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Theoretical and Experimental Study of Water Storage Tank with Earth Water Heat Exchanger in Hot Climates Regions

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Abstract

Concerning commercial and residential buildings, one of the major parts related to water supply systems is the water storage tanks. For gravity-fed buildings, the tanks must be installed on the roof. In Iraqi summer, the temperature of water in storage tanks reaches above 50 °C due to high solar intensity, which makes it inappropriate for domestic usage. One of the proposed solutions to overcome this problem is feeding the hot water into an earth-water heat exchanger (EWHE) which consists of a set of buried pipes installed underground level to reduce its temperature. The storage tank and the earth-water heat exchanger were studied experimentally and theoretically by using ANSYS 20/FLUENT software to estimating the water temperature in the storage tank and the temperature of the water leaving the EWHE. The most important results obtained theoretically and experimentally that when using pipe length, pipe diameter, and mass flow rate of 100 m, 0.016 m, 0.7 LPM respectively, at a depth of 3 m, the water temperature decreases by about 15 °C. Also, the results have shown a good agreement between the experimental and theoretical works. One can conclude that an earth-water heat exchanger is an effective way to decrease the temperature of the storage water to an acceptable level for domestic usages.

Keywords: Earth water heat exchanger, Soil temperature, Water storage tank, Water temperature, ANSYS20/FLUENT.

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1. Introduction

In summer, the ambient temperature in Iraq reaches over 50 °C due to high solar radiation. Thus, the temperature of water in storage tanks reaches 50 °C, which makes it inappropriate for domestic usage. There were no efficient local attempts for solar shedding or heat insulating regarding water tanks. One can utilize an Earth-Water Heat Exchanger (EWHE) or also referred to as underground pipes to reduce the temperatures of water storage tanks bypassing the water which flows down from tanks via heat exchangers which are buried in the ground [1] as shown in Fig. 1. Nikhil et al. [2] modeled and simulated a new system of cooling for the concentrating photovoltaic (CPV) that has been referred to as the EWHE (i.e. earth water heat exchanger). The simulation results have shown that the maximal concentrating photovoltaic (CPV) temperature level can go up to 416.36 °C at 3 Suns with no cooling and the concentrating photovoltaic (CPV) temperature can drop to 85.28 °C when using an earth water heat exchanger in the closed-loop with water flow rate is 0.022 kg/s. Joen et al. [3] produced analytical models for an EAHE and EWHE, in combination with the compact exchanger of the water-air heat. Results have shown that for the two heat exchanger types, at the higher rates of the flow, soil thermal resistance will be dominating, particularly for EWHE and CHE effectiveness has been high. Hamdan [4] studied the design of earth water heat exchanger and the viability of geothermal energy in heating and cooling systems for residential. Where studied the effect for the length of pipe and diameter and thermal conductivity of soil on earth water heat exchanger efficiency. Results showed the length of the pipe and thermal conductivity of soil were proportional inversely. Naili et al. [5] studied analytically and experimentally earth water heat exchanger in the Research and Technology Centre of Energy. Where examined the effect of water mass flow rate, volume, depth, and entry temperature of the earth water heat exchanger on the rate of the heat exchanger. Results showed that the rate of heat exchanger decreases with increased water mass flow rate and increases with increased length of pipe. Also, the results have shown good agreement between analytically and experimentally studied. Manoj et al. [6] studied theoretical and experimental analyses for the EWHE, which are utilized for cooling the photo-voltaic panels in the semi-region of Pilani, India. Experimental study results have shown that maximal temperature of the PV panel can go up to 73 °C with no cooling, and photo-voltaic panel temperature reduces in a range between 43.68 °C and 49.64 °C in the case of the EWHE with 38 m length and the rate of the 0.033 kg/s water flow. In addition to that, experimental results were validated by using the theoretical model utilizing the fundamental equations of the balance of the energy and have noticed an agreement with the error percentage of about 0.91 % to 12.09 %. Racine et al. [7] have advanced a model of optimization for the design parameters of the water heating systems, with the use of a routine of the numerical simulation, in the long-term transient regimes. Optimized designs have given the flat plate collector's area and slope, resulting in minimal cost over the lifecycle of the equipment. A thermo-siphon system of the solar water heating with the flat-plate collectors for the climate of Sao Paulo has been simulated and analyzed in economic terms in the case where it has been more attractive for increasing the solar energy gain in the period of the winter, with consequences of reducing the gains of the solar energy throughout the year, or for the adoption of sufficient slope, improving the annual gain of the solar energy. Han et al. [8] have conducted a study of a variety of research approaches and thermal stratification tank types, and energy storage reasons with problems of efficiency that are associated with applications have been presented, and the advantages that were presented by the thermal stratifications have been pointed out. The designs of the structure that has been based upon the theoretical predictions of the thermal-stratified water tanks performed at numerous organizations have been presented and compared against the results of the experimentations.

