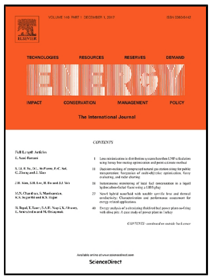

Experimental Study on the Performance of a Flat-Plate Collector Using WO_3 /Water Nanofluids

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PII: S0360-5442(17)31924-2

DOI: 10.1016/j.energy.2017.11.068

Reference: EGY 11856

To appear in: *Energy*

Received Date: 09 June 2017

Revised Date: 10 November 2017

Accepted Date: 11 November 2017

Please cite this article as: Mahmoud Ahmed Sharafeldin, Gyula Gróf, Omid Mahian, Experimental Study on the Performance of a Flat-Plate Collector Using WO_3/Water Nanofluids, *Energy* (2017), doi: 10.1016/j.energy.2017.11.068

Highlights

- WO_3 nano-powder dispersed into Distilled water and stable nanofluid was made.
- Different volume fraction of WO_3nanofluid and different mass flux rates were examined
- Noticeable Effect of WO_3 -water on the performance of flat plate solar collector was found
- The maximum efficiency of solar collectors increased by13.48%

Experimental Study on the Performance of a Flat-Plate Collector Using WO_3/Water Nanofluids

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Abstract

The investigation of nanofluids effects on the performance of solar energy devices has converted to an important topic of research in recent years. The present experimental study deals with the effects of using WO_3/water nanofluids on the efficiency of a flat plate solar collector which operates under weather conditions of Budapest, Hungary. First, water based nanofluids containing WO_3 nanoparticles (with an average size of 90 nm) at three different volume fractions including 0.0167%, 0.0333%, and 0.0666% have been synthesized. The stability of nanofluids has been evaluated through Zeta potential tests which unveiled the prepared suspensions have high stability. In the next step, the thermal performance of the flat plate solar collector using nanofluids is investigated at different mass flux rates including 0.0156, 0.0183, and 0.0195 kg/ s.m^2. The results showed that adding WO_3 nanoparticles to water ameliorates the efficiency of the solar collector. The experiment results reveal that the maximum enhancement in efficiency of the collector at zero value of [(Ti–Ta)/G_T] was 13.48% for volume fraction of 0.0666% and mass flux rate of 0.0195 kg/s.m^2 compared to water, which clearly shows the high potential of WO_3 nanoparticles for solar energy applications.

Keywords: Flat plate collector; WO_3 /water nanofluid; collector efficiency; Experimental study

Nomenclature

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A_c	surface area of the solar collector(m^2)	$\dot{V}$	Volume flow rate (dm^3/hr)
C_p	Heat capacity of (J/kg K)	**Greek symbols**	
C_{pbf}	Heat capacity of base fluid (J/kg K)	$\tau\alpha$	Absorptance-transmittance product
C_{pnp}	Heat capacity of nanoparticles (J/kg K)	η_i	instantaneous efficiency
C_{pnf}	Heat capacity of nanofluid J/kg K)	ρ_{nf}	Density of nanofluid (kg/m^3)
F_R	heat removal factor	ρ_{np}	Density of nanoparticles (kg/m^3)
G_T	solar radiation normal to collector (w/m^2)	ρ_{bf}	Density of base fluid (kg/m^3)
$\dot{m}$	mass flow rate of nanofluid(kg/sec)	φ	volume fraction of nanoparticles
T_a	ambient temperature (K)	**Subscripts**	
T_i	collector inlet temperature (K)	bf	Base fluid
T_o	collector outlet temperature (K)	nf	Nanofluid
Q_u	useful heat energy rate(w)	np	Nanoparticles
U_L	overall coefficient of heat losses (W/m^2 K)		

1. Introduction

In last few years, nanoparticles with dimensions less than 100nm have attracted the attention of many researchers due to their incredible properties. Researchers in the field of thermal science also utilized nanoparticles to enhance the efficiency of thermal systems through introducing a new generation of working fluids which are called “nanofluids”. Nanofluids containing solid nanoparticles have shown stunning effects on the efficiency enhancement of thermal systems. Flat plate solar collectors are a group of thermal equipment which nanofluids might enhance their efficiency remarkably [1].

A flat plate solar collector is the most popular solar energy based device which absorbs the heat of sun rays through its body (usually with black color for maximum absorption) and then transfers the absorbed heat to the working fluid for raising its temperature. The efficiency of flat plate solar collectors as a group of water heaters depends on many factors such as climate conditions (especially solar radiation intensity), materials and design of collector as well as the working fluid type and mass flux rate. The focus of present study is the influence of working fluid type (nanofluids with different concentrations) and mass flux rate on the flat plate solar collector performance. At identical conditions, by using a working fluid with lower heat capacity the outlet temperature of collector will be increased, also, with increasing the thermal conductivity of working fluid the heat transfer rate through the collector body to working fluid enhances. Therefore, working fluid might play a key role in the performance of solar collectors. Based on incredible properties of nanofluids, a considerable number of studies have been done on the performance evaluation of flat plate solar collectors where the working fluid is a nanofluid. Table 1 gives a summary of experimental studies conducted on solar collectors (mainly flat plate type) using nanofluids. It is observed that using nanofluids even at very low concentrations can enhance the efficiency of solar collectors remarkably.

There are some other experimental and theoretical studies that have investigated the effect of using nanofluids on the performance of solar collectors that are not presented here to save the space [26-29].

