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EXPERIMENTAL AND NUMERICAL STUDY OF MAGNETIC FIELD IMPACT ON THE THERMAL SOLAR COLLECTORS

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ABSTRACT

An experimental study has been conducted to determine the impact of magnetic field on the performance of thermal solar collectors. A numerical model has been developed after the mass and energy balances, presented, integrated and coded. The study compared between thermal solar collector's behavior with or without magnetic field at different solar radiations, magnetic field forces, as well as other conditions. Comparisons were made against data collected at different conditions for validation purposes of the model numerical predictions.

Contribution/Originality: This study contributes to the understanding of the impact of magnetic field on the heat transfer fluid circulating in thermal solar collectors. In addition, this study enhances our understanding of the behavior of thermal solar collectors and impact of the different solar radiations on the behavior of thermal solar collectors.

1. INTRODUCTION

Magnetically-treated water (MTW) has shown promising potential, offering a wide range of benefits, including soiled Stalinization (Bigham, 1996; Bogatin *et al.*, 1999; Hilal and Hilal, 2000; Cho and Lee, 2005; Chang and Weng, 2006; Gang *et al.*, 2012; Hilai *et al.*, 2013; Hachicha *et al.*, 2017). MTW has demonstrated the ability to reduce water consumption and improve performances compared with those of conventional treatment systems. In general, the three main observed effects of MTW are removal of excess soluble salts, lowering of pH values, and the dissolving of slightly soluble components such as phosphates, carbonate sand sulfates (Hilal and Hilal, 2000; Hilai *et al.*, 2013; Chaudhari and Walke, 2014).

Solar energy is currently one of the most important sources of clean, free, inexhaustible and renewable energy with minimal environmental impact. The solar energy can be defined as the energy which comes from the sun and can be converted into electricity and heat. The solar energy applications has received significant attention due to the growing demand of energy, limited availability of fossil fuels and environmental problems associated with them such as carbon dioxide emissions.

Solar thermal collectors are environmentally friendly and sustainable systems. The thermal solar collectors convert solar irradiation energy to thermal energy that is used to heat working fluids such as water for domestic and industrial applications. This also can be used to either generate electricity or for thermal storage in phase-change material for heat supply during non-solar periods (Farid *et al.*, 2004; Razali and Irwasnsyah, 2004; Saleh, 2012; Thirugnanam and Marimuthu, 2013; Tian and Zhao, 2013; Razali and Hamdani, 2014; Kasaeian *et al.*, 2015).

Thermal solar water heating systems includes mainly thermal solar panels collectors, a thermal storage tank and a pump as well as control valves. The heat transfer fluid (HTF) delivers the heat absorbed at the solar panel collectors to a water-storage thermal tank. The thermal solar collector absorbs solar radiation energy and converts it into thermal heat that is supplied to the thermal storage tank for further domestic or industrial use (Farid *et al.*, 2004; Razali and Irwasnsyah, 2004; Saleh, 2012; Tian and Zhao, 2013; Chaudhari and Walke, 2014; Razali and Hamdani, 2014; Kasaeian *et al.*, 2015).

Furthermore, The behavior of the thermal solar collectors and the enhancement of their efficiency has been investigated by references (Farid *et al.*, 2004; Razali and Irwasnsyah, 2004; Kakaç and Pramuanjaroenkij, 2009; Saleh, 2012; Thirugnanam and Marimuthu, 2013; Tian and Zhao, 2013; Nerella *et al.*, 2014; Sami and Tardy, 2015; Allen, 2105). In addition, these references studied enhancement of the thermal solar collectors efficiency and compared to other data reported in the literature. Also, it be noted that the thermal properties are the key factors to viable solar thermal energy storage system (Azo, 2004; Farid *et al.*, 2004; Razali and Irwasnsyah, 2004; Kakaç and Pramuanjaroenkij, 2009; Taylor *et al.*, 2011; Khullar *et al.*, 2012; Saleh, 2012; Thirugnanam and Marimuthu, 2013; Tian and Zhao, 2013; Nerella *et al.*, 2014; Sagadevan, 2015; Sami and Tardy, 2015; Sami and Zatarain, 2016; Allen, 2105) such as high thermal storage capacity, good heat transfer rate between the heat storage material, heat transfer fluid and good stability to avoid chemical and mechanical degradation.

This paper is concerned with an experimental study to determine the impact of magnetic field on the thermal behavior of thermal solar collectors. The study compared between thermal solar collector's behavior with or without magnetic field at different solar radiations, magnetic field forces, as well as other conditions. This paper intended to critically convey information on water magnetization and to discuss improvement of the behavior of thermal solar collector that employs magnetic field as an aid in efficiency enhancement.

Furthermore, in the paper, we present a mathematical model to describe the heat and mass balances of water as heat transfer fluid (HTF). The model was established after the energy conservation equations coupled with the heat transfer equations of the HTF. In the following sections, experimental data collected at the thermal solar loop and the predicted numerical results of a thermal solar panel using the heat transfer fluid different conditions are presented, analyzed and discussed. In addition, the predicted numerical results were also compared with available experimental data.

2. MATHEMATICAL MODEL

The thermal solar collectors' system with mounted magnetic elements under study is depicted in Figure 1. This system includes a thermal solar panel collector, thermal tank, and paraffin wax thermal storage material, piping, and pump as well as control valves. However, in this study, only the thermal tank with water was utilized. The thermal tank was equipped with a single-tube heat exchanger which was numerically divided into different elements to permit describing the energy and heat transfer equations of the HTF in finite-difference format. The model has the following assumptions; the HTF is homogeneous and isotropic, HTF is incompressible and it can be considered as a Newtonian fluid, inlet velocity and inlet temperature of the HTF are constant, thermophysical properties of the HTF are constant in each element of the heat exchanger.

The conservation equations and heat transfer equations of the HTF can be describes for each element as follows;

Energy Conservation and Heat Transfer Equations:

The heat released by the heat transfer fluid HTF is Sami and Zatarain (2016).

$$Q = m_w Cp_w \Delta T_w \quad (1)$$

ΔT_w : Heat transfer fluid temperature difference

m_w : Heat Transfer Fluid HTF flow rate

Cp_w : Specific heat of heat transfer fluid

The heat balance for the heat exchanger tube in the tank can be as follows Sami and Zatarain (2016).

$$(T_{in} - T_{out})Cp_w m_w = 2\pi Rlh(T_{in} - T_{sfc}) \quad (2)$$

Where the heat transfer coefficient, *h*, is approximated as Sami and Zatarain (2016).

$$h = \frac{K_W}{D_H} b_2 Re^n \quad (3)$$

$$Re = \frac{m_w D_H}{\mu A_f} \quad (4)$$

Where; the b_2 and n are numerical constants.

The following relationship was used to relate the thermal conductivity to thermal diffusivity and density of the heat transfer fluid as follows Allen (2105).

$\alpha = \kappa/(\rho.C_{p)}$ (5)

Where C_p is the specific heat, α is the thermal diffusivity, κ and ρ represent the thermal conductivity and density, respectively.

The (HTF) mass flow rate can be calculated from the heat released by the solar radiation as follows,

Mass Flow Rate of Water:

$$m_w = \frac{GAPanel}{1000 \times Cp_w \Delta T_w} \quad (6)$$

The finite difference formulation of the time derivative in Equation (2) can be used to predict the HTF behavior in the thermal storage tank as follows;

Thermal Tank:

$$T_{tank_{m+1}} = T_{tankt_m} + \frac{m_w Cp_w \Delta T_w}{\rho_s V_{tankt} Cpw_t} \Delta t \quad (7)$$

Where: m_w, Water mass flow rate $\left(\frac{kg}{s}\right)$

Cp_w, Specific heat of water $\left(\frac{kJ}{kg\,K}\right)$

G, Radiation $\left(\frac{W}{m^2}\right)$

R, Tube radius (m)

l, Tube length (m)

h, Heat transfer coefficient

b_2 & n, Constants equal to 0.3 and 0.6 respectively

D_H, Hydraulic diameter (m)

μ, Water viscosity $\left(\frac{m^2}{s}\right)$

K_w, Thermal conductivity of water $\left(\frac{kJ}{ms°C}\right)$

A_{Panel}, Area of solar panel (m^2)

A_f, Flow area (m^2)

Δt: Time interval in the finite difference formulation,

Re: Reynolds number

V_{tank}: Volume of water thermal tank

Where Equation (1) combined with Equation (7) can be used to calculate the heat released by the heat transfer fluid to water in the thermal tank.
Finally, the thermal solar panel efficiency can be obtained from the following expression;

$$\eta = Q/\, GA_{Panel} \tag{8}$$

Where Q is calculated by Equations (1) and (2) and

G represents the solar radiation $\left(\frac{W}{m^2}\right)$, and A_{panel} is thermal solar panel area.