The aim of the present study is reducing the water temperature of the storage tank in hot climates regions by using an earth water heat exchanger which is designed with a new type of pipes (polyethylene multilayer composite pipes), to improve heat transfer between the water and soil. The current work includes:

1. Experimental study of the water storage tank with an earth water heat exchanger.
2. Theoretical study of the water storage tank with an earth water heat exchanger by using ANSYS 20/FLUENT.

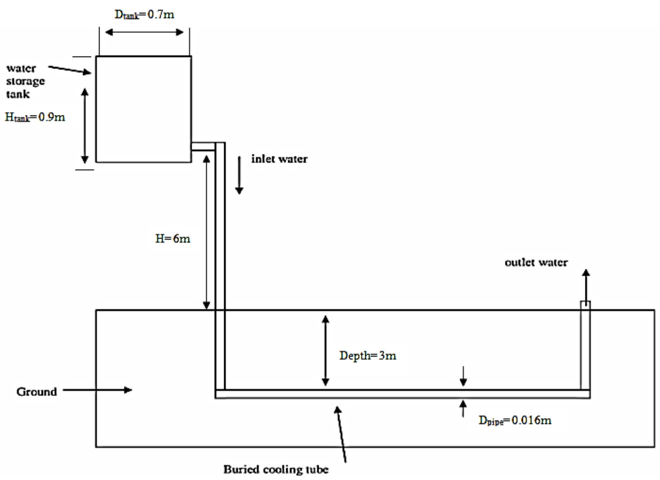

Fig. 1 diagram of a water storage tank with EWHE.

2. Description of the experimental

The experimental study has been performed by measuring the ambient temperature and the soil temperature in Najaf city at different soil depths. The ground surface temperature, and soil temperature at 1 m, 2 m, and 3 m depths were measured by four thermocouple type K sensors, one installed at the ground surface and the others at 1 m, 2 m, and 3 m depths as shown in Fig. 2.

Fig. 2 setting end each sensor at along stick woodenly each meter.

In the experimental part, poly-ethylene multilayer composite pipes (MLCP) grid of 100 m long, 0.016 m diameter was buried at 3 m soil depth as shown in Fig. 3. To measures the temperature of the outlet water from the earth water heat exchanger, one thermocouple type K sensor was fixed at the end of the EWHE.

Fig. 3 MLCP pipes buried on depth 3 m.

The other part of work is the water storage tank which is exposed to solar radiation during the day. The water storage tank material is Polyvinyl chloride (PVC) of 0.7 m outer diameter and 0.66 m inner diameter with 0.9 m height and capacity of 250 liters as shown in Fig. 4. Two thermocouples of type K sensors were fixed in the inner and outer surface of the tank to measure their temperatures. The water enters to the EWHE from the water storage tank via thermally insulated external pipe using a water pump. A flow meter and manual valve was used to measure and control of the water flow rate in the system.

Fig. 4 the water storage tank.

3. Modeling and simulation of the water tank with EWHE

The numerical approach was achieved using Computational Fluid Dynamics (CFD) method. CFD including solutions of the partial differential equations (continuity, momentum, and energy equations) that govern the heat transfer and fluid flow in a discretized way [9]. The complex processes of fluid flow and heat transfer that are included in any of the heat exchangers can be observed with the use of the CFD software, ANSYS20/FLUENT.

