Investigation of Flat Plate Solar Collector using Al_2O_3-water Nanofluid

اختبار مجمع شمسي مسطح باستخدام مائع نانوني (ماء + أكسيد الومنيوم)

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الملخص:

تعتبر الطاقة الشمسية مصدر طبيعي واقتصادي للطاقة يمكن استخدامها في العديد من التطبيقات خاصة في تسخين المياه بالمنازل حيث تستغل كمية كبيرة من الطاقة الكهربية في تشغيل سخانات المياه. ومن ذلك المنطلق نالت المجمعات الشمسية اهتمام الباحثين من أجل توفير الطاقة ومنذ ظهور تكنولوجيا النانو والتي تحسن من خصائص المائع الحرارية والفيزيائية والكيميائية اتجهت الأبحاث حديثا إلى استخدامها في تطبيقات انتقال الحرارة بدلا من المياه والزيوت والجليكول كوسيط عامل في المجمعات الشمسية. وفي هذا البحث تم دراسة أداء مجمع شمسي عمليا باستخدام مائع نانوني (ماء + أكسيد الومونيوم) وتم مقارنة النتائج باستخدام الماء كوسيط عامل. أجريت التجارب على جهاز الاختبار بالمعهد العالي للهندسة والتكنولوجيا بمدينة دمياط الجديدة حيث تم اختبار أداء مجمع شمسي مسطح باستخدام الماء ومائع النانو المحتوى على جزيئات أكسيد الألمونيوم بقطر متوسط أقل من 40 nm بنسب تركيز حجمي قدرة $0.02 \leq \phi \leq 0.14$. أظهرت النتائج أنه يوجد تحسن في كفاءة المجمع بزيادة نسبة التركيز لجزيئات النانو في الوسط المضيف (المياه) تصل إلى 20.7% عند $\phi = 0.14$ وأن نسبة الزيادة في معامل انتقال الحرارة بالتوصيل الفعال يصل إلى حوالي 45% مقارنة باستخدام الماء كوسيط عامل .

ABSTRACT

Solar energy is a natural and economical source available to meet energy requirement for various purposes, especially for domestic ones where water heaters consume a considerable electric power. Solar collectors are therefore drawing the attention of all interested people for saving energy. Since nanotechnology exhibits novel and significantly improved physical and chemical properties of nanofluids, workforce development is therefore very essential to reap the benefits of this nanotechnology in solar collector applications. The present work investigates experimentally the performance of a flat plate solar collector using city water as well as AL_2O_3-water based nanofluid as a working media. The test rig was developed at New Damietta higher institute of engineering & technology to carry out the experiments. Heat transfer rates were calculated using existing relationships in the literature for conventional fluids and nanofluids. The effect of nanoparticle concentration by volume, ϕ on thermal conductivity of nanofluid and on the collector efficiency under operational conditions was investigated. The used concentration value was $0.02 \leq \phi \leq 0.14$. Solar collector efficiency on daily basis increased with the increase of nanoparticle concentration, ϕ. At ϕ =0.14, the increase in thermal conductivity of nanofluid was about 45% and in collector efficiency of about 20.7% compared with those when city water was used, respectively.

Keywords: Solar energy, solar collectors, nanofluids, heat transfer, convection

NOMENCLATURE

A	Area, m^2
A_t	Total side and back area, m^2
C_p	Heat capacity, J/kg.K
D	Tube diameter, m
E	Voltage, V
h	Heat transfer coefficient, $W/m^2.K$
I	Intensity of solar radiation, W/m^2
L	Length of the collector, m
K	Thermal conductivity, W/m.K
m	Mass, kg
Nu	Nusselt number, dimensionless
Q	Rate of absorbed heat, W
T	Temperature, K
V	Volume, m^3
v_w	Wind speed, m/s
W	Width of the collector, m

Greek symbols

ε	Emissivity, dimensionless
Δ	Difference
σ	Stefan Boltzmann constant, 5.67×10^{-8} $W/m^2.K^4$
η	Efficiency
ϕ	Volume fraction of nanoparticles, m^3/m^3
ρ	Density, kg/m^3
μ	Dynamic viscosity, kg.m/s

Subscripts

a	Ambient
bb	Back box
bf	Base fluid
bp	Back plate
d	Daily
eff	Effective
G	Glass
i	Inlet
in	Instantaneous
L	Loss
L,b	Back losses
L,c	Loss due to convection
L,r	Loss due to radiation
m	Mean
nf	Nanofluid
o	Outlet
p	Particle
t	Tank
tot	Utilized in daily bases
u	Utilized in half an hour (instantaneous)
1,2	Initial & final, respectively

1. INTRODUCTION

The amount of solar energy which strikes the earth's surface in any given area depends on the location and weather conditions. But it averages out to around 1,000 W/m^2, under good weather conditions, when the sun's rays are perpendicular to the earth's surface. We have often heard about power shortage and scarcity of energy but it is so unfortunate that several watts of energy everyday are being wasted. Solar collector is therefore used in extracting the sun energy into more usable or storable form.

A solar water heater is a device which is essential to any solar heating system. It gathers the sun's energy, converts it into heat, and then transfers the heat into absorbing medium. This device is mainly used in water heating systems, pool heaters, and space heating systems with a negligible maintenance cost.

Solar water heaters are perhaps one of the most efficient ways for helping persons to get a sustainable lifestyle. Unlike other heating elements, solar water heaters keep the water hot throughout the day by making use of solar energy. The solar water heaters keep the water hot even in winter by producing minimum amount of energy.