3. NUMERICAL PROCEDURE

The energy conversion and heat transfer balances describing the mechanisms taking place during thermal heat absorbed by the heat transfer fluid circulating in the solar panel tubes and in the thermal solar tank have been outlined in Equations (1) through (8). The aforementioned equations have been, integrated, programmed and solved as per the logical flow diagram presented in Figure 2, where the input parameters and independent parameters are defined for at the start of the program such as the solar panel geometries and characteristics, as well as the other dependent parameters; solar radiations and fluid properties were calculated and integrated in the finite-difference formulations. Numerical iterations were performed until a converged solution is reached with acceptable iteration error. The numerical procedure starts with the use of the solar radiation to calculate the mass flow rate of the water circulating in the thermal solar panel and the thermal tank. This follows by predicting the characteristics of the heat transfer fluid circulating in the thermal solar panel heat exchanger tubes; heat released into the thermal tank, as well as the solar panel energy conversion efficiency using the finite-difference formulation.

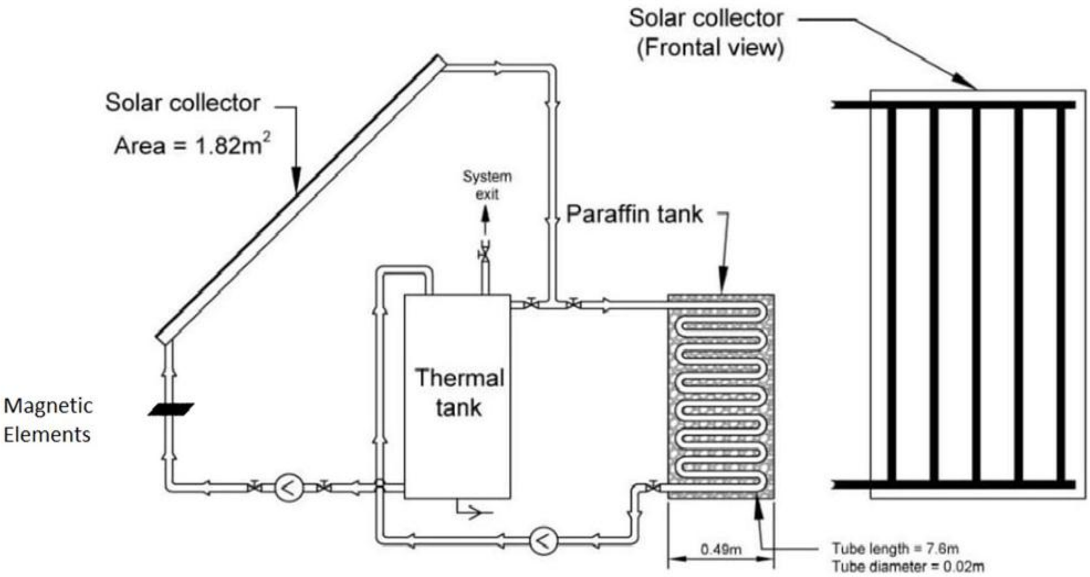

Figure-1a. Schematic diagram of thermal solar panel and Thermal tank.

Figure-1b. Thermal solar panel.

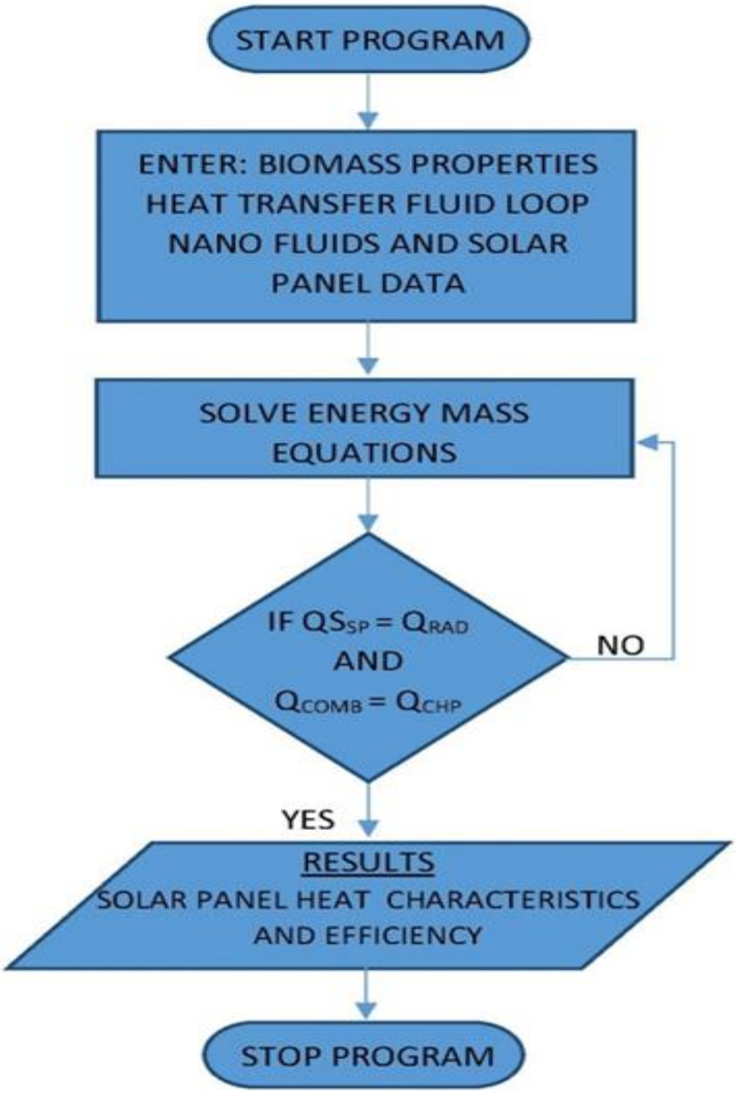

Figure-2. Logical flow diagram for finite- difference scheme.

4. RESULTS, DISCUSION AND ANALYSIS

The thermal solar collector-tank loop employed in this simulation study and presented in Figure 1, is composed of thermal solar panel equipped with temperature control valves, piping, circulating pump, control valves, thermal tank, temperature sensors, magnetic flow meter, and pressure sensor to control the tank pressure, pressure relief valve as well as an electric heater for emergency conditions. The thermal tank used in this study as shown in Figure 1, has a diameter of 0.49 meter and a height of 0.99 meter with a capacity of 100 liters and one path tube heat exchanger of 0.025 meter and 7.5-meter in length. On the other hand, the thermal solar panel has length and width dimensions of 0.90 meter and 12 heat tubes; each of the heat tubes has a diameter of 0.0254 meter. The heat transfer base fluid (HTF) used in this study is water and flows inside the aforementioned tubes of the thermal solar panel, in single-path tube heat exchanger in the solar thermal solar loop as presented in Figure 1.

A meteorological (HOBO) station equipped with sensors was employed in this study to measure the following parameters; temperature, wind speed, wind direction, solar radiation, rain accumulation, and humidity.

In order to study the impact of the magnetic field on the thermal solar collector 's behavior; five magnetic elements were employed with each one has magnetic force of 3500 Gauss. The following gives the characteristics of the magnetic elements as shown in Figure 3 were mounted on the exterior diameter of the heat transfer fluid diameter. The magnetic elements were mounted at the inlet pipe to the thermal solar collector at 25 pipe diameters from any elbows, obstruction or flow constrains.

Figure-3. Elements of Magnetic field each of 3500 Gauss.

- Dimension: 35x 28x 31 cm.
- Magnetic Force: 3500 gauss.
- Pipe diameter of application: 1-1/2 inches.

Figure 4 shows the calibration curve for the magnetic flow meter used in this study. The maximum flow rate attained was 0.411 liter/second.

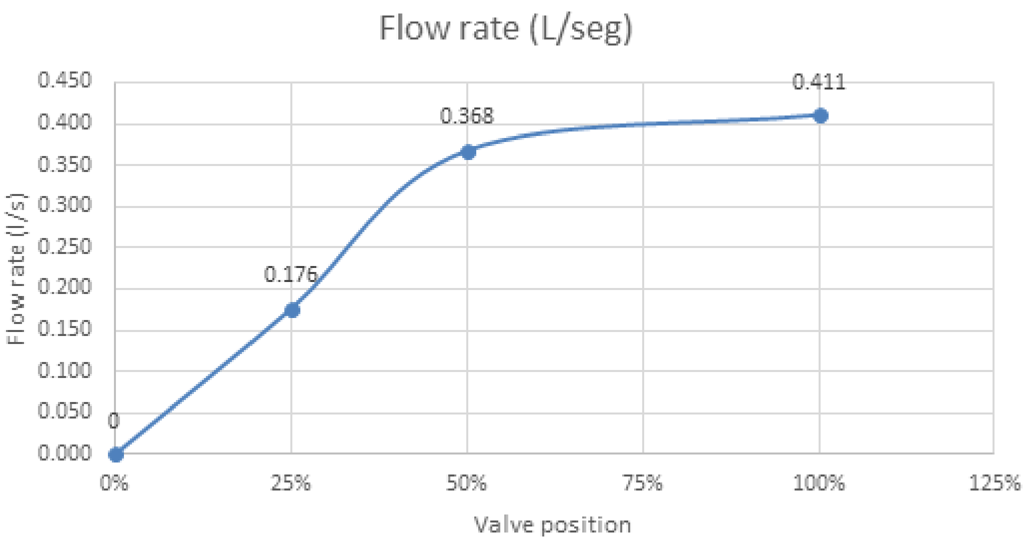

Figure-4. Flow meter calibration curve.