The ANSYS20/FLUENT packages include user interfaces sophisticated for problem parameters input and examination to results. In ANSYS20/FLUENT, CFD codes includes the preprocessor, solver, and post-processer. The preprocessing from input to flow problem of CFD program via means definition of region's geometry of interest: computational domain, generation of the grid-domain subdivision to a smaller number as mesh from cells (control elements or control volumes), chemical and physical phenomena selection which need to model, fluid's properties definition, specification of boundary's conditions appropriate in cells that coincide to domain's boundary or touch for it. Finite volume method produced to solving equations that governing heat transfer and flow for fluid at solver. Model's results are shown by contour, vector plots, etc. at post-processor. Thermal modeling and simulation of the water storage tank and earth water heat exchanger depicted in Figs. 5 and 6 are done using ANSYS20/FLUENT. Where the modeling for the water storage tank which is designed from Polyvinyl chloride (PVC) includes 0.7 m out diameter, 0.66 m inner diameter, and 0.9 m height. While the modeling for earth water heat exchanger which is designed from long pipes from poly-ethylene multilayer composite pipes (MLCP) includes 0.016 m out diameter, 0.012 m inner diameter, and 100 m long, have been buried 3 m deep below the level of the ground. The simulations of the CFD have been carried out, taking under consideration the 3D transient flow's turbulent (standard k-ε model) with enable's heat transfer and model of radiation (Rosseland). In each step is taken 100 s and 20 iterations as time steps for this transient analysis.

In this study, assumptions considered are: isotropic and homogeneous engineering material, incompressible water, and subsoil's temperature remains constant because penetration for heat from soil's surface is too slow. Fig. 7 presents the flow diagram for the system.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$\rho\left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right] = \rho\, g_x - \frac{\partial p}{\partial x} + \mu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \tag{2}$$

$$\rho\left[\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right] = \rho\, g_y - \frac{\partial p}{\partial y} + \mu\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right] \tag{3}$$

$$\rho\left[\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right] = \rho\, g_z - \frac{\partial p}{\partial z} + \mu\left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right] \tag{4}$$

$$\rho\, C_p\left[\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right] = k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] + \mu\, \Phi \tag{5}$$

The governing equations of the solar radiation are [10-12]

$$\delta = 23.45\ \sin\,[0.986\,(N + 284)] \tag{6}$$

$$\sin\beta = \cos L \cos\tau \cos\delta + \sin L \sin\delta \tag{7}$$

$$\tau = 15\,(t - 12) \tag{8}$$

$$\cos\gamma = \frac{\sin\beta \sin L - \sin\delta}{\cos\beta \cos L} \tag{9}$$

$$\cos\theta = \cos\beta \cos\gamma \sin\emptyset + \sin\beta \cos\emptyset \tag{10}$$

$$I = A\ \mathrm{e}^{-B/\sin\beta} \cos\theta \tag{11}$$

3.1. Boundary condition

The boundary condition that was selected for this study is the mass flow rate 0.7 LPM, initial water temperature 47 °C, and initial soil surface temperature 40 °C.

3.2. Mesh independent

The mesh dependence was reached at the program to get fine mesh after independence study for the mesh, different cases of mesh size are considered, and the total number of the elements was 1700000 tetrahedral elements that get accuracy and resolution.

The taken thermal and physical parameters of the simulation system have been listed in Table 1.

Table 1. Simulation's thermal and physical parameters.

Parameter	Properties	Unit
Outside diameter for water storage tank	0.7	m
Inside diameter for water storage tank	0.66	m
Height for water storage tank	0.9	m
Density for PVC	1350	kg/m^3
Specific heat for PVC	1200	J/kg°C
Diameter for EWHE pipe	0.016	m
Water mass flow rate for EWHE	0.7	LPM

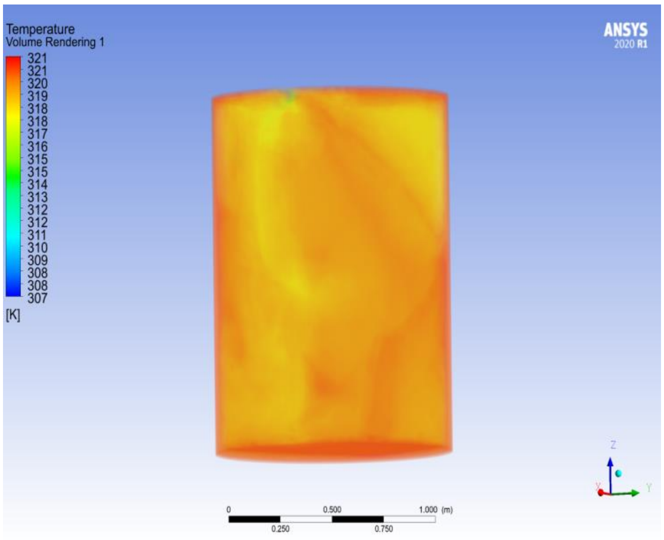

Fig. 5 temperature volume rendering for the water storage tank.