The review of research studies available in the open literature (Refs. [2-29]) as well as comprehensive review papers published on the use of nanofluids in solar collectors (Refs. [1] and [30-37]) unveils that there is no study on the application of Tungsten Trioxide (WO_3) nanofluids on the performance of flat plate solar collectors. Tungsten Trioxide nanoparticles are a type of semiconductors that are widely used in photothermal applications, however, based on the best knowledge of the authors, this type of particles have not been used yet in flat plate collectors as the additive to working fluid. Therefore, the present paper aims to study the effect of using WO_3/water nanofluids at different concentrations and mass flux rates on the performance of flat plate solar collectors, for the first time.

2. Experiments

This section is presented in four parts. The first part deals with nanofluid preparation, the second part describes the set-up that has been used for experiments on the flat plate solar collector, the third section gives details of testing method, and the last section presents the uncertainty analysis.

2.1 Nanofluid preparation

In this study, deionized water and water-based WO_3 nanofluids were used as the working fluid. Spherical-shaped WO_3 nanoparticles (supplier: M K impex Canada) with 99.5% purity, a density of 7.16 g/m^3, and an average diameter of 90 nm were utilized for the experimental investigation. Distilled water was used as the base fluid. The preparation of nanofluids was done by using two-step method where for each concentration; a specified value of WO_3 nanoparticles was dispersed into the base fluid directly. Next, the mixture was sonicated continuously for about 90 min in an ultrasonic homogenizer (Bandelin, SONOPULS HD 2200, output power maximum 200 W). Nanofluids have been synthesized at three different volume fractions including 0.0167%, 0.0333%, and 0.0666%. After nanofluid preparation, the stability of nanofluids was tested by a Zeta potential analyzer. The abovementioned steps in nanofluid synthesis have been summarized in Fig. 1.

2.2 Experiments on solar collector

The experiments on the flat plate solar collector were carried out in Budapest (latitude47°28′N longitude 19°03′E). The collector specifications are given in Table 2. The collector type is TS 300 collector provided by Naplopo Kft a solar energy equipment supplier in Hungary. Figures 2 and 3 illustrate a schematic of the experimental set-up, and a photograph of the flat plate solar collector, respectively. An electrical pump circulates the working fluid. A Heat exchanger transfers heat energy from solar collector to tank which has a capacity of 500 L. A static fluid oscillatory flow sensor measures the flow rate of fluid. A simple valve was installed to control the flow rate. A series of Pt-100 resistance type thermocouples were fitted on the collector (with accuracy of ±0.1 °C), measuring the temperature of the working fluid in the collector at the inlet and outlet. A thermometer was used to measure the ambient temperature. The solar radiation was measured by a LP PYRA 03 solar meter with accuracy of ±2%.

2.3 Testing method

In the current study, the instruction given in ASHRAE Standard 93-2003 [38] has been implemented to evaluate the thermal performance of the solar collector. The purpose of this standard is to explain test methods for detecting the thermal performance of solar collectors that use single-phase fluids without significant internal energy storage.

The experiments were performed in sunny days from 10 AM to 4 PM (local time). This period was divided into six time intervals where each time interval (or test run) was 60 min. Also, each test run was divided into several test periods to establish quasi-steady state condition that is necessary based on ASHRAE Standard. A test period was 15 minutes as in [3]. The experimental results are expressed in the form of graphs that indicates the collector efficiency against a reduced temperature parameter $[(T_i – T_a)/G_T]$. All the tested runs were collected during several days and the best results were chosen. The maximum variations in ambient and inlet temperatures in each test period were ±0.8 °C and ±0.5 °C, respectively, while the maximum variation in global radiation was ±30 W/m^2; this verifies that tests have been conducted in quasi-steady state conditions and in accordance with the ASHRAE Standard 93-2003. The efficiency of solar collector was examined at various mass flux rates of 0.0156, 0.0183 and 0.0195 kg/ s.m^2.

Thermal performance of the solar collector is checked by determining the values of instantaneous efficiency for different combinations of incident radiation, ambient temperature, and inlet fluid temperature. The instantaneous efficiency is defined as the ratio of useful energy gain to the solar energy received by absorber plate of the collector. It calculated with the use of Eq. (1).

$$\eta_i = \frac{Q_u}{A_c\, G_T} \tag{1}$$

The useful heat energy rate (Q_u) can be calculated using Eq. (2) as follows:

$$Q_u = \dot{m}\, C_p\left(T_o - T_i\right) = \rho\, V^{\cdot}\, C_p\left(T_o - T_i\right) \tag{2}$$

The useful heat energy rate can be also described as the difference between energy absorbed by the absorber plate and the energy loss from the absorber as:

$$Q_u = A_c\, F_R\, [G_T(\tau\alpha) - U_L\left(T_i - T_a\right)] \tag{3}$$

So the instantaneous efficiency (Eq.1) can be rewritten as one of the forms of Eqs. 4-6:

$$\eta_i = \frac{\rho\, V^{\cdot}\, C_p\left(T_o - T_i\right)}{A_c\, G_T} \tag{4}$$

$$\eta_i = \frac{A_c F_R [G_T(\tau\alpha) - U_L(T_i - T_a)]}{A_c G_T} \tag{5}$$

$$\eta_i = F_R (\tau\alpha) - F_R U_L (\frac{T_i - T_a}{G_T}) \tag{6}$$

F_R is known as the collector heat removal factor and is expressed by Eq. (7),

$$F_R = \frac{\dot{m} C_p(T_o - T_i)}{A_c[G_T(\tau\alpha) - U_L(T_i - T_a)]} \tag{7}$$

where $\dot{m}$ is the mass flow rate of working fluid, T_i is collector inlet temperature, T_o is collector outlet temperature, T_a is ambient temperature, G_T is global solar radiation normal to collector, A_c is surface area of the solar collector, $\tau\alpha$ is absorptance-transmittance product, U_L is the overall coefficient of heat losses , and C_p is heat capacity of working fluid.