The aforementioned system of Equations (1) through (8) have been integrated and coded in finite-difference forms and numerically solved and samples of the predicted results of the solar panel efficiency, and heat absorbed by solar panel are plotted in Figure 6 through 12 at different inlet condition; solar radiation conditions, and heat transfer fluid flow rates. Numerical simulations were conducted under solar radiations that varied from 500 W/m2 to 1200 W/m2. It should be also noted that the mass flow rate of heat transfer fluid flowing through the thermal solar loop (Figure 1) used in simulated results varies between 0.368 to 0.411 l/s as per the calibration curve presented in Figure 4.

Figure 5 presents the profile of time-variation of solar isolation (W/m2) measured at the site that has been employed in this simulation. It is quite clear that the intensity of radiations depends upon the hour of the day and the month of the year. It also can be noticed that the maximum average solar radiation occurs at noon time.

In general, it is cab be noted from Figures 6 through 23 that the heat absorbed by solar panel and solar panel efficiencies are influenced by the solar radiation and the number of magnetic elements used to magnetize the heat transfer fluid circulating in the thermal solar collector loop under investigation. In the following sections, we will discuss these issues in detail under magnetization and without magnetization conditions. Figures 6 through 9 present the characteristics of the solar collector without magnetization conditions and Figure 13 through 16 are under magnetization. Furthermore, Figure 9 and 10 have been constructed to present the solar panel and thermal tank thermal tank characteristics at solar radiation 712 w/m2 and without magnetization. The data presented in this figure clearly show that higher solar radiation increases the thermal capacity of the solar panel, and the thermal tank as well as the heat released into the thermal tank. It is quite important to highlight that the thermal tank capacity is direct representative and strong indicator of the thermal energy absorbed by the thermal solar collector. Therefore, the thermal heat capacity was employed in this study to characterize the thermal capacity of the thermal solar panel.

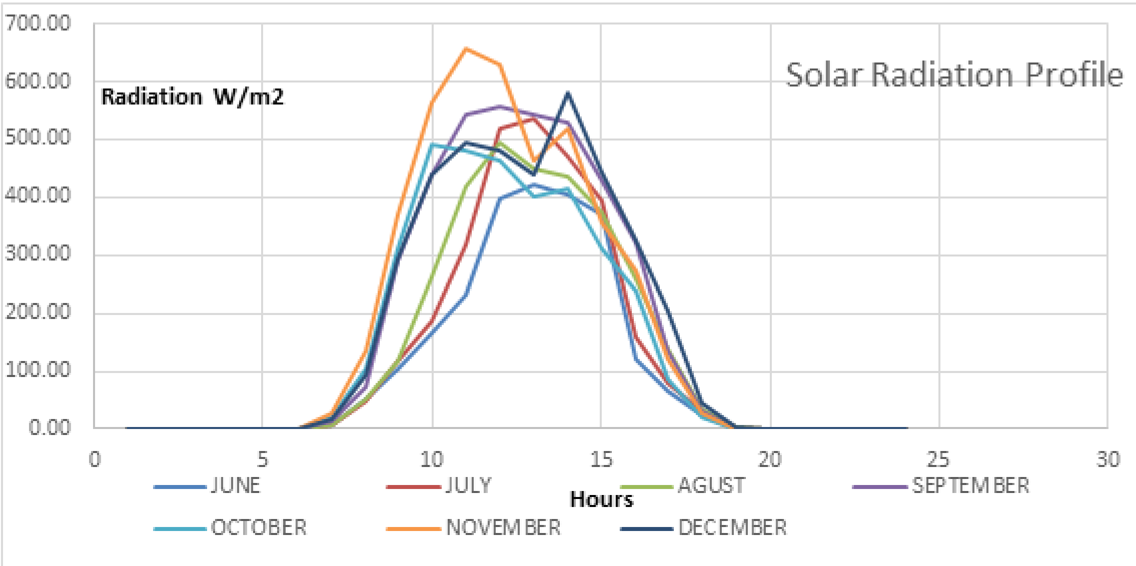

Figure-5. Time variation of solar intensity W/m2 during 2016.

It is quite clear from the numerical results presented in these figure that the heat absorbed by the thermal solar panel increases as the solar radiation increases. This is attributed to the fact that higher solar radiation increases the thermal, thermophysical properties and heat transfer properties of the HTF and which in turn increases the heat transfer from the solar radiation into the heat transfer fluid circulating in the heat tubes of the solar panel. However, it can also be observed that the solar radiation the higher the thermal solar panel efficiency as illustrated in Figure 6. On the other hand, Figure 7 presents the temporal characteristics of the different heat absorbed by the thermal tank that represents heat released by the thermal solar panel to the heat transfer fluid circulating in the solar collector. Furthermore, Figure 8 illustrates the solar panel efficiency at different solar radiation without magnetization, where the results displayed in this figure, show that the higher the solar radiation the higher the solar panel efficiency. Figure 8 present one of the important characteristics of solar panels, which is the Efficiency-Heat absorbed curve. This characteristics curve presented in Figure 8 show that at a constant solar radiation the higher heat absorbed the higher the solar panel efficiency at different solar radiation without magnetization. This also demonstrates that the higher the solar radiation the higher heat released to the heat transfer fluid. On the other hand, Figure 9 illustrates the dynamic characteristics of solar panel efficiency without magnetization at solar radiation of 712 w/m2. It can be seen from the data displayed in this figure that with time progresses, more heat is transferred to the heat transfer fluid and consequently the efficiency increases which is due to the thermal capacity build up in the heat transfer fluid.

Figure 10 shows the solar panel characteristics without magnetization and it can be observed from the data presented in this figure and the aforementioned figures that the higher the solar radiation the higher the heat released and the higher the thermal solar collector efficiency.

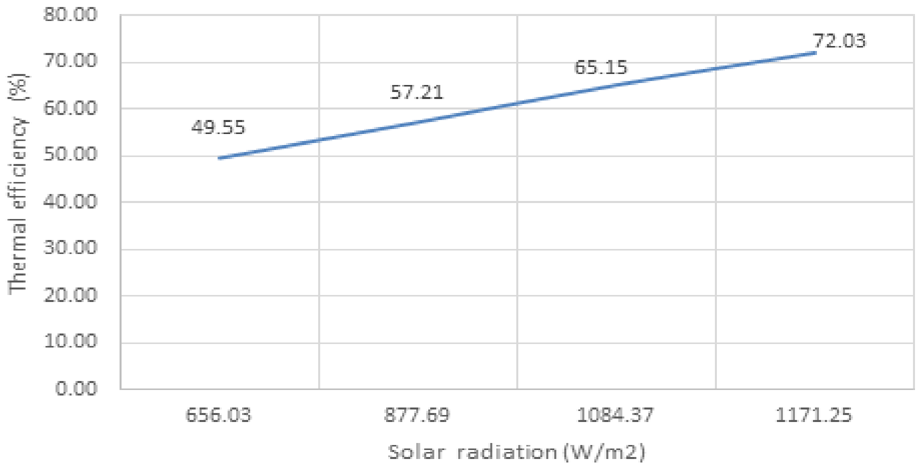

Figure-6. Thermal efficiency at different solar radiations without magnetization.

