The Iraqi Journal for Mechanical and Material Engineering, Vol.22, No1, March. 2022

EFFECT OF ELECTROMAGNETIC FIELD ON THE THERMAL EFFICIENCY OF CONCENTRATED SOLAR COLLECTOR (EXPERIMENTAL STUDY)

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ABSTRACT

In this work, the effect of electromagnetic field on thermal performance of concentrated parabolic trough solar collector is studied experimentally. A two-axis tracking parabolic trough collector formed of a reflector (mirror tapes matrix), of (2m *1m), and an absorber copper tube (receiver) is designed. Water and water-based magnetic iron oxide (Fe_3O_4) nanofluid are used as heat transfer fluid in the collector. Three volume concentrations (0.3%, 0.5%, and 0.9%) of nanoparticles are investigated under a magnetic flux of (3.2, 4.3, 6.2, and $7.9*10^3$ Gauss), which is installed at absorber inlet, middle, and exit. The three coils are connected to a DC-generator to control the electromagnetic field. The electromagnetic field effect on water flow in the absorber is found weak. A significant thermal improvement is figured when utilizing ferrofluid as a heat transfer fluid in the absorber. It is represented by higher temperature distributions in the absorber and higher solar collector efficiency compared with base fluid.

Keywords: Solar, electromagnetic field, ferrofluid, Parabolic solar trough collector.

INTRODUCTION

Dominant consuming fossil fuels such as oil, natural gas are related to environmental chemical and thermal pollution such as global warming. Adopting renewable energy becomes pivotal and solar energy among all the other options is considered as the most available in Iraq. Solar parabolic trough collector (SPTC) converts the energy of solar radiation to thermal energy by the circulated fluid medium. A trough-shaped parabolic reflector is utilized to concentrate the incident solar radiation on a receiver tube located at the reflector focal line Choi (1995). The energy absorbed from solar radiation in solar collectors is highly affected by the working fluid. Yang et al. (2013) performed a numerical optimization procedure on heat transfer enhancement for laminar nanofluid flow (Reynolds number of 250–1000) in a two-dimensional wavy channel. They found that the enhancement in heat transfer is mainly dependent on the nanoparticle volume fraction, the amplitude of the wavy wall, and the Reynolds number. The obtained thermal enhancement was 15%, 24% compared with pure fluid, with the particle volume concentration of ϕ (3% and 5%) of Cu/water nanofluids. So using nanofluid instead of conventional fluid is found as a potential area where the performance of solar collectors can be improved due to its thermo-physical properties. Electro-Magneto Hydro-Dynamics EMHD is concerned with the movement of conductive fluids subjected to electromagnetic forces i.e combining the concepts of fluid dynamics and electromagnetism. Electrically conducting, liquid metals, hot ionized gases (Plasmas) and electrolytes as well as non-magnetic fluid inserted with magnetic nanoparticles (ferrofluid) can be used, in these applications Luciano et al. (2013). Khalipe et al. [2015]