The heat capacity of nanofluid is calculated as follows [30].

$$(\rho C_p)_{nf} = (\rho C_p)_{np}(\varphi) + (\rho C_p)_{bf}(1 - \varphi) \tag{8}$$

Density of the mixture can be evaluated according to the following equation [39]

$$\rho_{nf} = \rho_{np}(\varphi) + \rho_{bf}(1 - \varphi) \tag{9}$$

Where φ indicates the volume fraction of nanoparticles,$C_{p,np}$, and ρ_{np} are 315 J/(kg.K) and 7160 kg/m^3, respectively, also, $C_{p,bf}$,and ρ_{bf} are 4180 J/(kg.K) and 1000kg/m^3 respectively.

The values of τ and α depend on the design of collector and the value of F_R depends on flow rate, hence, for normal incidence conditions and at given quantities of mass flux rate and volume fraction the values of F_R ,τ and α do not change significantly in the range of tested temperatures. So, according to Eq. (6), the collector efficiency is expressed as a straight line. This line intersects the vertical axis (efficiency) at F_R (τα). At this point, the collector efficiency reaches its maximum value, and the inlet temperature to the collector is equal to ambient temperature. The parameter F_R (τα) is called “absorbed energy parameter” or “optical efficiency”. The slop of straight line is equal to $F_R U_L$ and expresses how energy has removed from the solar collector; it is also called “removed energy parameter”.

2.4 Uncertainty analysis

Uncertainty analysis is an important task in experimental studies since it shows the accuracy of measurements. In this part, the aim is to determine the value of uncertainty in efficiency of solar collector. Based on Eq. (4), the uncertainty in efficiency depends on mass flow rate, heat capacity, inlet and outlet temperature of working fluid, surface area of the solar collector, and solar radiation. Therefore, the uncertainty in efficiency of solar collector can be determined by:

$$\frac{\delta\eta_i}{\eta_i}=\left[\left(\frac{\delta\dot{m}}{\dot{m}}\right)^2+\left(\frac{\delta C_p}{C_p}\right)^2+\left(\frac{\delta(T_o-T_i)}{(T_o-T_i)}\right)^2+\left(\frac{\delta A_c}{A_c}\right)^2+\left(\frac{\delta G_T}{G_T}\right)^2\right]^{0.5} \quad (10)$$

where $\delta\dot{m}/\dot{m} \le 1.5\%$, $\delta C_p/C_p \le 0.1\%$,

$$\delta(T_o-T_i)/(T_o-T_i) \le \left[\left(\delta(T_o-T_i)/(T_o-T)\right)^2+\left(\delta(T_o-T_i)/(T_o-T_i)\right)^2\right]^{0.5} = \left[(0.1/(40))^2+(0.1/(31))^2\right]^{0.5} = 0.4\%$$

$\delta A_c/A_c \le 0.12\%$, $\delta G_T/G_T \le 2\%$

Therefore, after calculation process the maximum uncertainty in the efficiency becomes 2.53%.

3. Results and discussion

The results are discussed in two main sections. First section discusses the stability of nanofluid since it is an important issue in experiments using nanofluids. Second part deals with thermal performance of solar collector using water and nanofluids. In the second part, the effects of concentration and mass flux on the efficiency of solar collector are discussed in details

3.1 Stability of nanofluids

Agglomeration between nanoparticles accelerates the sedimentation rate, and, hence, the stability time reduces. Ultra-sonication is used to break up agglomeration between nanoparticles and promote the dispersion of nanoparticles into base fluid to make more stable nanofluid. As **Mahbubul et al. [41]** reported sonication of nanofluids is a helpful technique to have more stable nanofluids by affecting the surface and structure of nanoparticles and breaking down the agglomerations. Stability of nanofluids directly depends on the volume fraction of nanoparticles.

With increasing the concentration obviously the stability level decreases. Therefore, if the stability is checked for the highest volume concentration, it will be reasonable that the samples with lower concentrations are stable too. Figure 4 has been presented to show that the prepared nanofluid with volume concentration of 0.0666% (the highest concentration) has been stable after one week since no visible sedimentation was observed by naked eyes. In the present work, the stability was also measured by zeta potential machine (PALS Zeta potential analyzer Ver. 3.37 from Brookhven Instruments) to verify the observations by naked eyes. Zeta potential reveals the electrostatic repulsion magnitude between nanoparticles in the suspension. When the amount of zeta potential is high, the probability of nanoparticles aggregation and consequently sedimentation reduces; therefore the sample will be more stable. Generally, a sample has an acceptable stability if the absolute quantity of zeta potential being bigger than 30 mV [42]. In the present study, the zeta potential for the sample with volume fraction of 0.0666% was measured just after preparation; its mean value was equal to -37.22mV which implies the prepared sample has had good stability. The zeta potential was also measured seven days after preparation. The results of the analysis showed that the mean zeta potential reached -37.11mv (insignificant decrease in absolute value); so it can be concluded that the nanofluid stability was acceptable during one week. It should be noted that the standard error in the measurement of zeta potential was 1.66 mv.

3.2 Solar collector performance

The corresponding results of solar collector performance are presented for water and nanofluids at different volume fractions of nanoparticles and mass flux rates.

3.2.1 Water as working fluid

Figure 5 shows the variation of collector efficiency versus the reduced temperature parameter for water and different mass flux rates. The experimental data are fitted with linear equations to obtain the characteristic parameters of the collector and having better judgment about the effect of mass flux rate on the thermal efficiency. As it can be seen, at a given value of reduced temperature parameter, with increasing the mass flux rate the efficiency increases. Based on Eqs. (1) and (2), the useful heat energy rate increases with an increase in mass flux, on the other hand, useful heat energy rate is directly proportional to efficiency; therefore, the efficiency increases with increasing mass flux. With increasing mass flux from 0.0156 to 0.0195 kg/s.m^2 the maximum enhancement in efficiency was found to be about 1%.