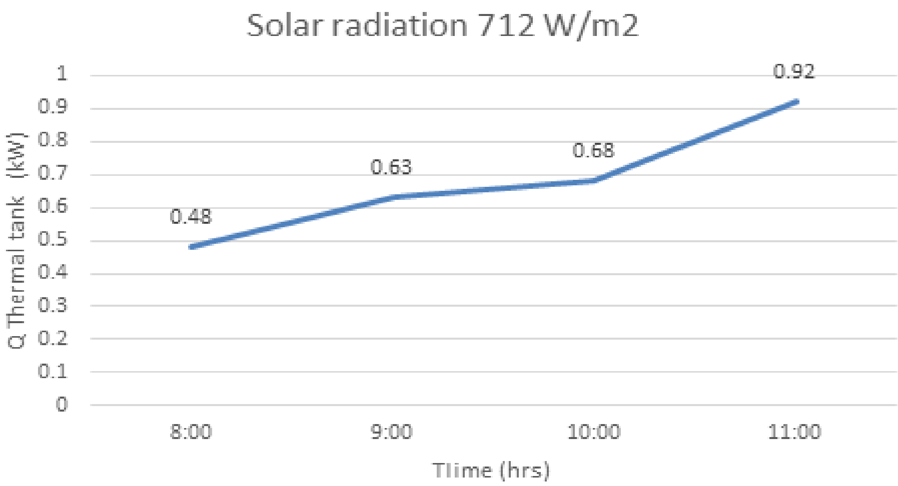

Figure-7. Temporal heat released at solar radiation 712 W/m2 without magnetization.

Figure 8 thermal heat released at different solar radiations without magnetization

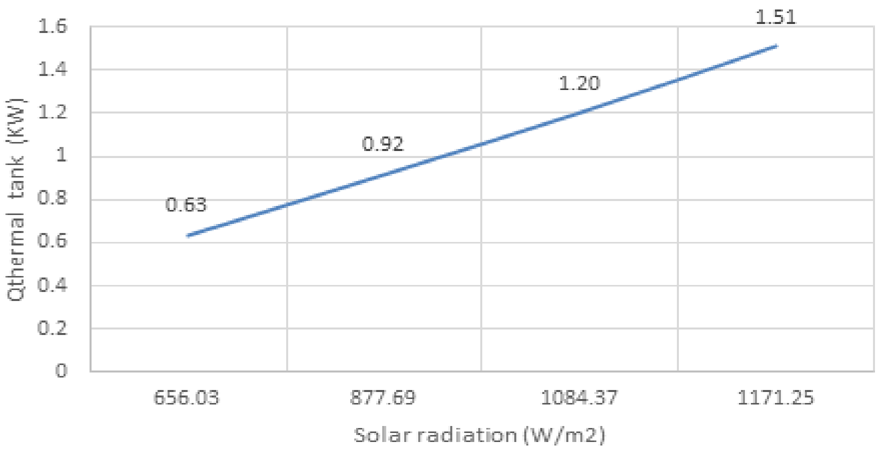

Figure-8. Heat released at 712 solar radiations without magnetization.

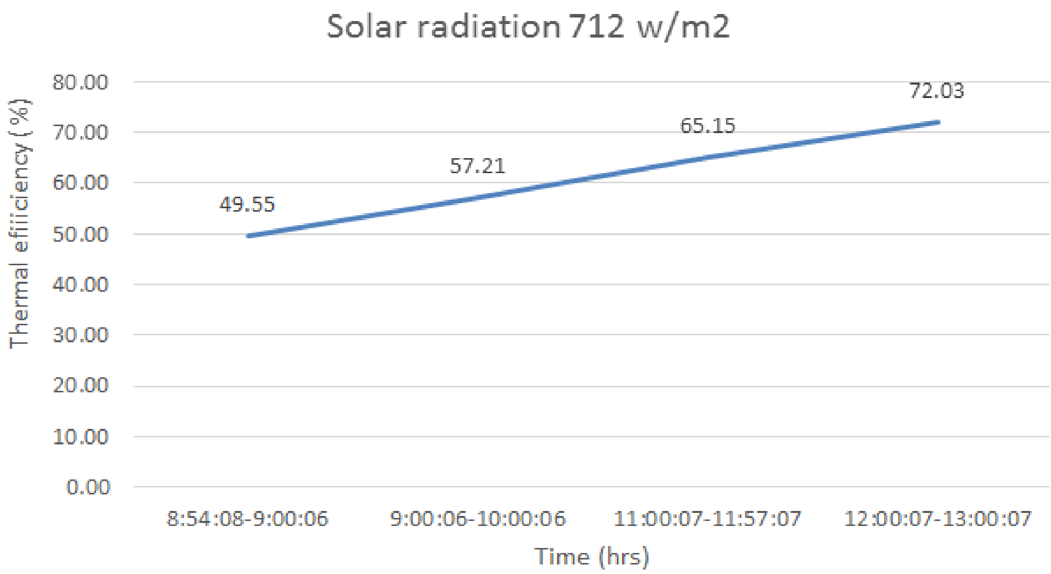

Figure-9. Dynamic characteristics of efficiency without magnetization.

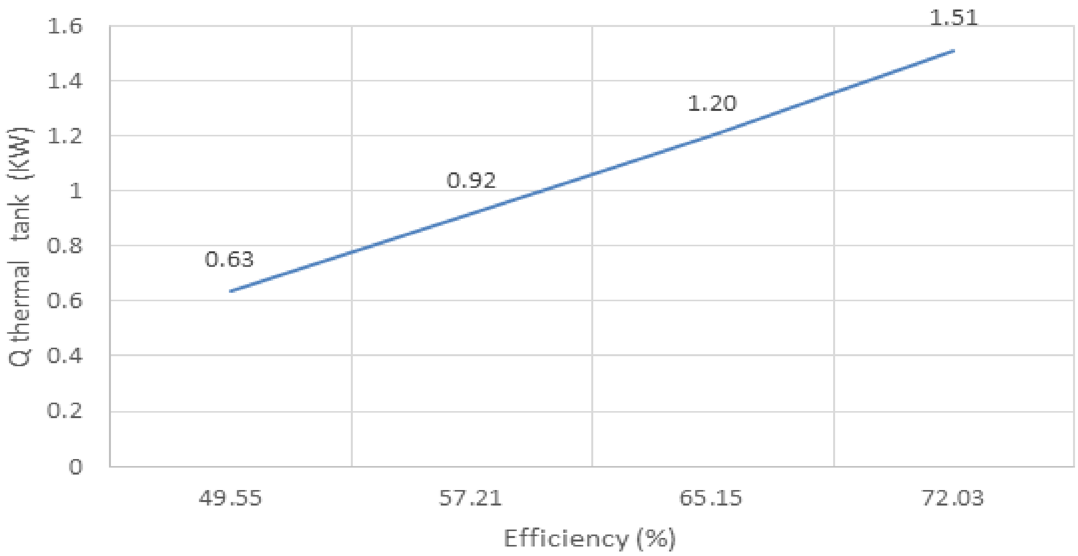

Figure-10. Thermal heat released at different efficiencies without magnetization at 712 W/m2.

On the other hand, the numerical simulated results of the solar panel efficiency calculated by Equation (8) were presented in the Figures 11 and 12 and compared to measures data for different solar radiations; 712 W/m2 and 500 W/m2. It can be observed from the simulated results presented in these figures that the model presented hereby predicted fairly the solar collector efficiency. However, there exist some discrepancies between 18 and 20% at solar radiations of 500 W/m2 and 712 W/m2, respectively. We believe that the discrepancy between the numerical prediction and the experimental data shown in Figures 11 and 12 can be attributed to the fact that the numerical model presented hereby does take into account the heat losses in the thermal solar loop and piping as well as the thermal tank and also can be attributed to the time-dependent variation of the solar radiation during the time of data collection.

Furthermore, the impact of magnetizing the heat transfer fluid circulating in the thermal solar loop is presented in Figures 13 through 16, on the different characteristics of the thermal solar panel such as the heat released and absorbed by the heat transport fluid and the efficiency of the thermal solar panel. In particular Figure 13 shows the thermal solar panel characteristic curve "Efficiency-Heat Absorbed" under magnetization and solar radiation of 712 W/m2, where it can see that the higher the solar radiation (C. F. Figure 15) the higher the heat released to the heat transfer fluid and the higher the thermal efficiency of the solar collector. The dynamic characteristics of thermal efficiency of the solar panel with magnetization at 712 w/m2 are presented in Figure 14, where it shows the increase of the thermal solar efficiency with time. Also as pointed out previously, Figure 15 illustrates the solar panel characteristics curve; Heat released-Efficiency at different efficiencies with magnetization, where it can be clearly seen from results presented in this figure that the higher the solar radiation the higher the efficiency. The other solar panel characteristic; efficiency is presented in Figure 16. Where, the solar panel efficiency as a function of solar radiations is shown in this figure under magnetization condition. It is quite clear from the results presented in this figure that the higher the solar radiation the higher the efficiency of the solar panel. This observation is similar to what has been observed during no magnetization.

Furthermore, in order to study the impact of magnetizing the heat transfer fluid circulating in the thermal solar collector on the solar panel characteristics Figures 17 and 18 were constructed. The data displayed in these figures show the heat released to the heat transfer fluid from the solar collector and the solar panel efficiency under magnetization and without magnetization at solar radiation of 712 and 500 W/m2, respectively.