Solar energy has the greatest potential of all the sources of renewable energy of methods introduced to enhance the efficiency of the solar collectors. But the novel approach is to introduce the nanofluids as a working fluid instead of conventional heat transfer fluids (like water). The poor heat transfer properties of these conventional fluids compared to most solids are the primary obstacle to the high compactness and effectiveness of the system. The essential initiative is to seek the solid particles having thermal conductivity of several hundred times higher than those of conventional fluids. An innovative idea is to suspend ultrafine solid particles in the fluid for improving its thermal conductivity.

The ideal thermal collector should efficiently absorb solar radiation in the wavelength range $0.25 < \lambda < 2.5$ μm, minimize heat loss by convection and radiation and keep system fouling / clogging and pumping costs to a minimum.

National Science Foundation [1] was the first to define nanotechnology. It is the creation and utilization of functional materials, systems with novel properties and functions that are achieved through the control of matter, atom-by-atom, and molecule by molecule or at the macro molecular level. A unique challenge exists to include nanoscale science and engineering concepts. The advances in nanotechnology have resulted in the development of a category of fluids termed nanofluids, first used by a group at the Argonne National Laboratory in 1995 [2]. Nanofluids are suspensions containing particles that are significantly smaller than 100 nm [3], and have a bulk solid thermal conductivity of orders of magnitudes higher than the base fluids.

Experimental studies conducted by [4-5-6] have shown that the effective thermal conductivity increases under macroscopically stationary conditions. Under laminar flow conditions, nanofluids in microchannels have shown a two fold reduction in thermal resistance [7] and dissipate heat power three times more than that of pure water. Studies conducted using Cu-water nanofluids of concentrations approximately 2% by volume was shown to have a heat transfer coefficient 60% higher than when pure water was used [8].

Some researchers have found moderate enhancements in thermal conductivity, but many have observed large enhancements with increasing volume fraction of nanoprticle in the base fluid. Murshed et al., [9] experimentally and theoretically studied the effective thermal conductivity and viscosity of nanofluids. The thermal conductivity and viscosity of nanofluids were measured and found to be substantially higher than the values of the base fluids. The thermal conductivity of nanofluids was also observed to be strongly dependent on the temperature.

The basic concept of using particles to collect solar energy was studied in the 1970s by Hunt [10] and Masuda et al., [11] who mixed particles into a gaseous working fluid. In the past 10 years or so, particles receivers have been extensively modeled and several prototype collectors have been built and tested. However, most of this work was devoted to find reversible chemical reactions to generate hydrogen or some other chemical fuel.

The volume fraction of nanoparticles in the base fluid must be chosen carefully to get the most out of nanofluid. If the concentration of nanoparticle is too high, all the sunlight will be absorbed in a thin layer near the surface of the receiver. If the concentration is too low, a significant portion of the light will be transmitted out of the fluid. Ideally, the least amount of particles needed to effectively absorb light will be used to minimize cost. These suspended nanoparticles change the transport properties and heat transfer characteristics of the base fluid.

In solar power plants nanoparticles provide too many benefits such as: allowing them to pass through pumps and plumbing without adverse effects, can absorb energy directly, can be optically selective, more uniform receiver temperature can be achieved inside the collector, enhanced heat transfer via greater convection and thermal conductivity which improve receiver performance, and enhance the absorption efficiency by tuning the nanoparticle size and shape to the application.

Since there are no commercial nanofluid solar collectors yet, this section will outline our assumptions, reasoning, and choices made in designing one. As mentioned above, nanofluids are a mixture of very small – sized particles and the conventional liquids used in a given application. Therefore, the first design choices to be made are in selecting those two components. Common base liquids in solar collector are water, heat transfer oil, or molten salt. The choice between these liquids is usually determined by the required operating temperatures. Water is commonly used for low temperature ranges (40-100℃). For efficient solar collection, the particles need to be highly absorptive, which limits our study to metallic particles.

In the present paper, experiments are performed using city water as well as Al_2O_3-water based nanofluid as a working fluids. The performance of the flat plate solar collector is investigated. City water is first used as an absorption medium. The effect of Al_2O_3 nanoprticle concentration, ϕ on the thermal conductivity as well as its effect on the instantaneous and daily efficiency of the flat plate solar collector is also investigated.

2. TEST RIG

2.1 Description of the test loop

A schematics illustration of the experimental test loop is presented in Fig. 1. It consists of (1) insulated hot water tank, (2) circulating pump (3) flat plate solar collector and pipes connecting in between these components. An isometric of the apparatus is shown in Fig 2.