Received : 15-4-2020
Accepted : 7-8-2020

tested the performance of closed evacuated tube heat pipe solar collector when CuO/H_2O nanofluid is used. Also the inclination angle and cooling fluid mass flow rate are investigated. Nanofluid figured higher thermal performance for the evacuated tube heat pipe solar collector compared with conventional one that used base fluid. The obtained enhancement in instantaneous collector efficiency was 18-20%. Ferrofluid or magnetic nanofluid is a kind of fluid that consists of super Paramagnetic nanoparticles suspended in a nonmagnetic carrier liquid. This liquid is considered an advanced set of nanofluids due to their special characteristics behavior. Their properties such as consistency and conductivity can be changed beneath an outside attractive field and their rheological characteristics can be precisely controlled. These properties and particularly their capability of warm exchange upgrade make this kind of liquid a curious issue for numerous analyses. One useful enhancement method for convective heat transfer is the usage of the magnetic field. When Lorentz force is subjected to fluid, its' rate of heat and mass transfer will be considerably affected. Heidary et al. (2015). (Ghadiri et al. 2015) tested the dependence of a PV/Thermal system efficiency on cooling the PV panel by using a magnetic fluid as a coolant. Distilled-water and (Fe_3O_4/water) ferrofluid of weight concentration of (1%, 3%) is used in a closed stream circuit and cooled by a shell and tube heat exchanger of a counter-flow. Constant and alternating magnetic fields are subjected on the ferrofluid in the cooling section of the PV/T system. The results show that the overall efficiency of the system is improved by 45% by using a 3% ferrofluid and when an alternating magnetic field of 50 Hz frequency was applied. The overall efficiency is increased to about 50% compared to that of the distilled water as a coolant fluid. Abdulhassan et al. (2016) tested the heat transfer and flow of nanofluid (Fe3O4/ water) in a horizontal pipe subjected to a constant magnetic field and a uniform heat flux of (11262-19562 W/m^2) and range of Reynolds number (2900-9820). The results demonstrate that the Nusselt number increases with the increment of magnetic flux and nanofluid concentration. It was (5.4, 26.4, and 42.7)% for the Ferrofluid of volume concentrations of (0.3, 0.6, 0.9)% respectively. The heat transfer enhancement diminishes with the increase of Reynolds's number with subjecting to the magnetic field. (Hatami et al. 2017) investigated experimentally the laminar forced convective heat transfer of nanofluid (Fe3O4-water) in a horizontal pipe. The applied particles volume concentrations is (0.1, 0.5, 1)%. The flowing fluid is subjected to a constant magnetic field and heat flux. Results showed a decrease of convection heat transfer coefficient is figured with the increment of nanoparticle concentration by the nearness of a magnetic field. (Gan et al 2018) presented a higher thermal conductivity for Ferrofluids and nanofluids than their base fluid due to the existence of the strong magnetic nanoparticle. A considerable heat transfer improvement when Ferrofluid is utilized. Results showed that for Ferrofluids, convective heat transfer is enhanced by expanding the magnetic particles’ volume concentration (the studied range is (0.2 to 0.4%). It is interesting to see that increasing magnetic flux decreases heat transfer improvement. This work presents a first attempt to study and discuss aspects of a novel solar concentrated thermal collector based on Ferro-fluid as absorber working fluid subjected to the electromagnetic field. Thermal properties of Ferrofluid such as conductivity and viscosity can be changed beneath an outside magnetic field and their rheological characteristics can be precisely controlled. These properties and particularly their capability of heat-transfer upgrade make this kind of liquid is a curious issue to study. This work is motivated to get a better understanding of the interaction between natural fluid circulations in solar absorbers when exposed to the electrical-magnetic field and to figure out the collector thermal characteristics for Iraq’s climate conditions. The aim of the present work is to test the thermal characteristics of a concentrated solar collector with water or ferrofluid flowing freely inside its receiver. The collector is tested with and without exposure to an electromagnetic field to recognize its effect on ferrofluid mass flow rate and its temperature distribution under Baghdad climate conditions.

EXPERIMENTAL WORK

A parabolic reflector was manufactured, designed and tested at the University of Baghdad-College of Engineering / Department of Mechanical Engineering.

Design Consideration of Parabolic Reflector

The absorber length (L_r) is (2000 mm), while its inner diameter (d_i) is (12.7mm) with (0.8 mm) wall thickness. Fluid mass filled this riser (m_r) is evaluated as:

$$m_r = \frac{\pi}{4}(d_i)^2 L_r \rho_f \, m_r \quad (1)$$

where

ρ_f is density of fluid inside the absorber (kg/m^3).

So mass of water included in the absorber is calculated as:

$$m_r = \frac{\pi}{4}(o.o127)^2 * 2 * 1000 \quad (2)$$

i.e the mass of water enclosed in the absorber is (0.253 kg).The power requested for fluid boiling (P_{boi}) can be estimated as:

$$P_{boi} = h_{fg} * m_r / t \quad (3)$$

where

h_{fg} is Latent heat for boiling at atmospheric pressure.

t is time (s), taken as (360 seconds).