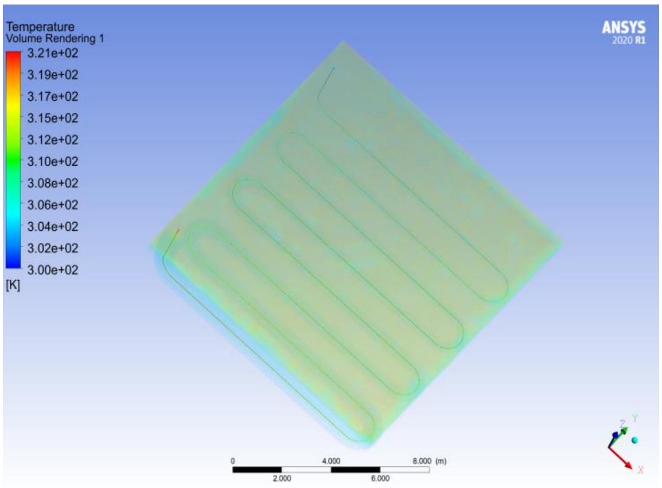

Fig. 6 temperature volume rendering for earth water heat exchanger.

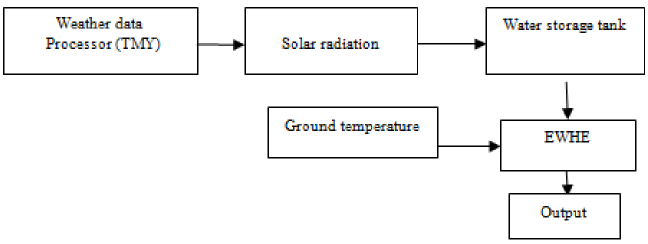

Fig. 7 ANSYS20/FLUENT information flow diagram for water storage tank with EWHE.

4. Model validation

This work can be validated with a theoretical study of Salman [1] in Table 2.

Table 2. Comparison of outlet water temperature between simulation result and theoretical result.

Simulation result	Theoretical result of Salman [1]
Outlet water temperature of EWHE 32.17 °C	Outlet water temperature of EWHE 32 °C

The temperature of the outlet water of earth water heat exchanger value is over predicted when compared to the reference of Salman [1]. This could be attributed to the different earth water heat exchanger geometry of the two works.

5. Results and discussion

The simulation with the ANSYS20/FLUENT for the EWHE was performed using the following input data: 100 m pipe length with 0.016 m diameter buried at 3 m depth, and 0.7 LPM water mass flow rate. The results show the water temperature reduction with the pipe length.

Figures 8-10 explain the temperature of the water and soil when the water inlet temperature is 47 °C and the temperature at the ground level is 40 °C and 3 m soil depth.

Figure11 shows the impact of the pipe length on the water temperature. The water temperature is the highest at the pipe inlet, then the temperature of the water decreases gradually due to heat exchange with the soil along the EWHE. The water temperature will be more closing to the soil temperature as the EWHE length be longer.

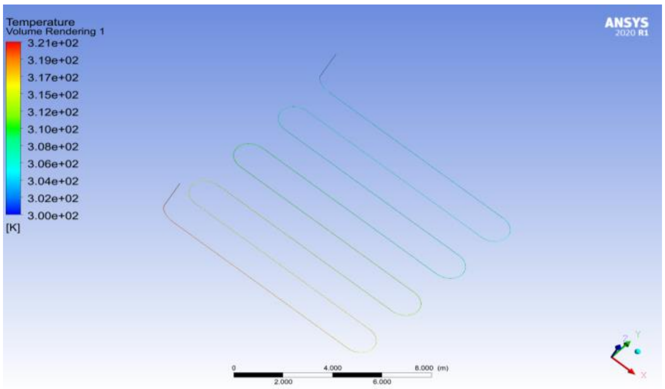

Fig. 8 temperature volume rendering for heat exchanger underground removed the soil.