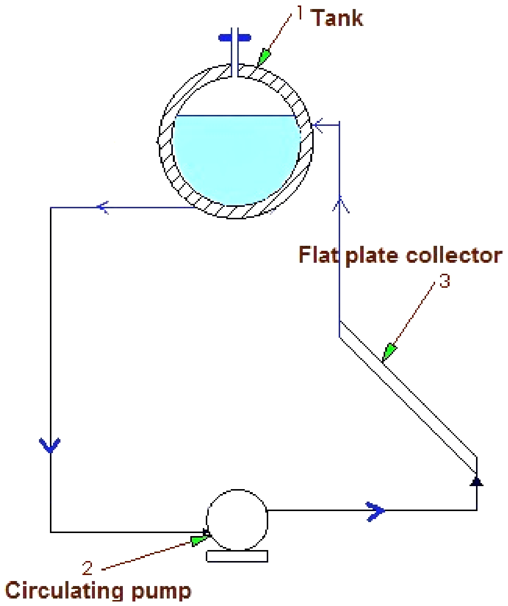

Fig. 1 Schematic illustration of the experimental test loop

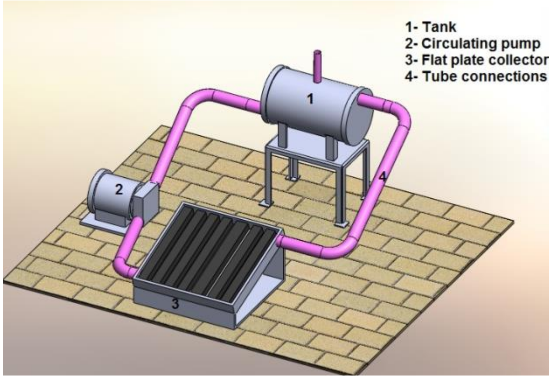

Fig. 2 Isometric of the experimental apparatus

The test rig is installed at higher institute of engineering & technology in New Damietta, Egypt (latitude 31.5° N).

The experiments were performed using city water first and then AL_2O_3-water based nanofluid as a working media. The working medium is flowing by a 20 W circulating pump at a rate of 0.05 L/s into the lower header of the flat plate collector. The absorber plate has 7 red copper tubes of 28 mm diameter welded to the lower and upper header of that collector which has a surface area of 0.9 m^2 as shown in Fig. 3.

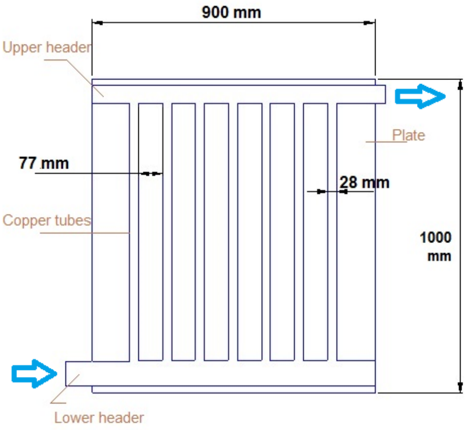

Fig. 3 Cross section of collector arrangement

The absorption surface of the collector is coated with selective coating of high absorptive and low radiation coefficient and its back casing is made of galvanized steel as shown in Fig. 4.

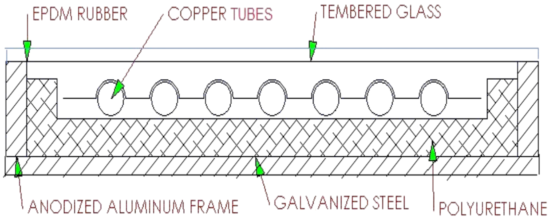

Fig. 4 Cross section of absorber plate

The flowing water receives solar radiation and gets hotter, then flow into the hot water tank via the upper header of the collector. The tank of 60 liters capacity is made from galvanized steel of two layers filled with Polyurethane insulation as shown in Fig. 5. The total amount of water in the tank was 25 liters.

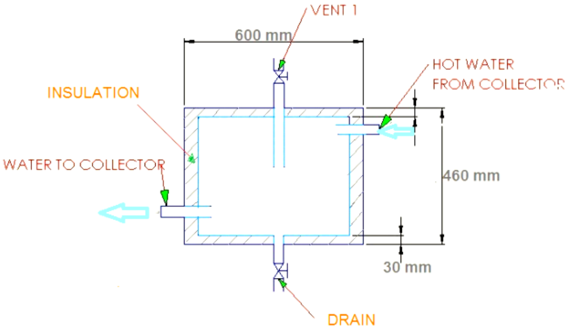

Fig. 5 Cross section of the tank

The collector frame is made of anodized aluminum and equipped for easy installation, and it is carried by steel structure coated by electrostatic paint, the title angle of the flat plate collector can be changed towards the sun from 19^{o} at summer to 49^{o} at winter by using a suitable mechanism as shown in Fig. 6. The working medium is continuously re-circulated through the collector to the hot water tank so that the temperature in the tank gradually builds up.

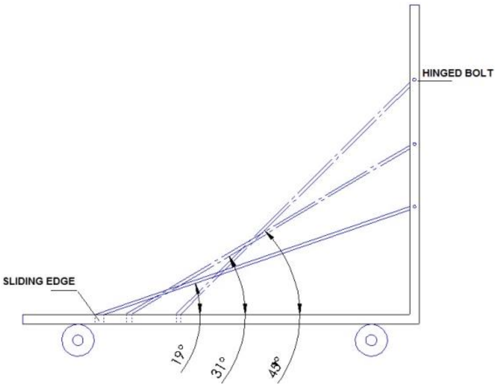

Fig. 6 Schematic of tilt angle variation mechanism

2.2 Temperature measurement

To investigate the performance of the solar collector, heat transfer calculations must be achieved through the measurements of temperatures of the ambient, the glass cover, inlet and exit temperature of the working medium and the temperature of the flat plate. Ten thermocouples type T are used to measure the temperature at the positions which are needed for heat transfer calculations, absorbed heat, heat loss by radiation and that due to convection. Two thermocouples are used to measure inlet/exit temperature of working fluid, one for ambient, one for glass cover, one for hot water inside the tank and the rest five are distributed among the flat plate to measure the average temperature of the plate surface. All thermocouples are connected to a multi-temperature recorder via a selector switch. To ensure the accuracy of the temperature readings, all thermocouples are calibrated with mercury thermometer.