So the power required for water boiling is :

$P_{boi} = 2257 * 1000 * 0.253/360$

$P_{boi} = 1586.1$W.

This power can be provided by incident solar radiation on the reflector receiving beam radiation I_b.. It is evaluated such that:

$$P_{boi} = I_b A_{ap} \quad (4)$$

where

I_b is beam solar radiation (W/m^2).

A_{ap} is the aperture area of the reflector (m^2).

The surface area of absorber ($A_{abs.}$=0.089 m^2) is neglected in this work, however the aperture area of the reflector is calculated as:

$$A_{ap} = L_r * W_r \quad (5)$$

where:

W_r is width of the reflector (m).

Consider the incident beam solar radiation I_b is equal to (750 W/m^2), so referring to eq.4 the width of the reflector is 1.05 m. The concentration ratio for the present design is calculated as :

$C_c = A_{ap} / A_{abs}$

So the concentration ratio is equal to 23.6.

Experimental system setup

Two axes tracking parabolic reflector with a focal line at which the copper absorber tube is located is used in this work. The schematic representation of system is displayed in Fig. (1), and the reflector specifications are given in table (1).

A DC power supply (MATKIN 1505TA) of (15 V DC, 5 Am) is used to provide the required power.

Eleven K-type Thermocouples are connected to (A LUTRON 12 channels Temperature Recorder Real-time data logger. Contains 12 channels of temperature measuring and saving data along with the SD memory card with the time data which is compatible with the Excel software. This recorder has 0.1 °C resolution and an accuracy of ± (0.4 %). A Gauss meter (Hirst magnetic instrument ltd. Tesla house tragohiggie, Falmouth Comwall, TR11 4SN England) is used to measure the magnet strength. The bulb of the Gauss meter is located on the pipe. A digital multi-meter (A VICTOR) is used to measure the generated voltage and current. The accuracy of this device for DC voltage and DC current are ±(0.5%) and ±(1.2%), respectively. The resolution is 10mV and 10mA. The range of measured DC voltage is (400mV to 1000 V) while DC current is (400 µA to 10A).

Error Analysis

The solar collector thermal efficiency (η_{th}), is defined as the ratio of useful heat gain Q_u per A_{ap}, and the incident solar radiation I_b, such that:

$$\eta_{th} = \frac{Q_u}{A_{ap}\, I_b} \tag{6}$$

Per the approach of error analysis presented by Holman (2012), the percentage error of thermal efficiency can be evaluated as:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \tag{7}$$

$$w_{\eta th} = [(\frac{\partial \eta}{\partial \Delta T}\, w_{\Delta T})^2 + (\frac{\partial \eta}{\partial Ib}\, w_{Ib})^2 + \ldots (\frac{\partial \eta}{\partial \dot{m}}\, w_{\dot{m}})^2]^{1/2} \tag{8}$$

where:

w_R is the uncertainty in the result and w_1, w_2, ... w_n is the uncertainty in the independent variables. The accuracy of different parameters are given in table (2).

$$w_{\eta_{th}} = \pm\sqrt{(\mathbf{0.05})^2 + (\mathbf{0.01})^2 + (\mathbf{0.01})^2 + (\mathbf{0.004})^2} = \mp \mathbf{5.2\%}$$

RESULTS AND DISCUSSION

The obtained experimental results are carried out during a clear days in Baghdad, Iraq (latitude of 33.33° North and longitude of 44.2° east). The thermal performance of the parabolic trough solar collector was analyzed experimentally under five different volume fractions of 0%, 0.3 %, 0.5%, 0.9% of nanoparticles (Fe_3o_4), as well as five different electromagnetic intensities of (0, 3240, 4320,6233 and 7970 Gauss).