Table 3 has been presented to provide more details regarding Fig. 5 and the solar collector performance when the working fluid is water. This table shows the values of the removed energy parameter$F_R U_L$, and the absorbed energy parameter $F_R\,(\tau\alpha)$ for the three mass fluxes. It is seen that both removed energy and absorbed energy parameters increase with an increase in the mass flux.

As Figure 5 and Table 3 show the value of $F_R\,(\tau\alpha)$ and the $F_R U_L$value of the collector for 0.0195 kg/s.m^2 is highest.

3.2.2 Nanofluid as a working fluid

The values of heat removal factor F_R are shown in Fig. 6. The results show that heat removal factor for nanofluid is greater than that of water. The heat removal factor rises with increasing the mass flux rate and nanofluid concentration. Therefore, it can be concluded that by using WO_3-nanofluids the solar collector performance improves.

Values of $F_R U_L$ and $F_R\,(\tau\alpha)$ for different working fluids and mass flux rates have been provided in Table 4. As presented in Table 4, at a given mass flux rate, the absorbed energy parameter $F_R\,(\tau\alpha)$ augments with an increase in the concentration of WO_3 nanoparticles. At low concentrations, the Brownian motion of nanoparticles may enhance significantly the effective thermal conductivity of working fluid. Therefore, the heat transfer rate in the collector increases by particle loading [43]. In addition, the thermophoresis phenomenon may also enhance the heat transfer rate in nanofluids. However, the performance enhancement by nanofluids also depends on the value of reduced temperature parameter. Figures 7-9 show the variation of collector efficiency against the reduced temperature parameter for water, and nanofluids at different concentrations. As seen, at low values of reduced temperature parameter the efficiency of the nanofluid-based collector is higher than that of water-based collector and the difference increases when the reduced temperature parameter tends to zero. In other words, at a specified value of (T_i-T_a), using nanofluid instead of water at higher values of solar radiation is more advantageous from the first law of thermodynamics viewpoint. Therefore, it may be stated that the effects of Brownian motion and thermophoresis on the collector performance enhancement highlight with increasing the solar radiation. With increasing the reduced temperature parameter, the efficiency line of water may cross the efficiency line of nanofluids. The point that efficiency lines of water and nanofluid cross each other can be called “critical reduced temperature parameter” so that for reduced temperature parameters higher than critical point the efficiency of water-based solar collector becomes higher than that of the water-based solar collector, and, hence, using nanofluid instead of water is not advantageous. Table 5 present the values of critical reduced temperature parameter for different mass flow rates and concentrations.

3.2.3 Effect of volume fraction of nanofluid on efficiency

Figures 7, 8 and 9 display the effect of volume fraction of nanofluids on the efficiency of flat plate solar collector for different volume fraction (φ%) of 0.0167%, 0.0333% and 0.0666% at several mass flux rates of 0.0156, 0.0183 and 0.0195 kg/s.m^2 respectively. The efficiency of collector for nanofluid is drawn against temperature parameters, [(T_i–T_a)/G_T]. As shown in Figures 7, 8 and 9 the efficiency of the flat plate solar collector with WO_3 nanofluid has a large depends on volume fraction. This conclusion can detect by finding the value of the absorbed energy parameter, $F_R\,(\tau\alpha)$ and the removed energy parameter, F_RU_L for WO_3 nanofluid in Table 4.

As shown in Figure 7 and Table 4 for the mass flux rate of 0.0156 kg/s.m^2, absorbed energy parameter, $F_R\,(\tau\alpha)$ values for WO_3 nanofluid is more than water by 2.85%, 6.04% and 7.44%for volume fraction (φ) 0.0167, 0.0333% and 0.0666%, respectively. Although the removed energy parameter, F_RU_L, values for WO_3 nanofluid rise by 7.11%, 42.46% and 52.32% for volume fraction (φ) 0.0167, 0.0333% and 0.0666% respect to water.

Based on Figure 8 and Table 4, going up in values of $F_R\,(\tau\alpha)$ for the mass flux rate of 0.0183 kg/s.m^2 is 3.78%, 8.47% and 10.08% for volume fraction φ 0.0167 ,0.0333% and 0.0666%, respectively and increasing in values of F_RU_L is 38.39%,64.75% and 68.53% for volume fraction (φ) 0.067 ,0.0333% and 0.0666%, respectively comparing to water.

Figure 9 and Table 4 showed values of $F_R\,(\tau\alpha)$ and F_RU_L for the mass flux rate of 0.0195 kg/s.m^2. Values of $F_R\,(\tau\alpha)$ is raised by 4.25%, 10%and 13.48% for volume fraction φ 0.0167, 0.0333% and 0.0666%, respectively. It is observed that the gain in values of F_RU_L for WO_3

nanofluid increased by 40.75%, 67.49% and 101.8% for volume fraction (φ) 0.0167, 0.0333% and 0.0666% respect to water.

The effect of volume fraction of nanofluid on the efficiency of flat plate collector is complicated. It is found that higher volume fraction of nanoparticles (φ) 0.0666% absorbed and removed more energy than other volume fraction 0.0167, 0.0333% and pure water as it has the maximum values of $F_R\,(\tau\alpha)$ and F_RU_L for all mass flux rate of nanofluids. The explanation of that is as the volume fraction increased the thermal conductivity of fluid rose because more particles were added.