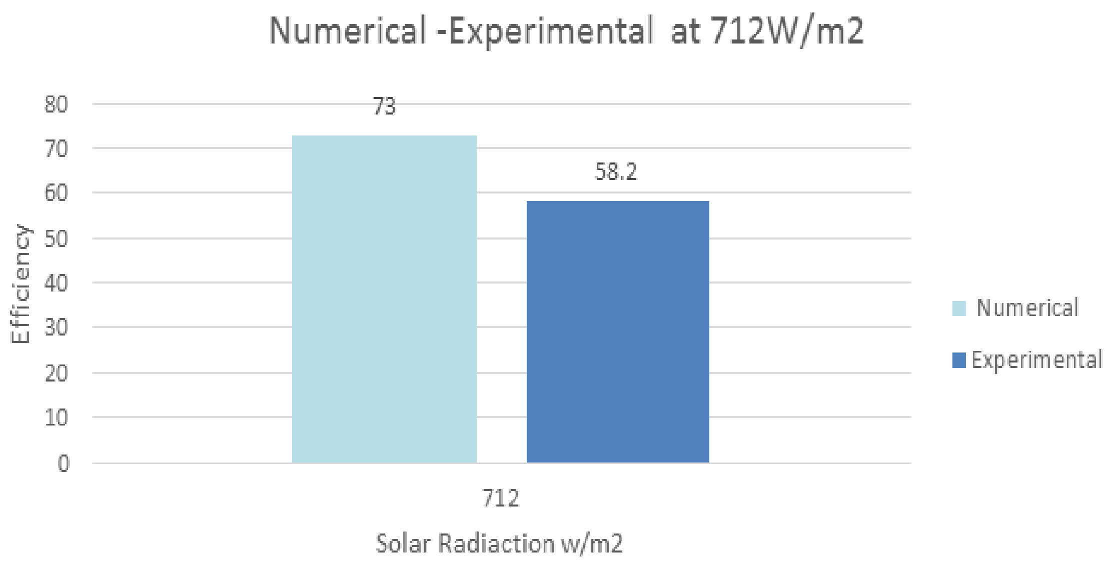

Figure-11. Comparison between thermal solar efficiency predicted 712 W/m2 without magnetization.

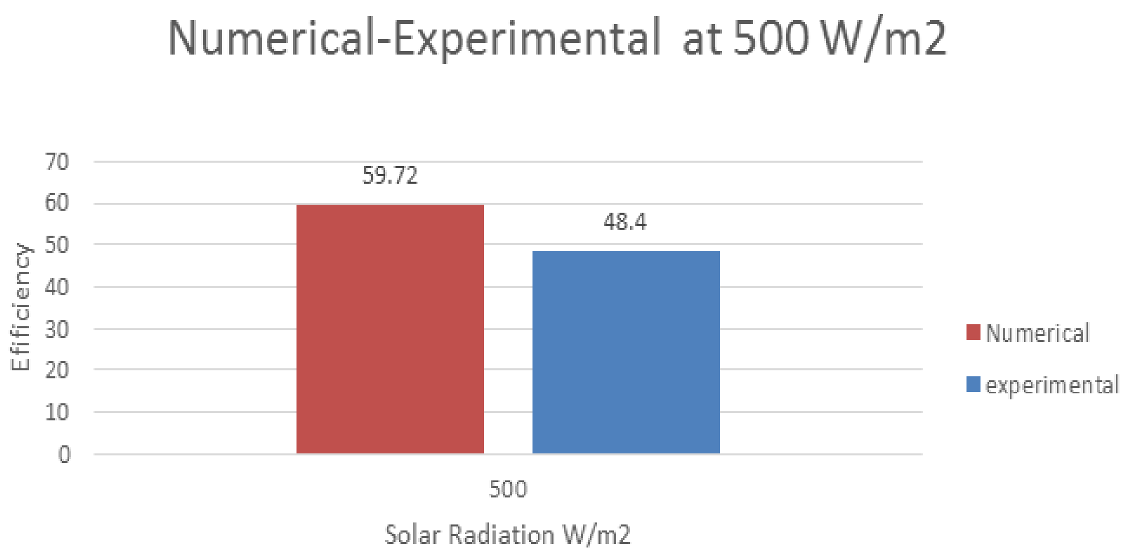

Figure-12. Comparison between thermal solar efficiency predicted 500 W/m2 without magnetization.

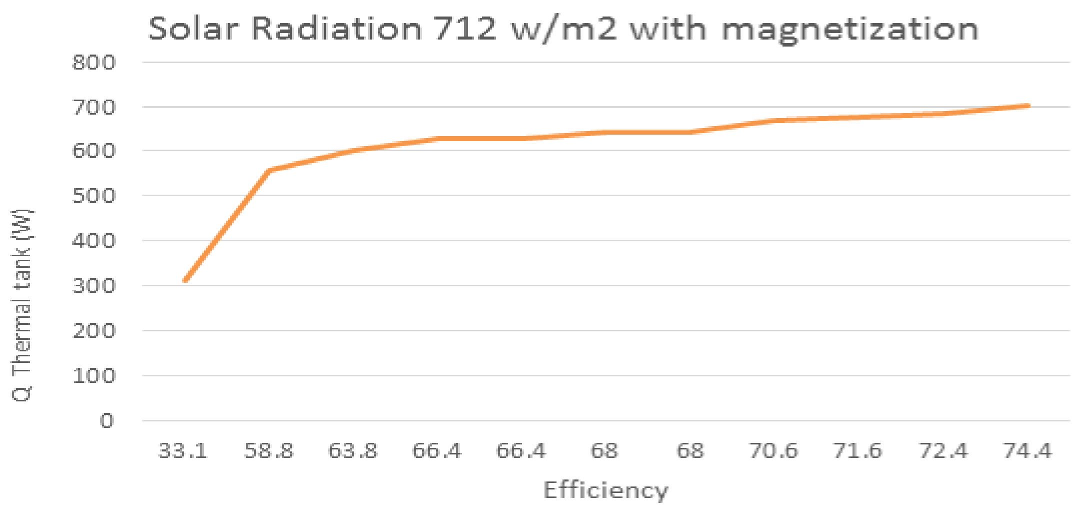

Figure-13. Solar panel characteristics with magnetization.

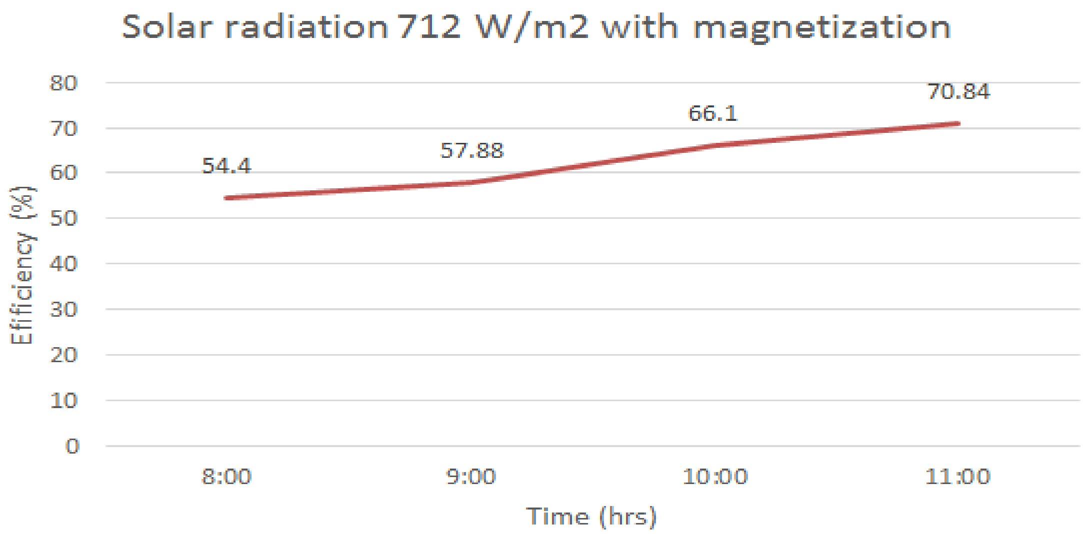

Figure-14. Dynamic characteristics of efficiency with magnetization at712 w/m2 with magnetization.