Figure (2) illustrates the hourly variation of the collector thermal efficiency when collector field water is subjected to different electromagnetic fields. It is noted that the value of thermal efficiency is high at the beginning of the test time, it was (83.4%) and at midday, it decreases and then begins with a gradual increase after that for the same electromagnetic intensity. It can also be noted that the effect of electromagnetic intensity is little on the value of thermal efficiency. Figure (3) presents the hourly variation of the collector thermal efficiency when the collector field is ferrofluid (water+Fe_3O_4) of volume concentrations of 0.3% subjected to the electromagnetic field of (0, 3240, 4320, 6233, and 7970 Gauss). It is noted that the value of thermal efficiency at 12:00 PM is the lowest for the various electromagnetic field. Figure (4) indicated the hourly variation of the collector thermal efficiency when the collector field is ferrofluid of volume concentrations of 0.5% subjected to the electromagnetic field. At 9:00

AM the thermal efficiency is 87.6% when electromagnetic field 7970 Gauss. When the volume concentrations value is 0.9% the maximum thermal efficiency value is 96.4% at the same electromagnetic field as shown in figure (5). Figure (6) illustrates the hourly variation of the collector thermal efficiency when the collector field is ferrofluid of volume concentrations of (φ =0, 0.3, 0.5, 0.9) % not subjected to electromagnetic. It is noted that the change in concentrations has a clear effect on the value of thermal efficiency at the same time without shedding an electromagnetic field. Figures (7) show the hourly variation of the collector thermal efficiency when the collector field is ferrofluid of volume concentrations of (φ =0, 0.3, 0.5, 0.9) % subjected to an electromagnetic field of (3240 Gauss). This figure shows that the value of thermal efficiency is affected by the electromagnetic field, the maximum value is 87.6% at 11:00 PM for φ =0.9 %. At the beginning of the test day, the collector's thermal efficiency value will be very big, then it will start to decrease to reach the minimum value at 1:00 PM, then it begins to decrease. While the maximum value was 92.7% at 16:00 PM for ferrofluid subjected to 4320 Gauss as shown in Fig. (8). The corresponding value for ferrofluid exhibited to 6233 Gauss was (94.6%) at 16:00PM and φ =0.9 as presented in Fig. (9). The hourly variation of the collector thermal efficiency when ferrofluid of volume concentrations of (φ =0, 0.3, 0.5, 0.9) % is circulated and the absorber is subjected to the electromagnetic field of (7970 Gauss) are presented in Figure (10). It is observed that the efficiency have inconsiderable variation during the daily test for each volume concentration. However, rising the nanoparticle concentration within the heat transfer fluid strongly enhances the collector efficiency since the thermal conductivity of the fluid enhanced. The effect of the magnetic field on the collector efficiency is clear.

CONCLUSIONS

This work is carried out to investigate the effect used magnetic nanofluid flow with and without an electromagnetic field. The nanofluid containing oxide metal nanoparticles has a magnetic behavior in water. Based on the obtained experimental results, the followings are concluded:-

1- The effect of the electromagnetic field is very little or not noticeable when water is used as the working fluid.

2- Utilizing ferrofluid (Fe_3O_4+water) as a working fluid in the solar collector figured a noticed heat transfer enhancement. The maximum enhancement is (28 %) originated for ferrofluid of volume concentrations of (φ =0.9%) subjected to electromagnetic field 7970 Gauss and the minimum enhancement is (5.2 %) originated for ferrofluid of volume concentrations of (φ =0.3%) when the absorber is not subjected to electromagnetic field.

4- The effect of the electromagnetic field can be observed when using ferrofluid (water +Fe_3O_4).compared to base fluid.

5- The maximum useful heat gain (Qu) of parabolic trough solar collector is (1599.6 W) for ferrofluid (water +Fe_3O_4) with a concentration 0.5 % and electromagnetic field 6233 Gauss.