However, the efficiency of solar collector doesn't depend only on values of $F_R\,(\tau\alpha)$ and F_RU_L but also lean on the reduced temperature parameter [(Ti–Ta)/G_T]. The efficiency of collector with volume fraction of nanoparticles (φ) 0.0666% is more than others in case of lower values of [(T_i–T_a)/G_T]. Although, the efficiency of volume fraction of nanoparticles (φ) 0.0333%and 0.0167% got higher as the value of [(T_i–T_a)/G_T] rises. The collector efficiency in case of water at the highest values of [(T_i–T_a)/G_T] become the maximum. The sequence was the same whatever the mass flux as shown in Figures 7, 8 and 9.

The lower values of [(T_i–T_a)/G_T] could be due to increase in solar radiation or by reducing temperature difference. Hence, higher volume fraction of nanofluid is considered useful as it absorbed more heat than others. Also, less particles tend to agglomerate compering to lower volume fraction nanofluid. The micro watts of heat transfer increased as the collision of particles raised. Based on these reasons, the efficiency of solar collector increased with the rising of the volume fraction.

On the other hand side, higher viscosity of nanofluids and wider thickness of the boundary layer were found as the values of [(Ti–Ta)/G_T] increased because the mean fluid temperature rose. At the same time the solar radiation decreases which reduced absorbed energy and increases heat loss. Hence, less performance and lower efficiency was detected as the heat transfer rate reduced [7]. All of the above explanation give the fact that the efficiency of solar collector has a noticeable depend on the value of [(Ti–Ta)/G_T].

3.2.4 Effect of mass flux rate of nanofluid on efficiency

Figures 10, 11 and 12 present the efficiency of solar collector using volume fraction (φ) of 0.0167 %, 0.0333% and 0.0666% of WO_3 with different mass flux rates 0.0156, 0.0183 and 0.0195 kg/s.m^2. The values of $F_R U_L$ and $F_R\,(\tau\alpha)$ are given in Table 4, as previously. The changes of F_R $(\tau\alpha)$ and $F_R U_L$ values for different volume fraction(φ) and mass flux rates are mentioned previously here they are not repeated. Based on present results, it is found that both values of F_R $(\tau\alpha)$ and $F_R U_L$ for all studied mass flux rates more than the values for water. Generally, the F_R $(\tau\alpha)$ energy absorbance factors and the $F_R U_L$ heat loss factor values are increased as the mass flux rates rises in case of each volume fractions. As shown in from Figures 10, 11 and 12 the efficiency lines intersect each other. As seen, the efficiency of solar collector rises with increasing the mass flux rate for the wide range of reduced temperature parameter, $[(T_i–T_a)/G_T]$ and different concentration of nanoparticles. The enhancement of solar collector efficiency due to mass flux augmentation is greater at higher concentrations; this can be attributed to the increase of Brownian motion in the nanofluid, and, consequently the increases of interruptions in the boundary layer.

Conclusions

A study was carried out experimentally to present the efficiency curves of a flat plate solar collector with using nanofluid of WO_3-water as working fluid. The stability of WO_3-water nanofluid was 7 days. Different volume fractions of 0.0167%, 0.0333%, and 0.0666% were examined at three mass flux rates, including 0.0156, 0.0183, and 0.0195 kg/s.m^2. The experiments and results clarify that using WO_3-water nanofluid increases the efficiency of solar collector more than using water only. Findings showed that the maximum efficiency when the reduced temperature parameter, $[(Ti–Ta)/G_T]$ equals to zero was 71.87% for volume fraction(φ) 0.0666% and mass flux rate 0.0195 kg/s.m^2. The highest increase in the absorbed energy parameter, $F_R\,(\tau\alpha)$ was 13.48% for volume fraction(φ) 0.0666% and mass flux rate 0.0195 kg/s.m^2 so this case has the maximum increase in efficiency comparing to water. The maximum increase in $F_R U_L$ was for volume fraction(φ) 0.0666% and mass flux rate 0.0195 kg/s.m^2 .The changes in absorbed energy parameter,$F_R\,(\tau\alpha)$, vary from 6.04% to 13.48% and in removed energy parameter, $F_R U_L$, vary from 42.46% to 101.8% comparing to the water. The efficiency of collector is directly proportional with both volume fraction of nanoparticles and mass flux rate.

To our knowledge, this is the first study, which is searching for the efficiency analysis of a flat plate solar collector using WO_3-water nanofluid. Accordingly, using different values of volume fraction(φ) and several mass flux rates must be done, in order to find out the effect of these variables on the flat plate solar collector efficiency.

Acknowledgment

The authors would like to thank Prof. István Csontos and Dr. Enikő Krisch for their help and support. The authors would like to thank the "Egyptian Ministry of Higher Education (MOHE) for the support. The Ph.D. study held in Hungary in the frame of Stipendium Hungarycum.

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Table1. A summary of experimental studies on solar collectors using nanofluids

