sensor

temperature sensor, with a screen, to measure the temperature of the suction and discharge of the compressor and the temperature of supply and return air of the indoor unit of the air conditioner. The device is also equipped with a sensor to measure the humidity of the air.

4- Manifold

used in refrigeration cycles to check operating pressures and charge the air conditioner with refrigerant, and it is used to measure the suction and discharge pressures during operation.

5- AVO meter

Used to measure operating voltage

6- Ampere clamp meter

Used to measure the current during operation

7- Anemometer

Used to measure the speed and flow rate of the supply air of indoor unit.

FIG. 4. VIEW OF THE EXPERIMENTAL UNIT

Table 2

Measurement devices and instrument properties

Parameter	Measurement instrument	Unit	Range	Accuracy
Water flow rate	Flow meter	L/s	0~25	±1%
Air velocity	Anemo meter	m/s	0.4~25	±2%
Air flow rate	“Fluke 925”	m^3/s	0.01~99.99	±2%
Temperature	PT100	ºC	-200~850	± 0.3 ºC
Humidistat	Relative Humidity	%	10~99%	±1%
Ampere	Ampere clamp meter	A	0~50	±0.5%
Voltage	AVO meter	V	0~600	±1%
Freon pressure	manifold	Psi	0~500	±0.1%
Water pressure	Pressure gauge	bar	0~6	±1%

FIG. 5. MEASUREMENT DEVICES AND INSTRUMENT

IV. Climate and Soil Properties:

The thermal properties of the soil, conductivity and diffusivity can be obtained by taking samples from the geological layers at the site of the exchanger installation and analyzing them in the laboratory to know their composition, then comparing this composition with the types mentioned in Table 3 to obtain the optimal values

Table 3 [9]

Thermal Conductivity and Diffusivity of Sand and Clay Soils

Soil Type	Dry Density kg/m^3	5% Moist K	a
Coarse 100% Sand	1920	2.08-3.29	0.089-0.139
	1600	1.38-2.42	0.072-0.121
	1280	0.87-1.9	0.056-0.121
Fine Grain 100% Clay	1920	1.04-1.38	0.045-0.059
	1600	0.87-1.04	0.045-0.054
	1280	0.52-0.87	0.033-0.056

Soil Type	Dry Density kg/m^3	10% Moist K	a
Coarse 100% Sand	1920	2.42-3.46	0.086-0.121
	1600	2.08-2.6	0.089-0.111
	1280	1.04-1.9	0.056-0.102
Fine Grain 100%	1920	1.04-1.38	0.049-0.037
	1600	0.87-1.04	0.037-0.045

Clay	1280	0.61-0.87	0.033-0.046

Soil Type	Dry Density kg/m^3	15% Moist K	a
Coarse 100% Sand	1920	2.40-3.81	0.085-0.111
	1600	2.25-2.77	0.083-0.102
	1280	1.04-2.08	0.047-0.093
Fine Grain 100% Clay	1920	1.38-1.9	0.043-0.059
	1600	1.04-1.21	0.034-0.045
	1280	0.69-0.95	0.032-0.04

Soil Type	Dry Density kg/m^3	20% Moist K	a
Coarse 100% Sand	1920	-	-
	1600	2.42-2.94	0.078-0.093
	1280	1.21-2.08	0.048-0.084
Fine Grain 100% Clay	1920	-	-
	1600	1.04-1.38	0.038-0.051
	1280	0.69-1.04	0.028-0.042

These values were obtained by calculating the mean of the calculated values using five different methods.

The temperature of the ground is determined by direct tests at the geothermal site or by using geothermal maps approved by geological institutions, or by relying on publications issued by institutions working in the field of geology. Table 4 shows soil temperatures for some cities in the world at a depth of 10 meters.

Table 4 [9]

soil temperatures for some cities in the world at a depth of 10

Country	City	GT °C	Country	City	GT °C
Syria	Damascus	22	USA	Dallas	20
Egypt	Cairo	23	KSA	Riyadh	28
UAE	Dubai	27	Qatar	Doha	28
Spain	Madrid	16	Kuwait	Kuwait	27
Germany	Berlin	11	Bahrain	Manama	27
France	Paris	12	*Tunisia*	Tunis	21
Finland	Helsinki	8	Turkey	Ankara	11
UK	London	12	Japan	Tokyo	18
Italy	Rome	16	China	Biking	12

Australia	Sydney	19	China	Hong Kong	25
USA	Miami	26	Brazil	Brasilia	27

The following equations can also be used to calculate Soil temperature at different depths [1]:

$$T_{g,Max} = \overline{T_g} + A_S \times e^{(-X_S \sqrt{\frac{\pi}{365\times a}})}$$

$$T_{g,Min} = \overline{T_g} - A_S \times e^{(-X_S \sqrt{\frac{\pi}{365\times a}})}$$

Whereas: $T_{g,Max}$ is the ground temperature in the summer and $T_{g,Min}$ in winter, X_S the depth, A_S is the annual surface temperature amplitude, and $\overline{T_g}$ the mean annual surface soil temperature.