6- The maximum thermal efficiency of parabolic trough solar collectors is (95.3%) and (85.1%) for ferrofluid and water respectively.

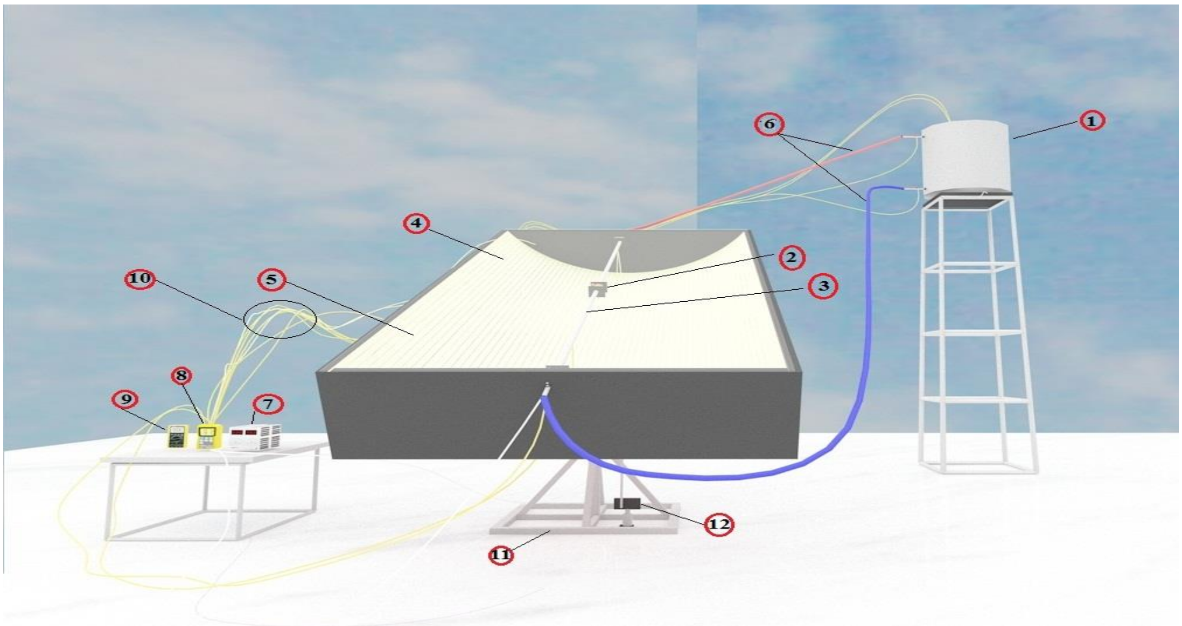

Fig. 1. Schematic diagram of the system.
1-storge tank, 2- electromagnetic coil, 3- absorber tube, 4- reflector surface, 5- glass covered, 6- connecting fitting, 7- DC power supply, 8- thermometer recorder, 9- multi-meter (Current and Voltage meter), 10 – thermocouple, 11- stationary main base, 12- the moving base

Table 1. Description of the Reflector

Depth of parabolic	0.28 m
Mode of tracking	Two-axis
Length	2.2 m
Aperture area	2.2 m^2
Rim angle	92.3^o
Aperture width	1.06 m
Concentration ratio	26.4
Focal point	0.2531 m
The thickness of the glass cover	3 mm

Table 2. accuracy of parameters used in the calculation of the error analysis. percentage error of thermal efficiency

Independent Variables	Accuracy
Temp.(T)	± 0.4%
Heat capacity (Cp)	1%
Current (I)	1.2%
Voltage (V)	0.5%
Area (A_{ap})	0.25%