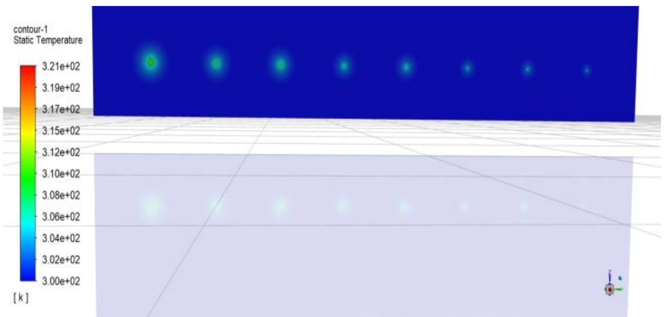

Fig. 9 vertical section contour colored by static temperature for heat exchanger underground.

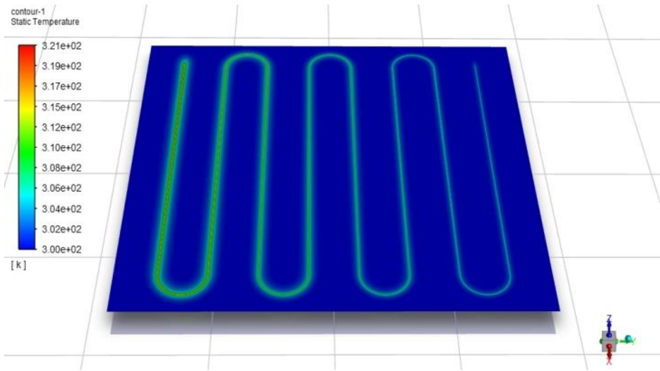

Fig. 10 horizontal section contour colored by static temperature for heat exchanger underground.

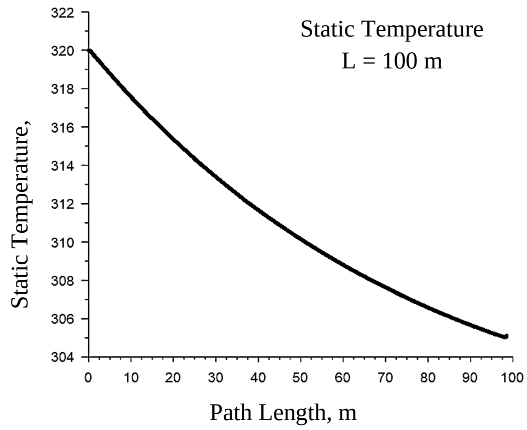

Fig. 11 water temperature along with heat exchanger underground.

Figure 12 shows the effect of EWHE diameter on the EWHE outlet temperature. Different pipe diameters were used (0.016 m, 0.032 m, and 0.050 m). For 0.016 m diameter, the pipe outlet temperature was 305.1 K, 304.5 K, 303.9 K. For the pipe's diameters 0.016 m, 0.032 m, and 0.050 m respectively. The figure showed that the higher pipe diameter has higher performance in comparison with the small one.

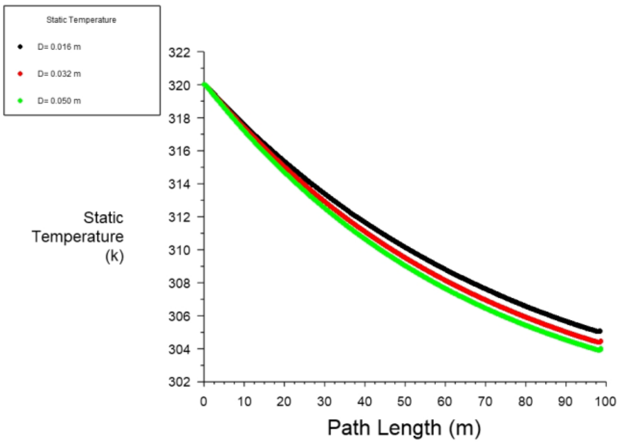

Fig. 12 the outlet water temperature for various diameters.

Figure 13 presents the effect of water mass flow rates, (0.7 LPM, 1 LPM, and 1.25 LPM) on the water outlet temperature. The results showed that the increase of the mass flow rate increases the outlet water temperature. When the mass flow rate was 0.7 LPM, the outlet temperature is 305.1 K while it be 306.8 K for 1 LPM, and 307.8 K when the mass flow rate was 0.125 LPM.