2.3 Solar radiation intensity measurement

Solar radiation intensity was measured by photovoltaic cell, which is initially calibrated with perheliometer. It gives an output voltage reading which is directly proportional to the intensity of the solar radiation. The relation between the output voltage, E and solar intensity, I of the calibrated cell formulated as follow,

$$I = 0.000143539 \times E^{6.15344}, \text{ W/m}^2 \qquad (1)$$

3. DATA REDUCTION

To carry out the necessary heat transfer calculations, the experimental data related to the solar collector and the working fluid flowing inside the tested loop were measured. These measurements include the temperatures of collector plate, inlet/outlet of the working fluid, and the ambient one. The intensity of solar radiation was also measured. The existing thermo physical properties in the literature for conventional fluids and nanofluids are then used for these calculations.

3.1 Nanofluid thermo-physical properties

Thermo and physical properties of nanofluids are calculated using the formulas summarized by Buongiorno [12]. The following relation can be used for calculating nanofluid density as

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \qquad (2)$$

Where; ϕ is the nanoparticle volume fraction of AL_2O_3-water nanofluid.

It should be noted that for calculating the specific heat of nanofluid some of prior researchers have used the following correlation [12]

$$c_{p_{nf}} = (1-\phi)c_{p_{bf}} + \phi c_{p_p} \qquad (3)$$

Batchelor [13] considered the effect of the Brownian motion of particles for an isotropic suspension of spherical particles, and the viscosity of nanofluid can be calculated therefore by

$$\mu_{nf} = (1+2.5\phi)\mu_{bf} \qquad (4)$$

The most commonly used thermal conductivity equation was proposed by Hamilton and Crosser [14] for the mixtures containing micrometer size particles. They assumed that the following equation is applicable for the nanofluids as well

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + (n-1)k_{bf} - (n-1)\phi(k_{bf} - k_p)}{k_p + (n-1)k_{bf} + \phi(k_{bf} - k_p)} \qquad (5)$$

In the above equation n is the shape factor where given by

$$n = \frac{3}{\psi} \qquad (6)$$

Where ψ is the sphericity, defined as the ratio of the surface area of a sphere with a volume equal to that of the particle to the surface area of the particle and is equal to 3 for spherical nanoparticles. X. Zhang et al. [15] have showed that this correlation accurately predicts the thermal conductivity of nanofluids. The properties of base fluid (water) at different temperatures are available in [16].

3.2 Useful heat from solar radiation

Mass of the fluid in the whole system can be calculated from the following equation

$$m = \rho V \qquad (7)$$

Where: ρ, V are the density and the volume of fluid, respectively.

The amount of useful heat by solar collector can be calculated as:

$$Q_u = \frac{mc_p(T_2 - T_1)}{time \text{ int} erval} \qquad (8)$$

Where, T_1, T_2 are the initial and final temperature of the water in the tank at a period of half an hour. The useful heat flux, q can then be calculated as

$$q_u = \frac{Q_u}{A} \qquad (9)$$

Where, A is the surface area of the collector (A= W L), m^2

3.3 Solar collector efficiency

The instant efficiency of the solar collector, η_{in} is given by

$$\eta_{in} = \frac{Q_u}{I \times A} \times 100\ \% \qquad (10)$$

Where: I is the intensity of solar radiation (W/m^2)

The daily efficiency of solar collector, η_d can be obtained from the following relation

$$\eta_d = \frac{\sum Q_u}{\sum I \times A} \times 100\ \% \qquad (11)$$

3.4 Convective heat transfer coefficient

The convective heat transfer coefficient, h can be calculated as:

$$h = \frac{q_u}{T_p - T_m} \qquad (12)$$

Where: q_u is the useful heat flux and (T_p-T_m) is the temperature difference between the average temperatures of the plate, T_p and that of the working fluid, T_m, respectively. The Nusselt number is then given by

$$Nu = {h \times D}/{k} \qquad (13)$$

Where, K and D are thermal conductivity of the working fluid and tube collector diameter, respectively.

3.5 Total Heat Loss

Heat loss from collector is due to convection, radiation and back losses. It can be calculated from the following equations.

$$Q_L = Q_{L,r} + Q_{L,c} + Q_{L,b} \qquad (14)$$

Where

$$Q_{L,r} = \varepsilon\, \sigma\, A\left(T_G^{\,4} - T_s^{\,4}\right) \qquad (15)$$

$$Q_{L,c} = h_c A\left(T_G - T_a\right) \qquad (16)$$

$$Q_{L,b} = kA_t\left(T_{bp} - T_b\right) \qquad (17)$$

Where, $Q_{L,b}$ is very small so we can neglect it. T_s is the sky temperature and h_c is the convective heat transfer coefficient of the surrounding atmosphere. It can be calculated from the following empirical equation.

$$h_c = 10.45 - v_w + 10 v_w^{\,0.5} \qquad (18)$$

Where, v_w is the wind speed.

4. RESULTS AND DISCUSSION

4.1 Using city water

Preliminary experiments with city water as a working fluid were performed to study the performance of the flat plate solar collector at a given water flow rate (0.05 lit/s). Fig. 7 shows the variation of sun's light intensity during the day time. The results were taken at Jan. 2, 2014 from 9.00 am to 17.00 pm. It is seen that the intensity of light goes up until its maximum value at noon. The light intensity is then dramatically decreases as the time proceed until it gets its lower value near the time of sun set.