Authors	Nanofluid type	Volume (weight) fraction	Nanoparticle size	Remarks
Said et al. [2]	Al_2O_3/ water	0.1 and 0.3 vol%	13 nm	-Efficiency enhanced by 83.5% using 0.3 vol%
Yousefi et al. [3]	Al_2O_3/water	0.2 and 0.4 wt%	15 nm	- Efficiency enhanced up to 28.3% using nanofluid with 0.2 wt%. - Efficiency increased by 15.63% using Triton X-100 as surfactant.
Faizal et al. [4]	SiO_2/water	0.2 and 0.4 vol%	15 nm	- Efficiency increased by 23.5 %
Moghadam et al. [5]	CuO/water	0.4 vol%	40 nm	- Efficiency raised by 16.7%
Yousefi et al. [6]	MWCNT/water	0.2 and 0.4 wt%.	10–30 nm	-Particle loading and using surfactant enhances the efficiency
He et al. [7]	Cu/water	0.01- 0.2 wt%	25 and 50nm	- Efficiency enhancement up to 23.83%
Meibodi et al. [8]	SiO_2/ EG-water	0.5,0.75, and 1 vol%	40nm	- Efficiency increased approximately between 4 and 8%.
Jamal-Abad et al. [9]	Cu/water	0.05and 0.1 wt%	35 nm	-About 24% increase in efficiency
Faizal et al. [10]	Al_2O_3/water	0.2 and 0.4wt%	15 nm	- Collector size can be decreased up to 24% by using nanofluid instead of water.
Said et al. [11]	TiO_2/water	0.1 and 0.3vol%	21 nm	-Efficiency enhanced by76.6%
Said et al. [12]	SWCNTs/water	0.1 and 0.3 vol%	D = 1–2 nm L = 1–3 μm	- Remarkable enhancement in both energy and exergy efficiencies.
Polvongsri and Kiatsiriroat [13]	Ag/water	1,000 and 10,000 ppm	20 nm	-Solar collector performance enhanced by using nanofluids
Ahmadi et al. [14]	Graphene/water	0.01and 0.02 wt%	thickness less than 100nm	- Thermal efficiency increased by 18.87%.
Devarajan and Munuswamy [15]	Al_2O_3, CuO, and ZrO_2 (water as base fluid)	0.2 and 0.4 wt%	40nm	- Efficiency for nanofluids having Al_2O_3, CuO, ZrO_2, and water was 55, 51.3,47, and 38%, respectively.
Jeon et al.[16]	Gold Nano-rods suspensions	gold Nano-rods dispersed in three plasmonic	16 nm	- Solar thermal collectors performance was enhanced using plasmonic nanofluids.

		nanofluids are 1.85, 2.65 and 5.17		
Verma et al.[17]	Graphene, CuO, Al_2O_3, TiO_2, SiO_2, MWCNTs (water as base fluid)	0.25-2 vol%	From 7nm to 45nm differ from material to another	Maximum efficiency enhancement (compared to water) was 23.47% obtained by MWCNTs/water, and the minimum was 5.74% for SiO_2 .
Noghrehabadi et al.[18]	SiO_2/water	1wt%	12nm	-Thermal efficiency was enhanced by using nanofluids.
Vakili et al.[19]	Graphene/water	0.0005, 0.001 and 0.005 wt%	diameter 2µm and thickness of 2nm	- Enhancement of efficiency up to 33% by using 0.005 wt% nanofluid.
Vincely and Natarajan [20]	Graphene oxide/water	0.005, 0.01 and 0.02 wt%.	300nm	- Collector efficiency increased by 7.3%
Kim et al.[21]	Al_2O_3/water	0.5,1,1.5 vol%	20,50 and 100nm	- Highest efficiency obtained using 1vol% and particle size of 20nm.
Verma et al.[22]	MgO/water	0.25, 0.5, 0.75, 1.0, 1.25, and 1.5 vol%	40 nm	- Collector efficiency enhancement was 9.34% for 0.75 vol%.
Owolabi et al.[23]	Fe/water-propylene glycol	0.5 wt%	40-nm	- Efficiency enhanced by 9% using nanofluid.
Goudarzi et al. [24]	CuO/water	0.1, 0.2 and 0.4 wt%	40 nm	- Using surfactant enhanced the maximum efficiency by 24.2%.
Munuswamy et al. [25]	Al_2O_3/water and CuO/water	0.2 and 0.4 vol%	40nm	- Efficiency enhancement of 12% for Al_2O_3 and 7% for CuO(at 0.4 vol%)