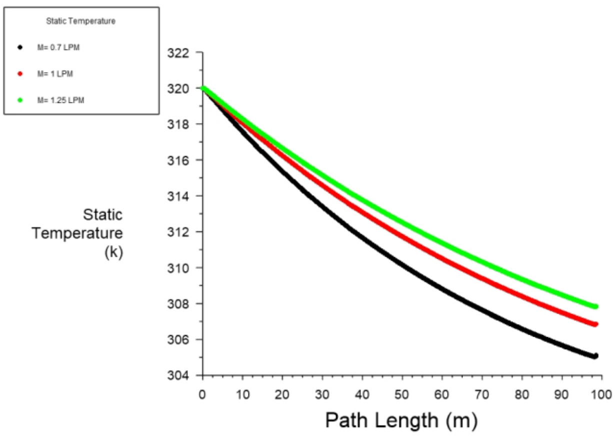

Fig. 13 the outlet water temperature for various mass flow rates.

A study the effect of the soil depth on the EWHE outlet temperature was also performed. Three different soil depths; 1 m, 2 m, and 3 m, were selected. 3 m depth provided a minimum pipe outlet temperature. The results showed that the temperature of the water outlet temperature is decreased with the increasing the soil depth as shown in Fig. 14. The water outlet temperatures were 305.1 K, 307.6 K and 309.9 K at a soil depth of 3 m, 2 m, and 1 m respectively.

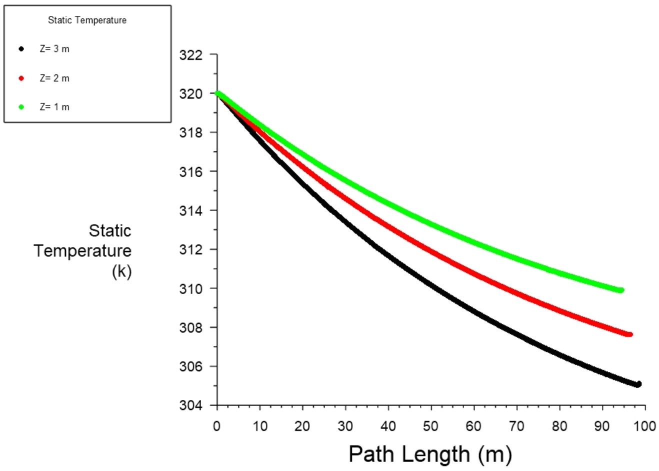

Fig. 14 the outlet water temperature for various soil depths.

Figures 15 to 19 comparing the data obtained for the outlet water temperature of EWHE for the hot season (April, May, June, July, and August) theoretically and experimentally. The results explained a good agreement between the theoretical and experimental work. The maximum temperature difference between the experimental and theoretical results was about 0.3 °C.

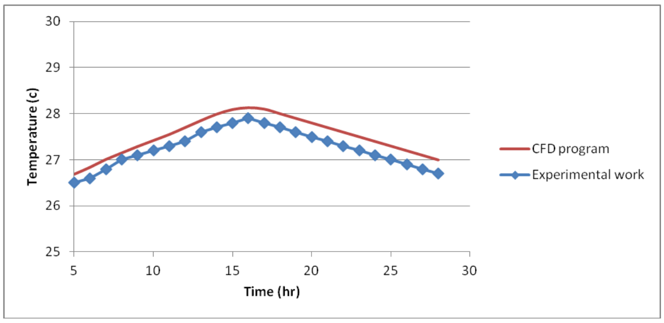

Fig. 15 outlet water temperature of EWHE in April from fieldwork and ANSYS 20/FLUENT program.

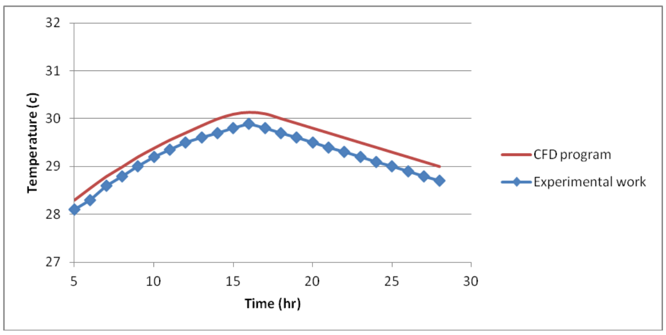

Fig. 16 outlet water temperature of EWHE in May from fieldwork and ANSYS 20/FLUENT program.