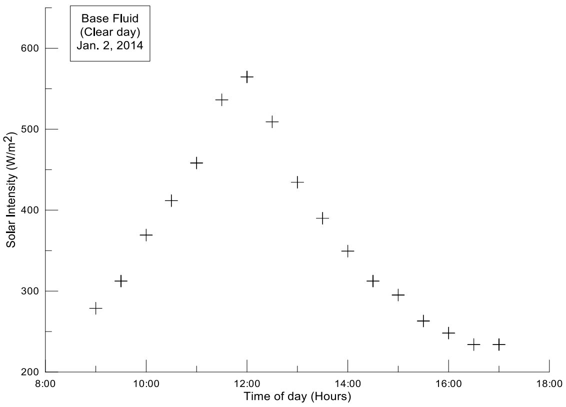

Fig. 7 Variation of the solar intensity during the day time (Jan. 2, 2014)

Fig. 8 shows the plot of plate and fluid tank temperatures versus day time. It is seen that all temperatures increase with increasing day-time due to the increase of radiation intensity. The results were taken at Jan. 2, 2014

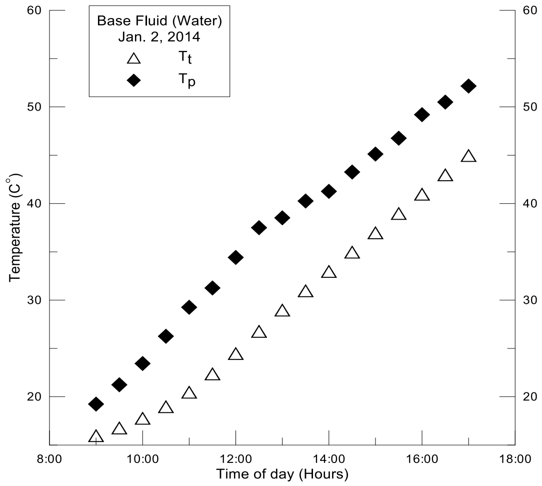

Fig. 8 Variation of the Plate and water tank temperatures versus the daytime (Jan. 2, 2014)

Fig. 9 shows the plot of the temperature difference, $(T_o\text{-}T_i)$ between outlet and inlet fluid temperature from the collector against day time when using city water as a working medium. It can be noticed that with increasing day time the temperature difference, starts to increase gradually until mid day, where it gets maximum value. This is due to the high intensity of solar radiation at that time.

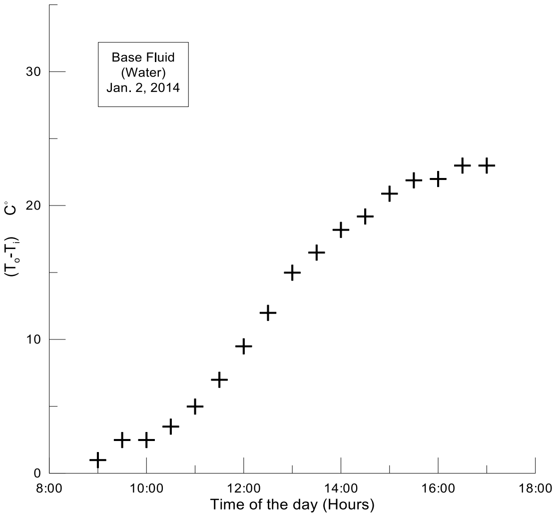

Fig. 9 $(T_o\text{-}T_i)$ versus day time (Jan. 2, 2014)

Fig. 10 shows the variation of the collector efficiency with $\left(\frac{T_i - T_a}{I}\right)$ in case of city water as a working medium. It can be noticed that the efficiency is dramatically decreased with the increase of $\left(\frac{T_i - T_a}{I}\right)$.

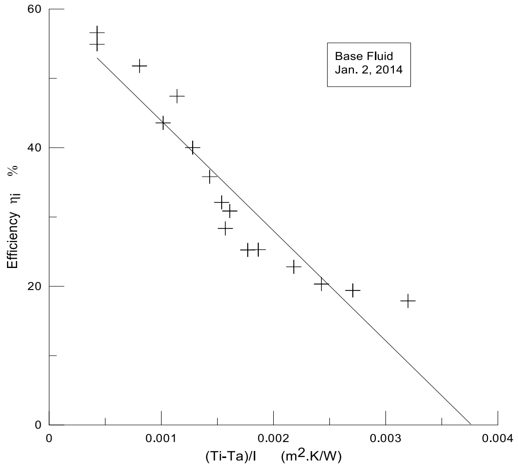

Fig. 10 Effect of $\frac{T_i - T_a}{I}$ on the Collector efficiency, (Jan. 2, 2014)

4.2 Using AL_2O_3-water bases nanofluid

The intensity of solar energy is measured through the whole day time each half an hour. Figs 11upto16 represent the solar intensity versus time when using nanofluid with different concentrations 0.02, 0.04, 0.06, 0.08, 0.10 and 0.14, respectively, as a working medium. It can be observed that the intensity dramatically increased with time. It gets its maximum value at the noon, where it started to decrease again. The lowest intensity was detected near the time sunset.

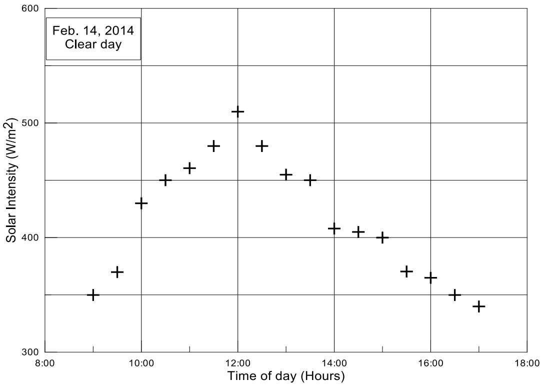

Fig. 11 Variation of the solar intensity during the day time, (ϕ=0.02).