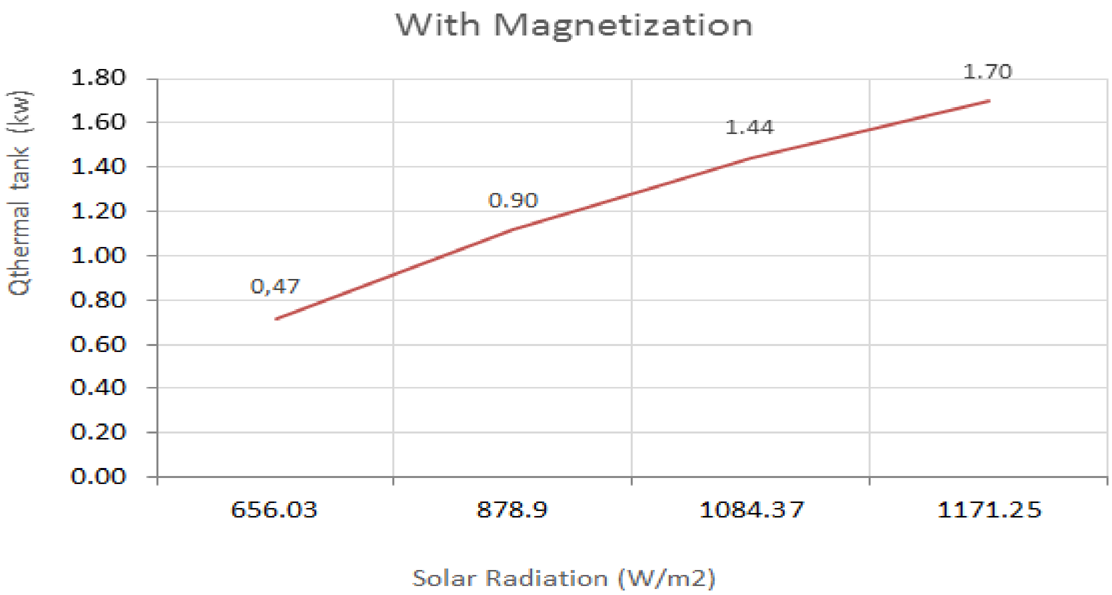

Figure-15. Solar Panel characteristics; heat released at different efficiencies with magnetization.

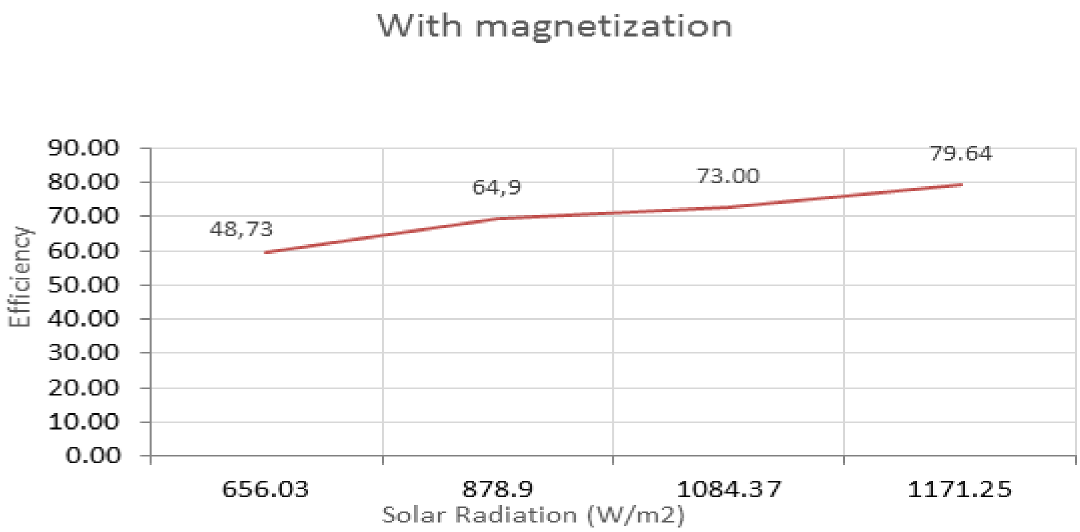

Figure-16. Solar Panel characteristics; efficiency at different solar radiations with magnetization.

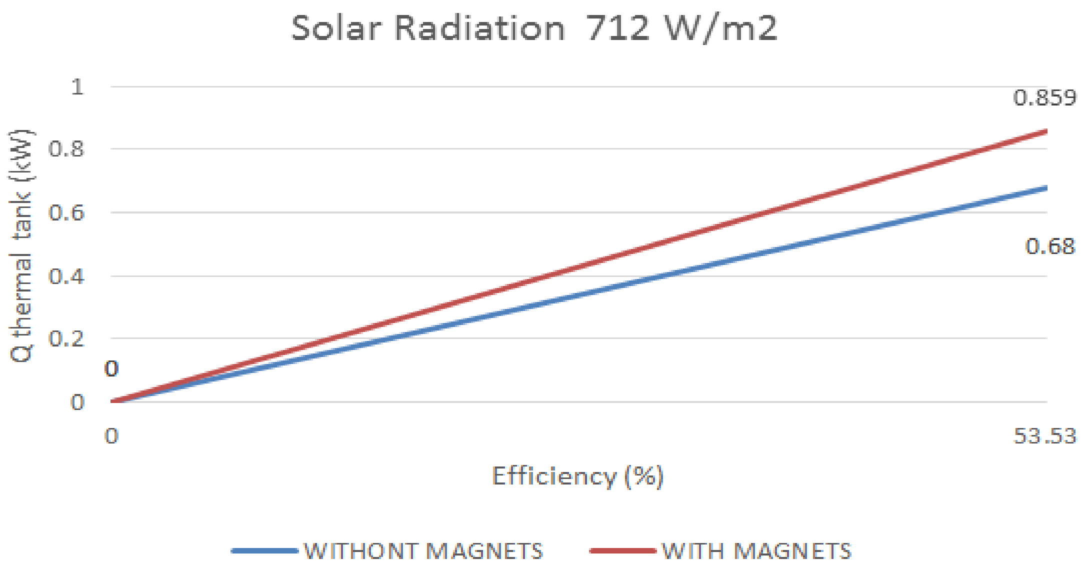

Figure-17. Solar Panel characteristics; heat released at 712 W/m2 solar radiation with and without magnetization.

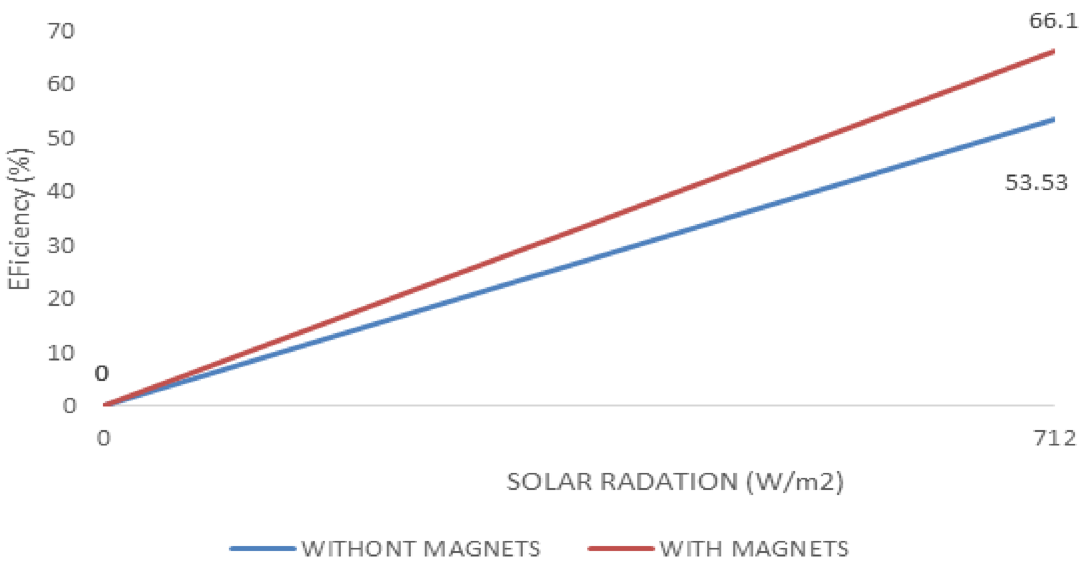

Figure-18. Solar panel efficiency at solar radiation 712 W/m2 with and without magnetization.