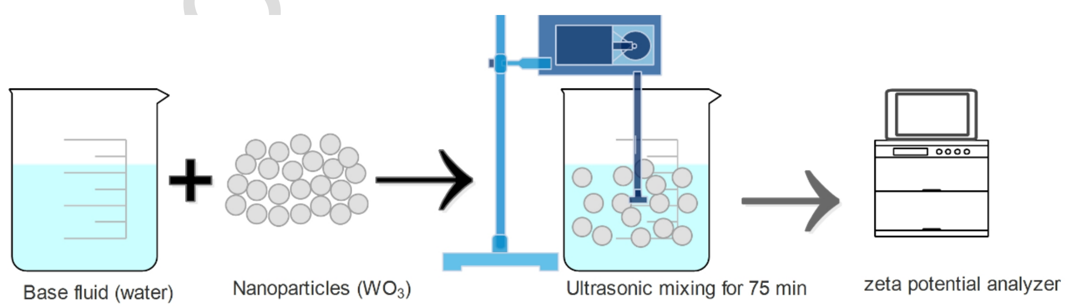

Fig. 1 Preparation steps of nanofluids

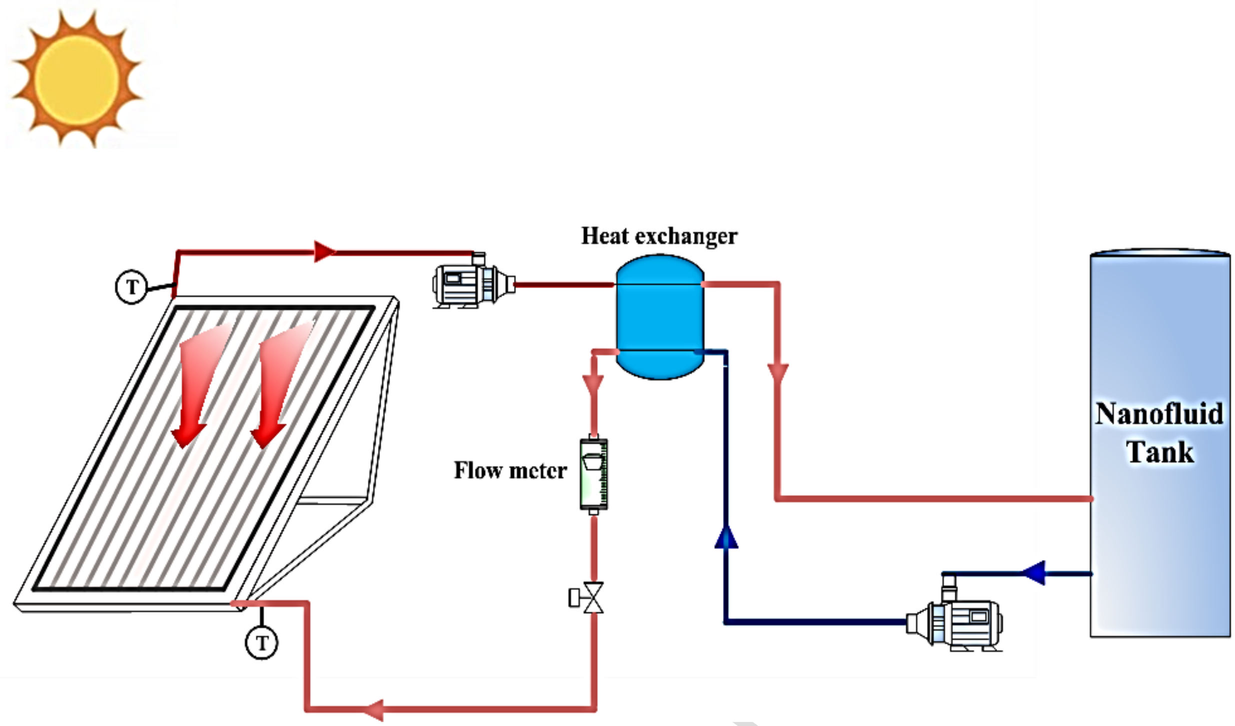

Fig. 2 Schematic of the experimental set-up.

a) Front view

b) Back view

Fig. 3 Picture of test rig

Table 2 Specifications of the flat-plate solar collector

Specification	Dimension
Width:	1009 mm
Height:	2009 mm
Depth:	75 mm
Width Module size:	1040 mm
Full solar surface:	2.03 m 2
Free glass surface:	1.78 m 2
Absorber surface:	1.78 m 2
Liquid space capacity:	1.57 liter
Cover glass thickness:	4mm
Thermal insulation thickness and material:	40 mm rock wool
Absorber absorption coefficient	0.95
Absorber emission factor	0.13

a) Fresh prepared b) After 7 days

Fig 4 Stability of WO_3/ water nanofluid after 7 days of preparation

Table 3. Values of $F_R U_L$ and $F_R\,(\tau\alpha)$for water for different mass flux rates.

Mass flux (kg/s.m²)	$-F_R U_L$	$F_R\,(\tau\alpha)$	R^2
0.0156	-3.6257	0.621	0.9734
0.0183	-3.7574	0.6301	0.9896
0.0195	-3.8961	0.6333	0.968

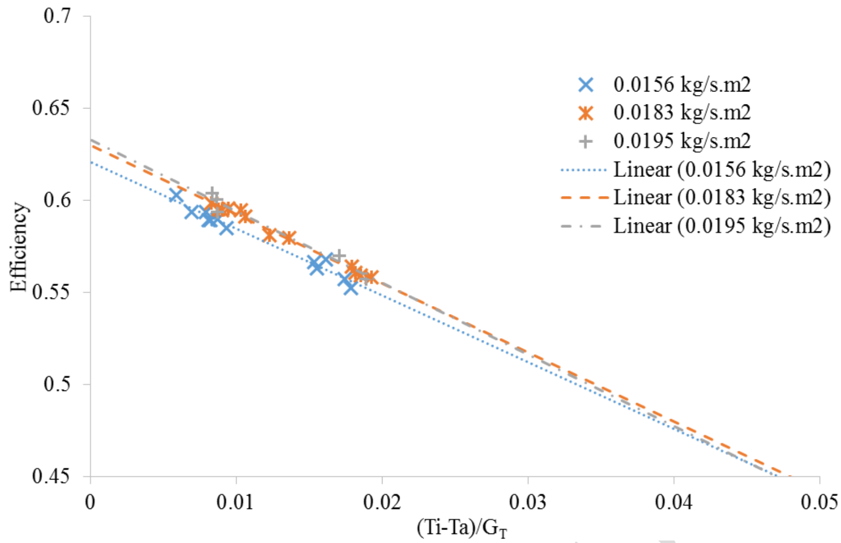

Figure 5. Efficiency of solar collector using water only

Table 4. Values of $F_R U_L$ and $F_R(\tau\alpha)$ for WO_3/water nanofluid and water in case of different volume fractions and mass flux rates.