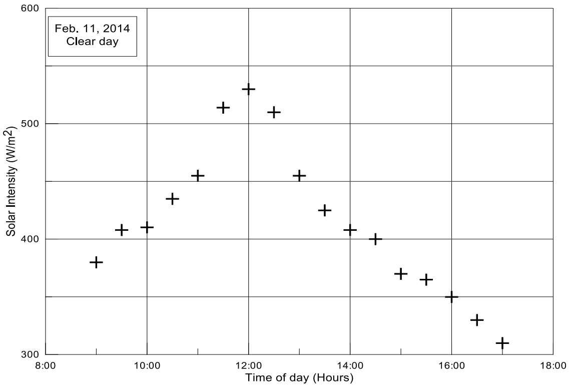

Fig. 12 Variation of the solar intensity during the day time, (ϕ=0.04).

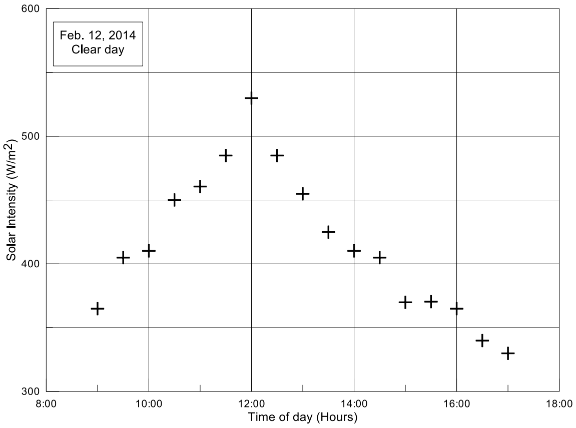

Fig. 13 Variation of the solar intensity during the day time, (ϕ=0.06).

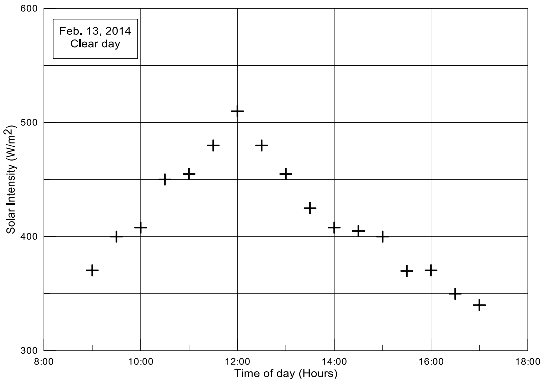

Fig. 14 Variation of the solar intensity during the day time, (ϕ=0.08).

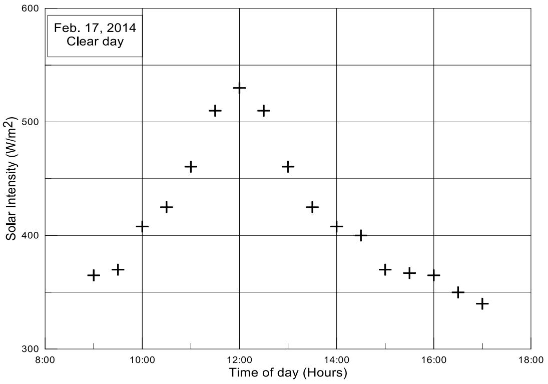

Fig. 15 Variation of the solar intensity during the day time, (ϕ=0.10).

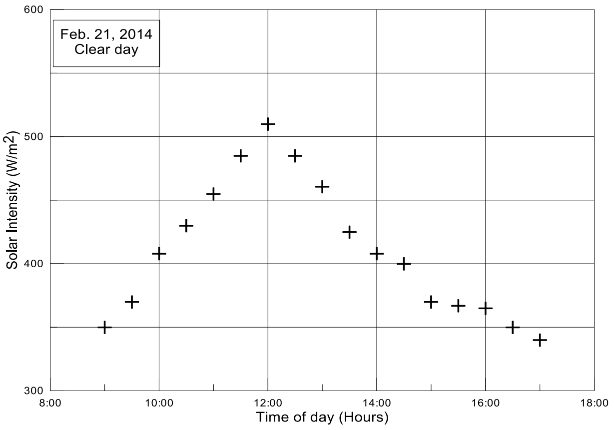

Fig. 16 Variation of the solar intensity during the day time, (ϕ=0.14).

Figs 17 and 18 show the effect of using nanofluid with different concentrations 0.02, 0.04, 0.06, 0.08, 0.10 and 0.14 on outlet fluid temperature from collector and that for its plate, respectively, the results were taken on 11, 12, 13, 14, 17 and 23 Feb.2014, respectively. It is noticed that as the value of ϕ increases, both the outlet temperature of the working fluid and that for collector plate increases. This means that the presence of nanoparticles in the base fluid increases the rate of absorbed heat from solar radiation.