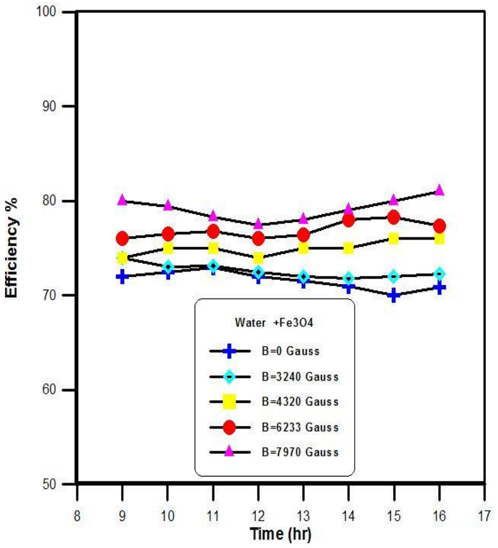

Fig. 2. Variation of collector efficiency with time for different electromagnetic field (water).

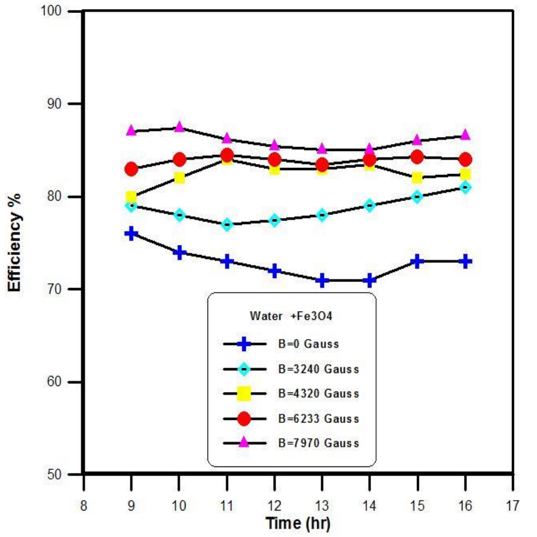

Fig.3. Variation of collector efficiency with time for different electromagnetic field (ferrofluid (φ =0.3).

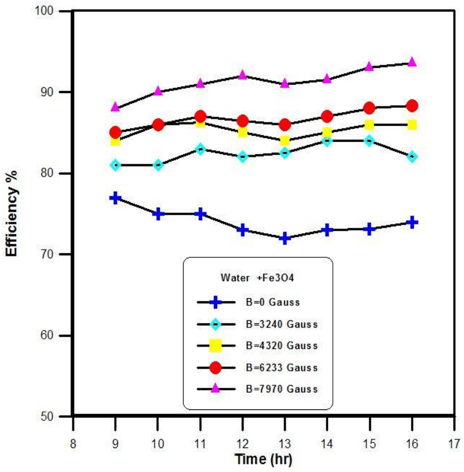

Fig. 4. Variation of collector efficiency with time for different electromagnetic field (ferrofluid (φ =0.5%water).

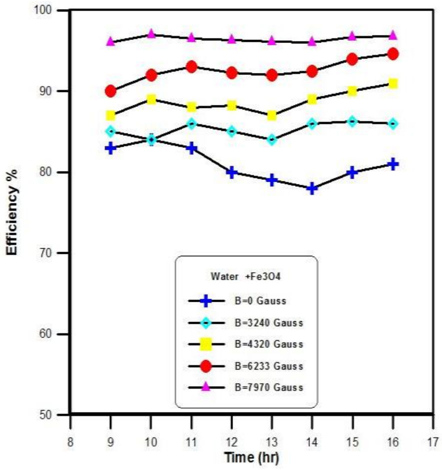

Fig. 5. Variation of collector efficiency with time for different electromagnetic field (ferrofluid (φ =0.9%water).

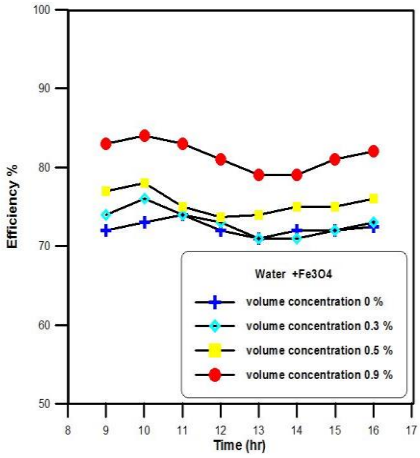

Fig.6. Thermal efficiency of the collector for ferrofluid not subjected to electromagnetic field.