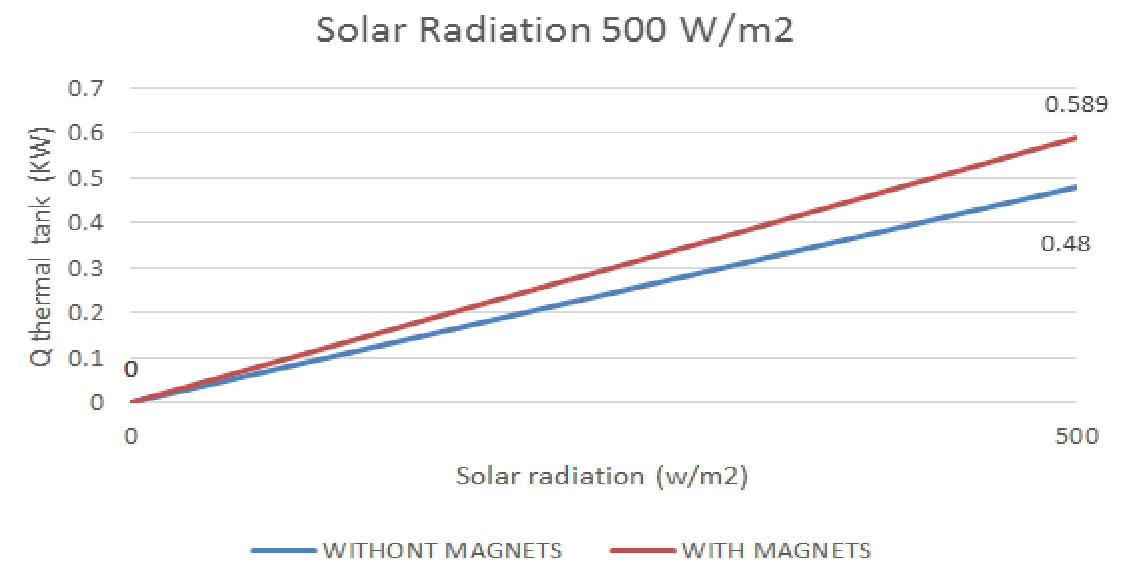

Figure-19. Solar panel heat released at 500 W/m2 solar radiations with and without magnetization.

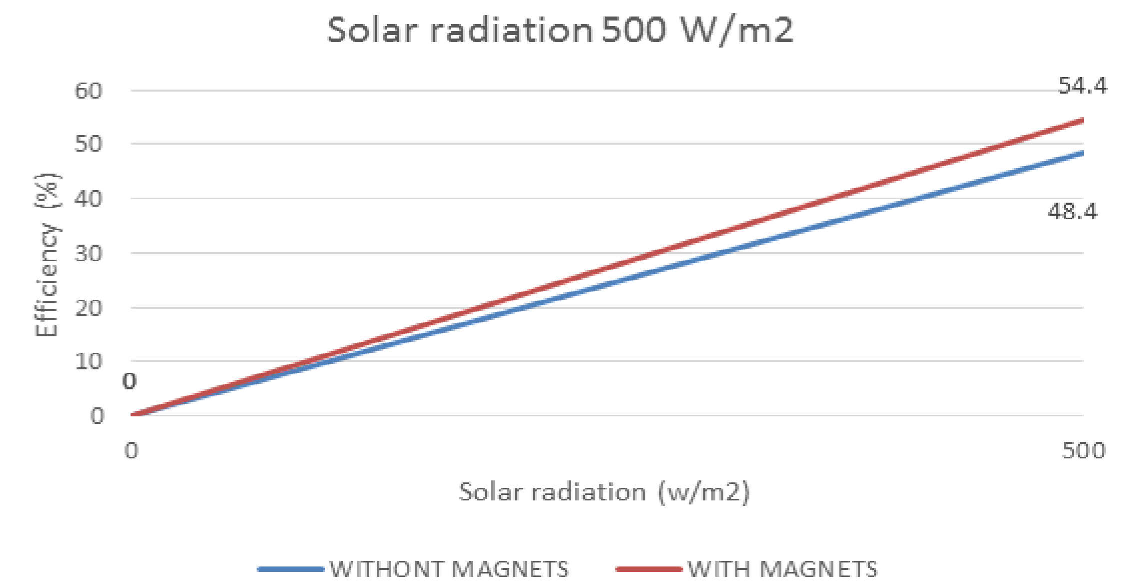

Figure-20. Solar panel efficiency at 500 W/m2 solar radiations with and without magnetization.

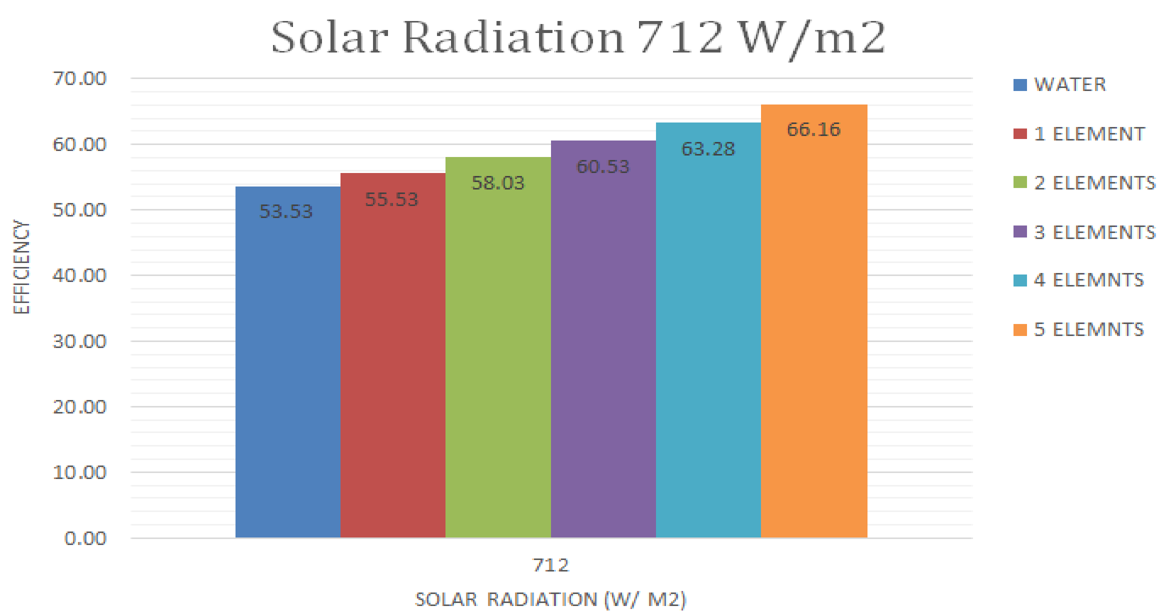

Figure-21. Solar panel efficiency at different magnetic elements.

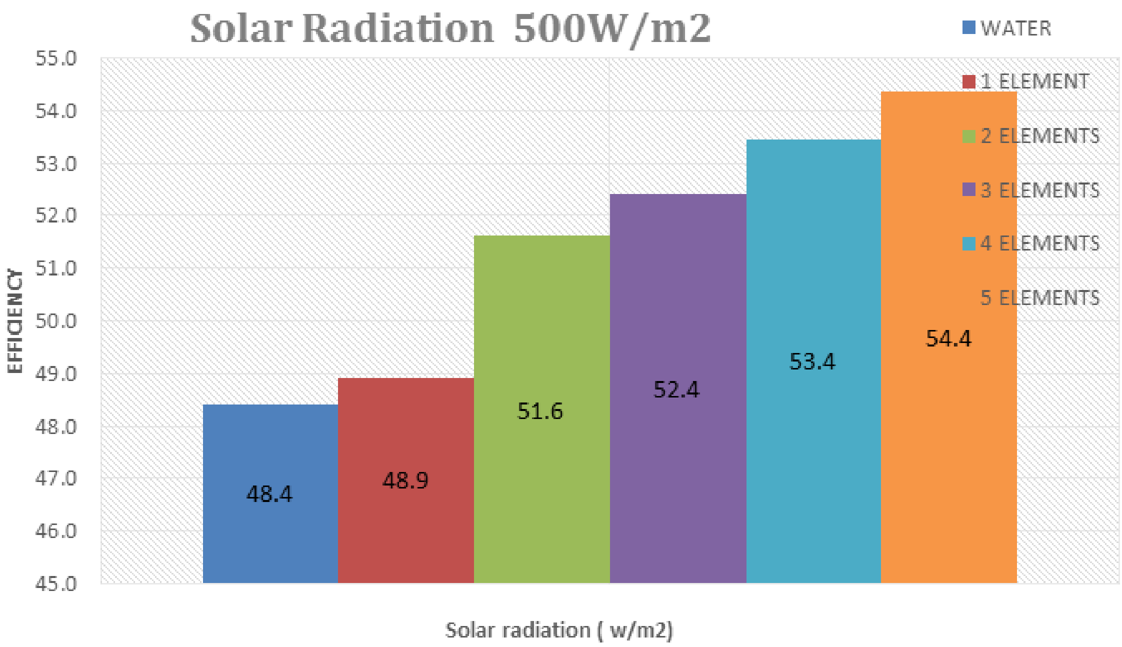

Figure-22. Solar panel efficiency at different magnetic elements.