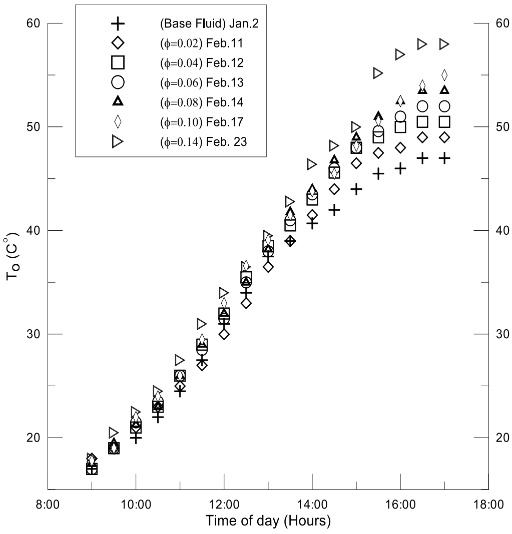

Fig. 17 Effect of volume fraction, ϕ on the outlet temperature, T_o

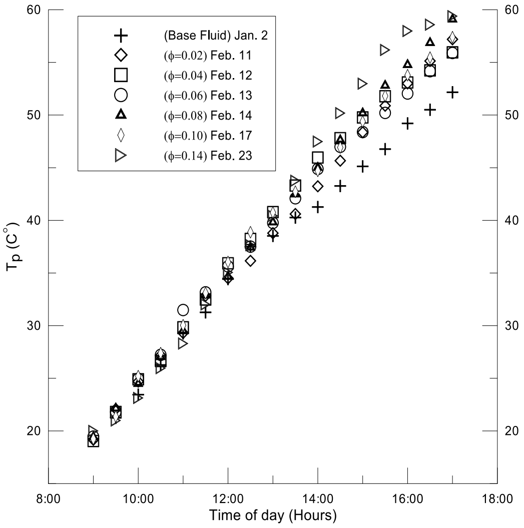

Fig. 18 Effect of volume fraction, ϕ on the plate temperature, T_p

Fig 19 shows the effect of using nanofluid with different concentrations 0.02, 0.04, 0.06, 0.08, 0.10 and 0.14 on (T_o-T_i). It is seen that the variation of ΔT with time have the same trend as that for pure water. In the meantime the temperature difference, ΔT increases with the increase of nanoparticle concentration. This is due to the increase of extracted heat from solar radiation with increasing nanoparticle concentration.

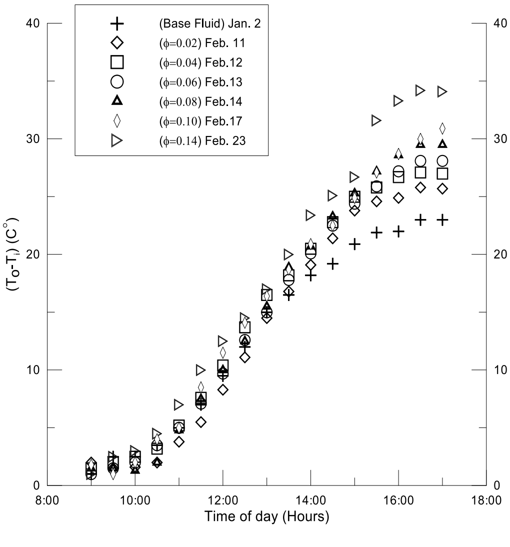

Fig. 19 Effect of volume fraction, ϕ on the temperature difference(T_o-T_i)

Fig. 20 shows the variation of collector efficiency, η on a daily basis with ($\frac{T_i - T_a}{I}$) in case of using Al_2O_3-water nanofluid as a working media over the above mentioned range of ϕ, It can be observed that the value of η is sharply decreased with the increase of ($\frac{T_i - T_a}{I}$) and has the same behavior as noticed with using city water. The relation is nearly a straight line.

Using nanofluid instead of city water as a working fluid improved the performance of solar collector as discussed earlier, this mainly due to the improvement in heat extraction mechanism due to the presence of nanoparticles in the base fluid. Fig. 21 shows the effect of volume fraction, ϕ on daily efficiency, η_d of the collector. It is seen that the efficiency of the collector greatly increased with the increase of ϕ.

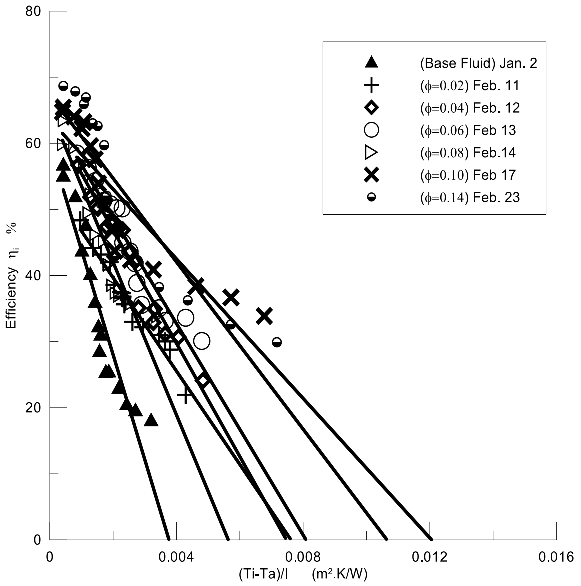

Fig. 20 Effect of $(T_i - T_a)/I$ on the collector efficiency, ($0 \le \phi \le 0.14$)