The experimental unit were installed in DAMASCUS 33 41 N, 36 51 E, 1998 feet (609 meters) above sea level [10]. Fig 6 shows the maximum temperature in summer of the ambient air

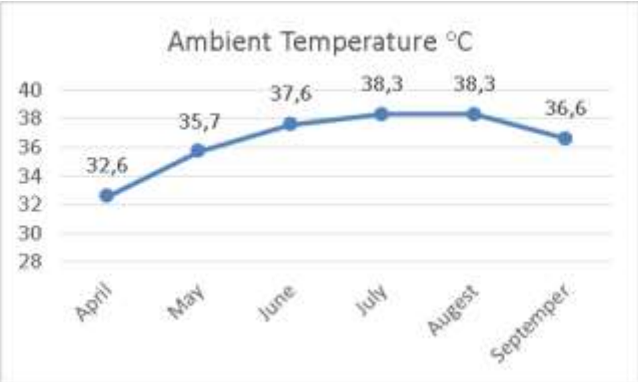

FIG 6. MEAN VALUES OF OUTDOOR AIR

The indoor unit of the air conditioner is installed in a 12 m^2 room and the total estimated cooling load is 3 Kw and the direction of the external wall is east [12,13]. the relation between the solar gain and the cooling load is clarified in Fig 7

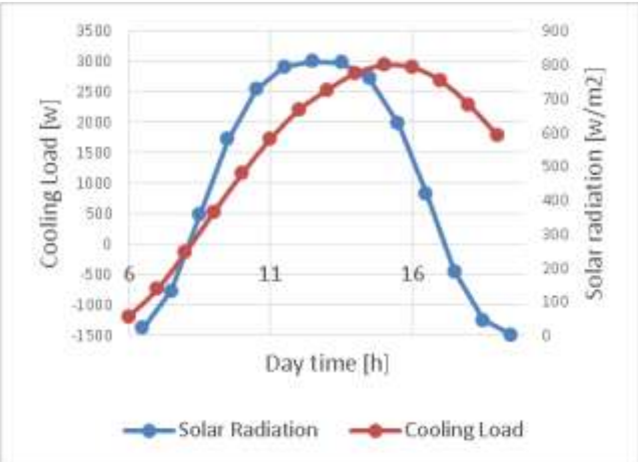

FIG 7. COOLING LOAD OF THE EXAMINED ROOM

V. Results and discussions:

Testing and collecting data phase was after finishing the commissioning of the unit and the calibration of R22 Charge [14].

At the beginning, the system must be given an of about 3- 4 hours. for the data to stabilize, and the unit was being run continuously for 8-12 hours a day, the results were being collected for one month (August – 2021). Temperatures were being collected using the HMI screen, which are: Temperatures at the inlet and outlet of the plate exchanger from the water side and from the Freon side, and the temperatures along the geothermal exchanger and soil temperature.

Fig.8 shows the required capacity of the AC to conditioning the room during one day of operation from morning to evening, according to the calculated cooling load of the room which variate with the change of solar radiation. It's clear that the AC capacity is not sufficient for the air-conditioned room at the peak time from two to four o'clock approximately. the obtained results show that the capacity of the plate exchanger, 1 ton, used in the unit is not sufficient due to its low efficiency.

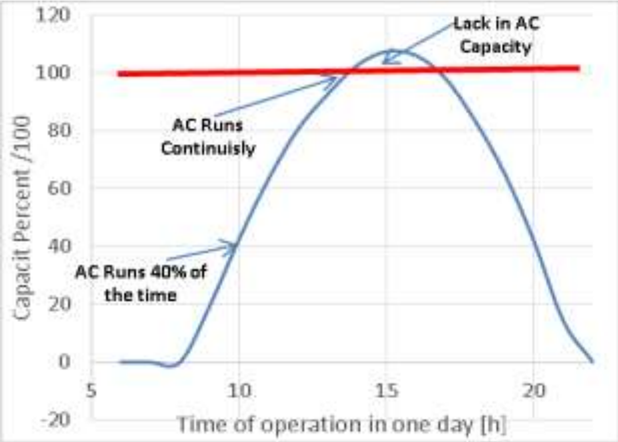

FIG 8. AC CAPACITY VS ROOM LOAD

Fig 9 shows the temperature of the refrigerant R22 at the inlet to the compressor (t1) it's clear, there is superheating about 1 to 26 °C in the evaporator. Thus, the refrigerant enters the compressor in the state of superheated steam and without drops of refrigerant liquid, which protect the compressor from damage. The manufacturer of air conditioners chose the evaporating temperature to be about 5-7 °C