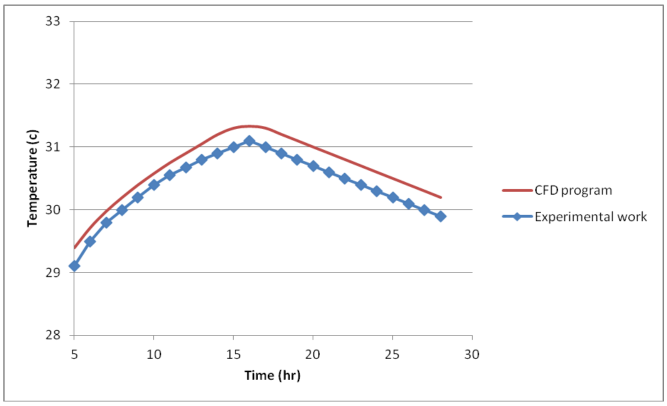

Fig. 17 outlet water temperature of EWHE in June from fieldwork and ANSYS 20/FLUENT program.

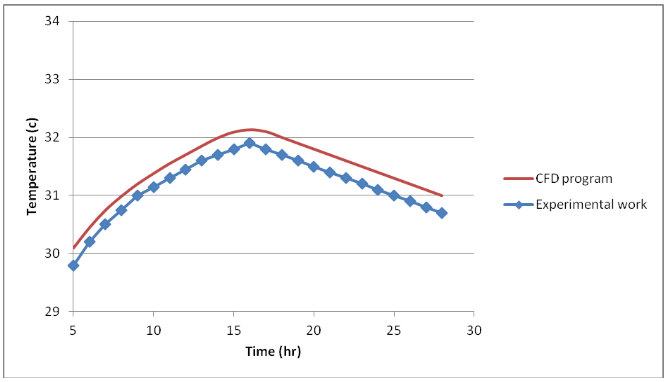

Fig. 18 outlet water temperature of EWHE in July from fieldwork and ANSYS 20/FLUENT program.

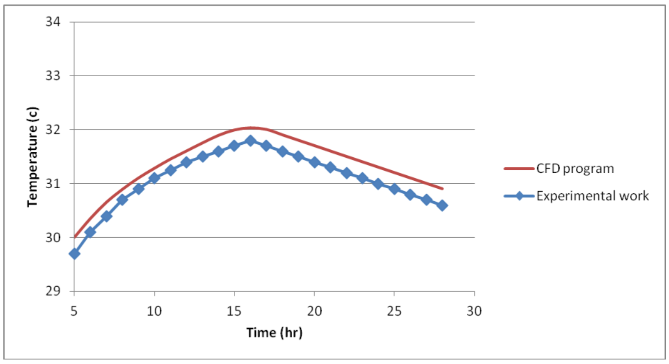

Fig. 19 outlet water temperature of EWHE in August from fieldwork and ANSYS 20/FLUENT program.

6. Conclusions

1. The heat exchanger of the earth-water is an effective technique to decrease the water's temperature to a level suitable in use.
2. The maximum temperature of the water in the storage tank reaches 50 °C during the summer season in Iraq.
3. A new type of pipe (polyethylene multilayer composite pipes), can be improving heat exchange between water, pipe, and soil.
4. Water mass flow rate, soil depth, pipe length, and diameter of earth water heat exchanger are parameters affecting the water outlet temperature of the EWHE.
5. The best results were obtained theoretically and experimentally when the pipe length (100 m), pipe diameter (0.016 m), mass flow rate (0.7 LPM), and soil depth 3 m. The outlet water temperature of EWHE decreased by 15.17 °C and 15.40 °C respectively for theoretical and experimental works.
6. The results have shown good agreement between the theoretical and experimental works.

Nomenclature		
Symbol	**Description**	**Unit**
x	Horizontal coordinate	m
y	Vertical coordinate	m
T	Temperature	°C
t	Time	hours
P	Pressure	N/m^2
g	Gravity acceleration	m/s^2
u	Velocity of x direction	m/s
v	Velocity of y direction	m/s
w	Velocity of z direction	m/s
k	Thermal conductivity	W/m °C
Cp	Specific heat	J/kg °C
Φ	The dissipation function	-
I	Solar radiation	W/m^2
Greek Symbols		
Symbol	**Description**	**Unit**
μ	Dynamic viscosity	kg/m.s
ρ	Density of the fluid	kg/m^3
δ	Declination angle	deg
β	Altitude angle	deg
τ	Hour angle	deg
L	Latitude angle	deg
γ	Azimuth angle	deg
θ	Incident angle	deg

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