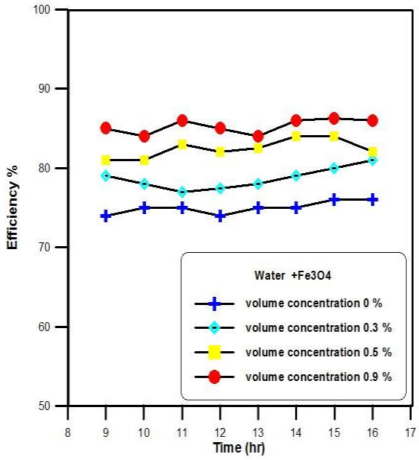

Fig.7. Thermal efficiency of the ferrofluid subjected to electro-magnetic field (3240 Gauss).

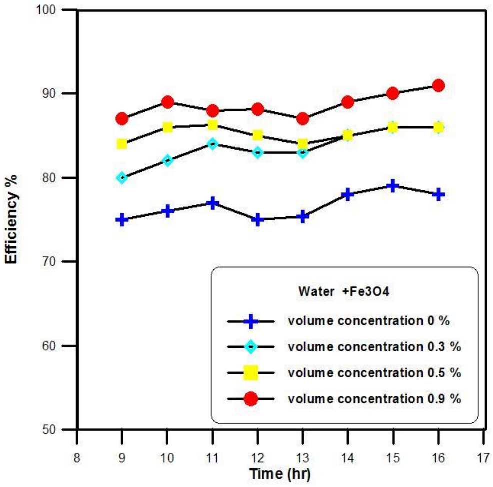

Fig. 8. Thermal efficiency of the ferrofluid subjected to an electromagnetic field (4320 Gauss)

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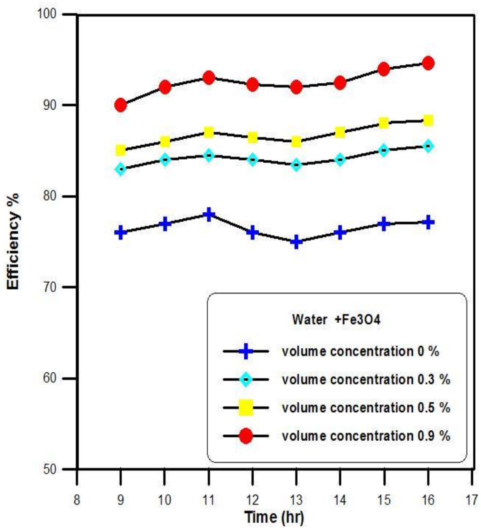

Fig.9 Thermal efficiency of the collector ferrofluid subjected to electromagnetic field (6233 Gauss).

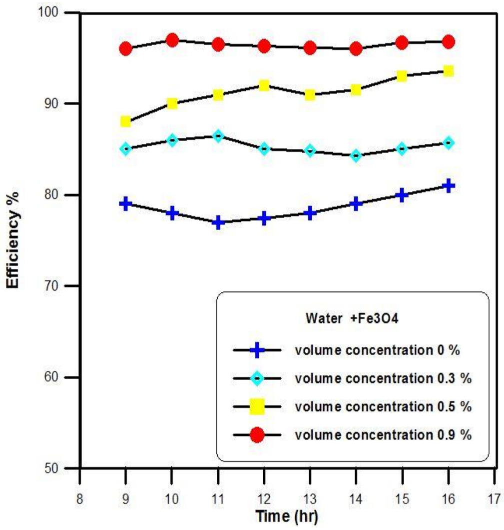

Fig. 10. Thermal efficiency of the collector ferrofluid subjected to electromagnetic field (7970 Gauss).

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