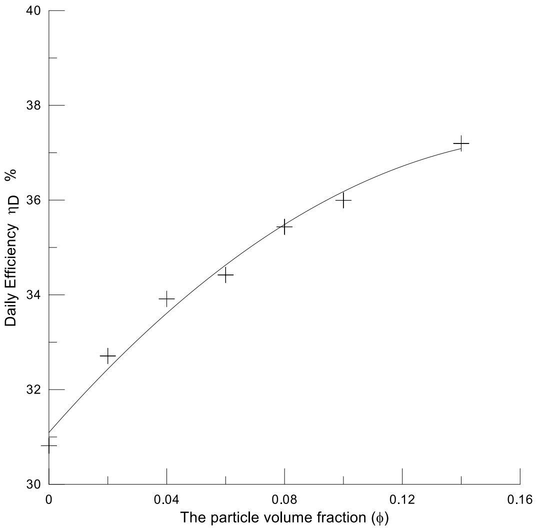

Fig. 21 Effect of volume fraction, ϕ on the collector daily efficiency, η_d

The instantaneous performance of solar collector is greatly affected by the intensity of solar radiation. The performance is also improved with the presence of nanoparticles in the base fluid. Fig. 22 shows the instantaneous efficiency against time of the day for the two working fluids used in experiments. It can be seen that as the concentrations of nanoparticles, ϕ increases, the efficiency increases. With $\phi = 0.14$ the percentage increase in solar collector daily efficiency of about 20.7 % higher than that for city water.

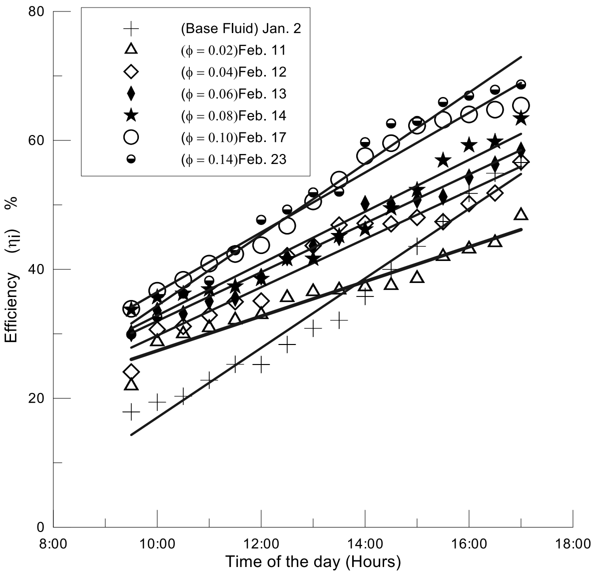

Fig. 22 Variation of the instantaneous efficiency during the day time

4.3 Effect on particle volume fraction on the thermal conductivity

The main reasons for improving the rate of heat exchanged between solar radiation and the working fluid is the presence of nanoparticles. It improves solar absorptivity of the working fluid to the radiation. Moreover, it enhances the thermal conductivity of the working fluid. The thermal conductivity of nanofluid can be calculated from equation (5). Fig. 23 shows the effect of volume concentration of Al_2O_3 nanoparticles, ϕ on thermal conductivity of the nanofluid. It can be seen that as the concentration ϕ increases the effective thermal conductivity dramatically increased. With $\phi = 0.14$, the percentage increase in thermal conductivity is about 45 % compared to that of the base fluid.

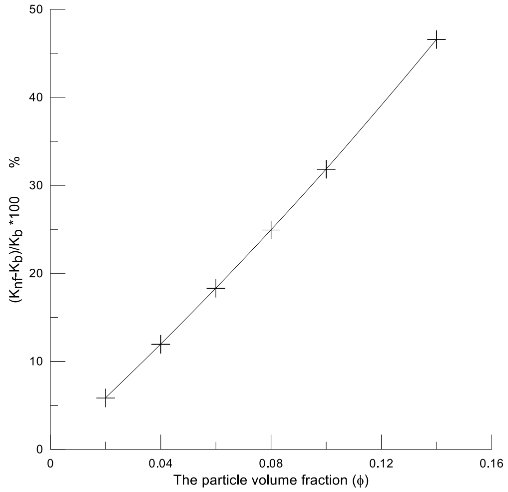

Fig. 23 Effect of particle volume fraction on the thermal conductivity

4.4 Effect on particle volume fraction on Nusselt Number

As previously mentioned, the rate of heat extracted by the collector due to the presence of nanoparticles is enhanced. This can be shown in Fig. 24 which describes the relation between *Nu* and the volume fraction of nanoparticles, ϕ. It is seen that *Nu* increases with the increase of nanoparticle concentration, ϕ.

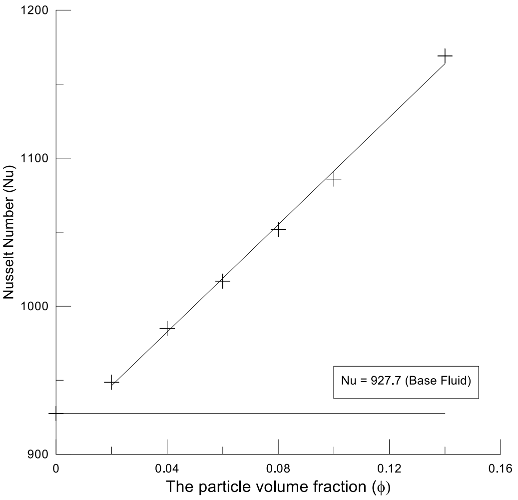

Fig. 24 Effect of nanoparticle volume fraction on Nusselt Number

5. CONCLUSIONS

The performance of a flat plate solar collector has been investigated using city water and Al_2O_3-water nanfofluid as working fluids. The performance was detected along the day time in New Damietta (31.5° latitude). The following conclusions may be obtained:

1-The presence of nanoparticles improves the absopitivity of the working media to the solar radiation.

2- Using nanofluid with volume fraction of $\phi = 0.14$ as working fluid enhances the collector efficiency about 20.7% compared to that of city water.

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