and the superheating is: $\Delta t_h = t_1 - t_o$

Fig 9 also shows t3, which is the temperature at the outlet of the condenser. It's clear that the condensation temperature

of the refrigerant is 40 degrees, by comparing t3 with subcooling in Fig 10, subcooling is: $\Delta t_c = t_c - t_3$

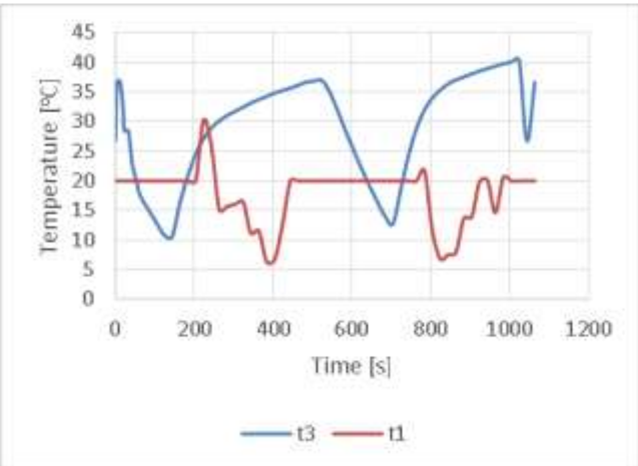

FIG 9. TEMPERATURE AT THE INLET OF THE COMPRESSOR, AND THE OUT LET OF THE CONDENSER

Fig 10 shows the subcooling in the condenser during the operation of the air conditioner, $\Delta t_c = -1$ at several operating points. This indicates that the refrigerant does not condense completely while it passes through the plate exchanger. This is because the low efficiency of the plate heat exchanger. Also it's noted that, Δt_c is up to 25 degrees, which is a positive thing that leads to a higher coefficient of performance.

The figure also shows the amount of dryness fraction at the evaporator inlet, and its value ranges between 0-56%, it is related to subcooling value, the lower the dryness fraction is the higher cooling productivity you get. When the dryness fraction is equal to zero this means that the entire refrigerant amount entering the evaporator is in its liquid state and it is the best condition possible.

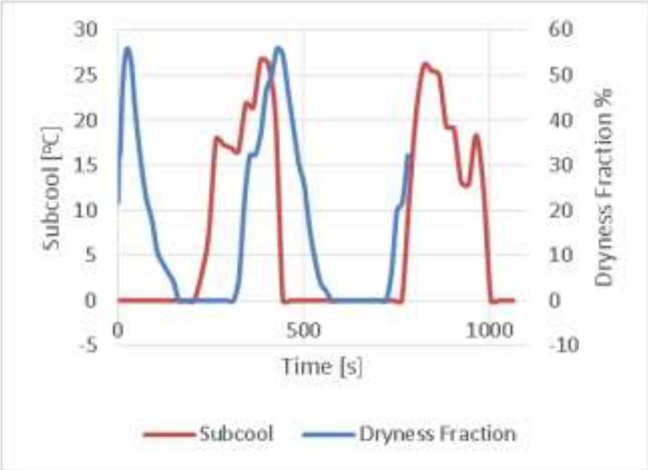

FIG 10. SUB COOL AND DRYNESS FRACTION

Figure 11-12 shows the relation between the capacity of the air conditioner and the capacity of the ground exchanger during operation. It's noted that the minimum and the maximum value of the capacity are equal, but with a time shift of 214 seconds. The figure also shows that the amount of the working wave is 592 seconds.