It quite clear from the comparison presented in Figures 17 through 20 that there is an ample enhancement in the solar panel efficiency and the heat released from the solar panel with magnetizing the heat transfer fluid entering the solar collector. In addition, it can be seen that the higher the solar radiation the higher the enhancement of the solar panel efficiency and heat released. The results presented in these figures also show that the solar collector efficiencies have been increased with the use of the magnets by 23.6% and 12.7% at solar radiations conditions of 712 W/m2 and 500 W/m2, respectively.

It believed that an increase in cluster size in liquid water is caused by a magnetic field force which in turn increase the heat absorbed by the heat transfer fluid and that leads to the enhancement of the solar collector efficiency. This observation has been reported by Kitazawa *et al.* (2001) and supported in the literature by Cai *et al.* (2009); Seyfi *et al.* (2017). In addition, these effects are consistent with has been reported (Seyfi *et al.*, 2017) that the magnetic fields weakens the Van der Waals bonding forces between the water molecules, which in turn help to increase the thermal capacity and heat absorbed by the water i.e. heat transfer fluid .

Furthermore, the impact of different magnetic field Gauss power on the efficiency of the solar collector is illustrated in Figures 21 and 22 for 712 W/m2 and 500 W/m2, respectively. Where the efficiency is plotted at different magnetic elements and compared with water without magnetization as the base fluid before magnetization. It should be noted that each magnetic element has 3500 Gauss magnetic force. The application of the magnetic field was at 20 diameters from the pipe elbow before entering the thermal solar collector. The results shown in these two Figures 21 and 22 show clearly that the solar collector efficiencies have been increased with the use of the magnetic field (five magnets) by 23.6% and 12.7% at solar radiations conditions of 712 W/m2 and 500 W/m2, respectively, with full heat transfer fluid flow of 0.411 l/s circulating in the solar collector thermal loop.

The results displayed in particular in Figures 21 and 22 are extremely significant since they showed also that the higher the magnetic force in Gauss the higher the energy conversion efficiency of the thermal solar panel. In our opinion, this is due to the fact that the heat transfer fluid, water, is affected by magnetic field forces. The following contributes to our interpretation of impact of magnetic field on the enhancement of its thermal capacity and energy conversion efficiency of the heat transfer fluid. Water is diamagnetic and may be levitated in very high magnetic fields. Magnetic fields have shown to increase the number of monomer water molecules and increase the tetrahedrality at the same time as pointed out by reference (Kitazawa *et al.*, 2001). As previously pointed out ese effects are consistent with the magnetic fields weakening the Van der Waals bonding forces between the water molecules and since the water molecules are being more tightly bound, and due to the magnetic field the thermal motion of the inherent charges are increased, thus, reducing the interfacial forces between the molecules. Furthermore, this is in agreement with what has been reported in the literature (Kitazawa *et al.*, 2001; Cai *et al.*, 2009; Seyfi *et al.*, 2017) that such magnetic fields effect can also increase the heat transfer and the evaporation rate of water and the dissolution rate of oxygen.

Furthermore, in order to study the impact of magnetic field on solar collector performance at different flow rates of the heat transfer fluid. The data collected was presented in Figure 23 at 712 W/m2 solar radiation, which showed inconsistent variation of the solar collector energy conversion efficiency at 75% flow; 0.3088 l/s under different magnetic forces. The inconsistency of the results presented with the 75% flow of the heat transfer fluid can be attributed to what has been observed that the flow experienced turbulence and separations conditions in the boundary layer in the proximity of the pipe's wall that prevented the formation of the fully developed flow of the heat transfer fluid and not being in full contact with the pipe's wall. This limited the exposure of the flow to full magnetization by the applied magnetic field and it also can be noted that the magnetic force and the magnetization of the flow was never stabilized. This obviously, prevented the heat transfer from the solar energy to be fully released to the heat transfer fluid and thus resulted in inconsistency in the data collected under different magnets. This phenomenon has been observed for other flows less than the fully developed flow of the heat transfer fluid.

Furthermore, it should also be pointed out that it is highly recommended when magnetizing heat transfer fluids to avoid separation and turbulence conditions that may cause the flow not to be fully developed and magnetized. Similar phenomena in inconsistency of magnetization were observed at other solar radiations.

5. CONCLUSIONS

During the course of this study, the characteristics of heat transfer fluid (HTF) circulating in thermal solar panel and thermal tank loop have been studied with and without magnetization conditions of the flow.

Under no magnetization, a numerical model has been developed, presented, analyzed and compared to experimental data. This model was established after the energy and mass conservation equations coupled with the heat transfer equations of the heat transfer fluid. The numerical results presented in this paper showed an enhancement of the solar panel energy conversion efficiency and thermal heat absorbed by the heat transfer fluid (HTF) flow rate at higher solar radiation under magnetization conditions.

In addition, under no magnetization conditions, the simulated results of our numerical model presented hereby fairly predicted the heat transfer characteristics of the HTF such as the solar panel efficiencies, the heat transferred from the solar collector and compared well with experimental data.

Finally, under magnetization conditions using different magnetic elements, it was observed that the higher magnetic field force and the higher solar radiation the higher the thermal solar panel efficiency and heat released from the solar panels.

It is highly recommended when magnetizing heat transfer fluids to avoid separation and turbulence conditions that may cause the flow not to be fully magnetized. Similar phenomena of inconsistency of magnetization were observed at different solar radiations.

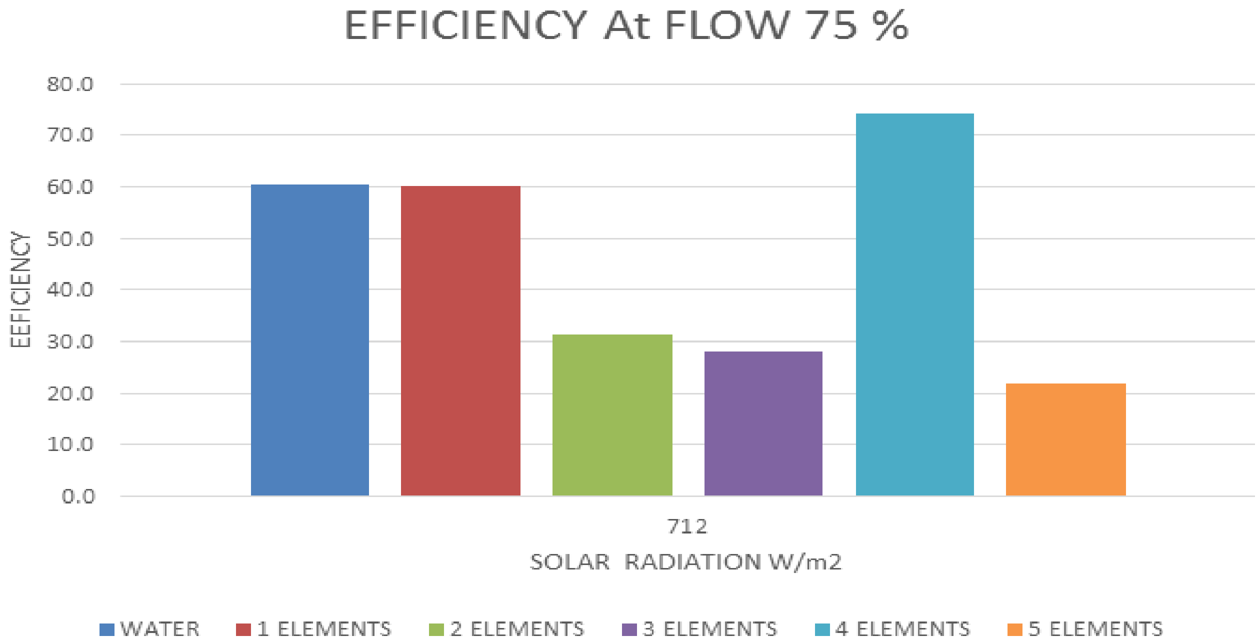

Figure-23. Solar panel efficiency at 75 % full flow 0.308 l/s using different magnetic elements and solar radiation 712 w/m2.

NOMENCLATURE

A_{Panel}, Area of solar panel (m^2)

A_f, Flow area (m^2)

C_{pw}, Specific heat of water (kJ/(kg K))

D_H, Hydraulic diameter (m)

G, Radiation (W/m^2)

h, Heat transfer coefficient

K_w, Thermal conductivity of water (kJ/(ms°C))

l, Tube length (m)

m_w, Water mass flow rate (kg/s)

N: number finite different element (N: 1-12)

Q_{tub}, Heat (kJ)

R, Tube radius (m)

$T_{(water]]\ \_m}$), Temperature of HTF at “m” element (°C)

Greek

ρ_w, Density of water flow (kg/m^3)

μ, Water viscosity (m^2/s)

Subscripts

H	Hydraulic
w	HTF
Tub	tube
w	Water

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