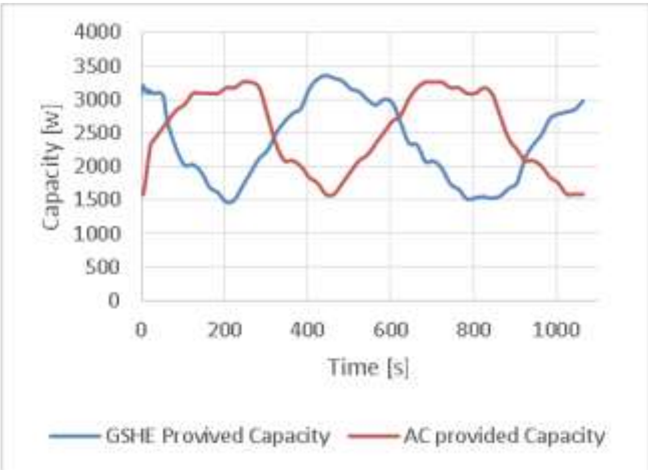

FIG 11. AC AND GSHE CAPACITY

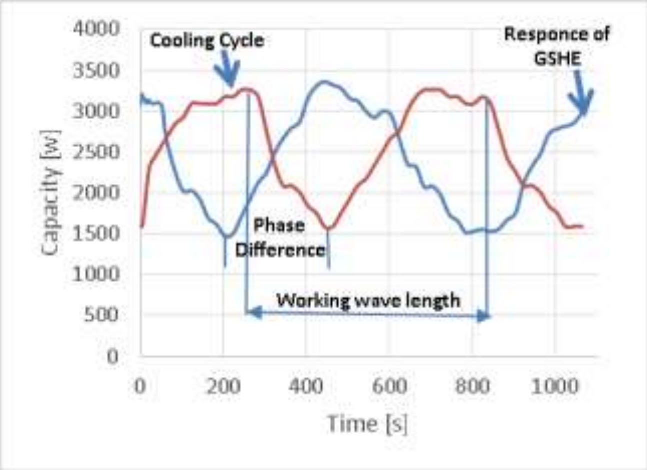

FIG 12. RESPONSE OF GSHE

Figure 13 shows the coefficient of performance of the air conditioner during operation. It's noted that its average value is 3.5, which is more than the average value of the air conditioner with an air condenser, which is about 2.6 [15] due to the lower condensation temperature in the ground condenser compared to the air-cooled condenser. The maximum value of the coefficient of performance is when increasing subcooling in its maximum value

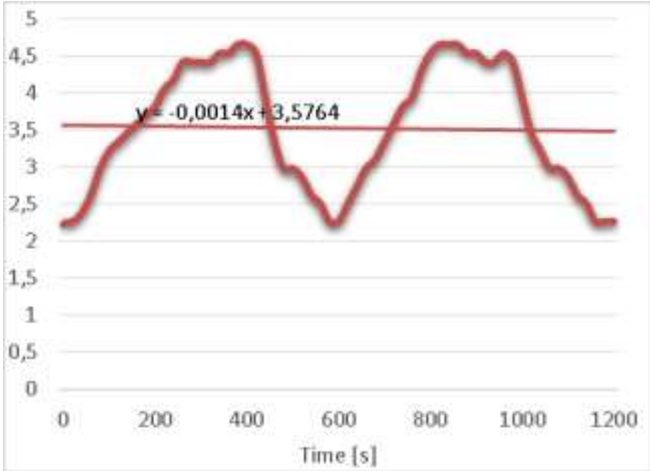

FIG 13. COOLING COEFFICIENT

I. Conclusions & Recommendations:

VII.I conclusions

Out of the previous study, the following findings are conducted:

1- Ground source heat pump can be applied in Syria with higher efficiency comparing with air cooled heat pump
2- PEX pipes can be used instead of HEPE to form GSHE with effective heat transfer to and from the soil
3- The helical exchanger can be an alternative to the horizontal and vertical exchangers in ground source heat pump applications.
4- The appropriate choice of the ground source heat pump system according to the nature of the building, its location, the available land area will affect the performance of the system
5- Using helical GGHE will reduce the initial cost comparing with vertical exchangers which require deep digging depths
6- Ground source heat pump has higher COP Values comparing with air cooled heat pump
7- The correct design of the required exchanger and appropriate for the required application ensures obtaining the required capacity from the system

VIII.II Recommendations:

1- The geothermal pump can be adopted instead of the traditional pump, especially in rural areas due to the availability of a large area of land for the exchanger to be placed
2- There is a need to study the performance of the circuit in winter, as the study was conducted in summer days.
3- Further research should be conducted on the effect of irrigating the exchanger area on the performance of the system

4- PEX tubes can be used instead of HPDE pipes, as they serve the desired purpose with exact same degree of flexibility in regard to forming coils in the case of the helical exchanger

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