Volume fraction $\varphi\%$	Mass flux rates(kg/s.m^2)	$-F_R U_L$	$F_R(\tau\alpha)$	R^2
0.0167	0.0156	-3.8835	0.6387	0.9461
	0.0183	-5.1998	0.6539	0.9746
	0.0195	-5.4837	0.6602	0.9981
0.0333	0.0156	-5.1652	0.6585	0.9821
	0.0183	-6.1904	0.6835	0.9729
	0.0195	-6.5256	0.6966	0.9935
0.0666	0.0156	-5.5225	0. 6672	0.9943
	0.0183	-6.3325	0.6936	0.9782
	0.0195	-7.8624	0.7187	0.967
water	0.0156	-3.6257	0.621	0.9734
	0.0183	-3.7574	0.6301	0.9896
	0.0195	-3.8961	0.6333	0.968

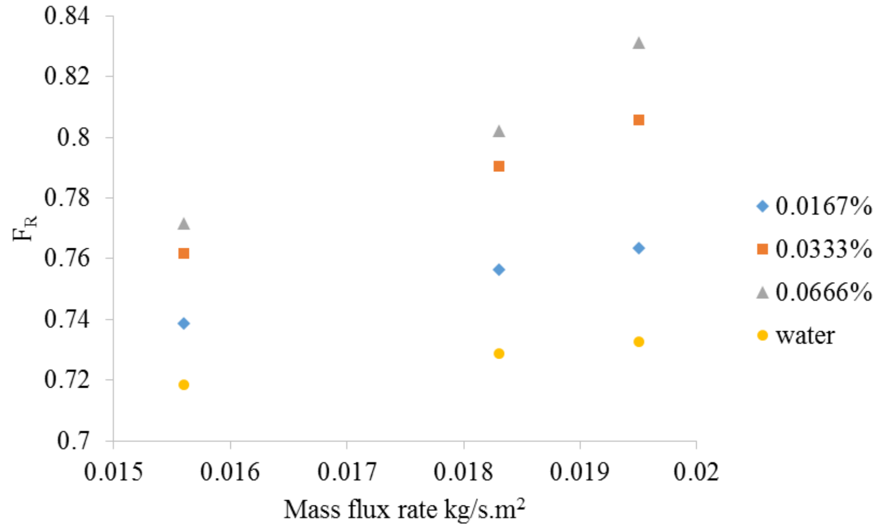

Figure 6. Heat removable factor at different flow rate and different volume fraction of nanofluid

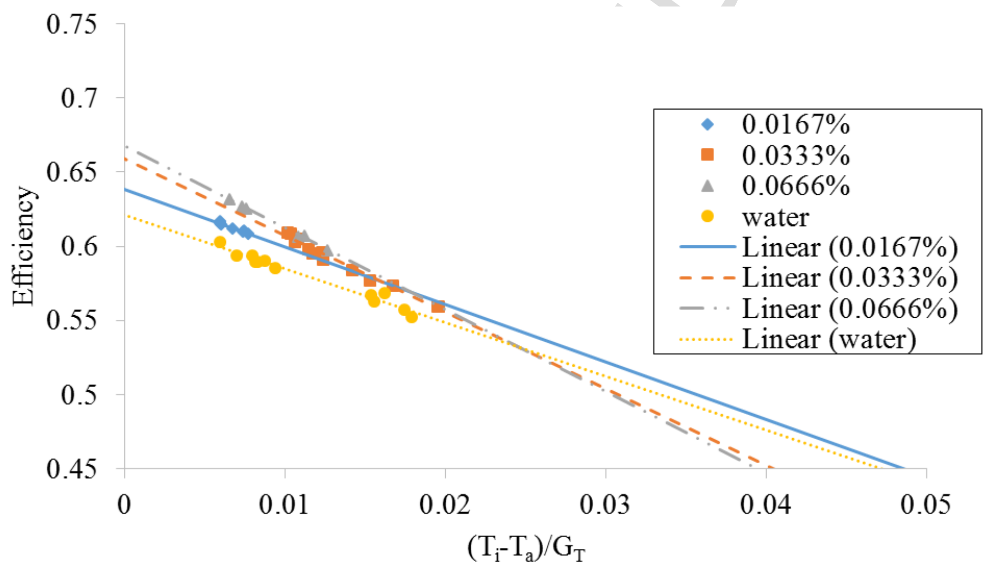

Figure 7. Efficiency of solar collector using WO3-water nanofluid and water for 0.0156 kg/s.m2 volume flow

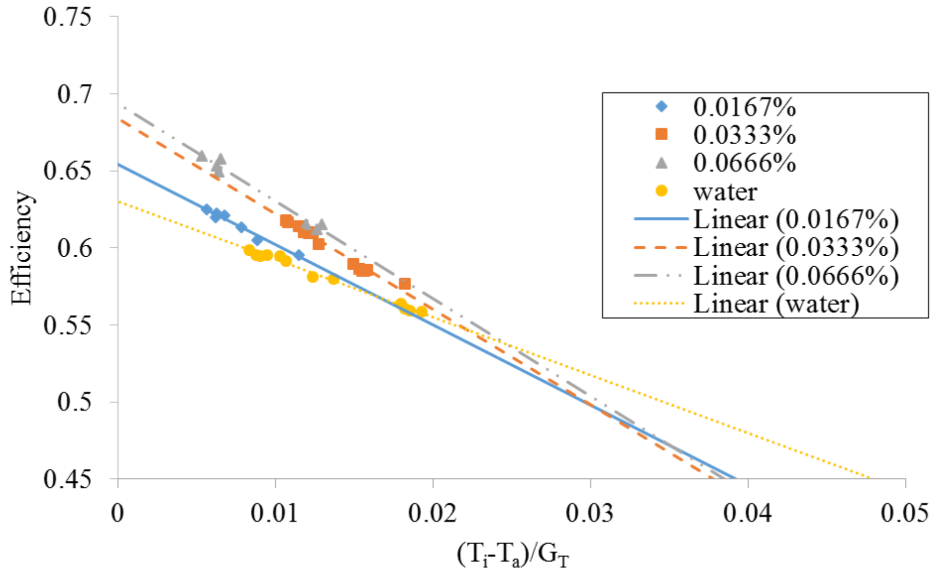

Figure 8. Efficiency of solar collector using WO3-water nanofluid and water for 0.0183 kg/s.m2 volume flow

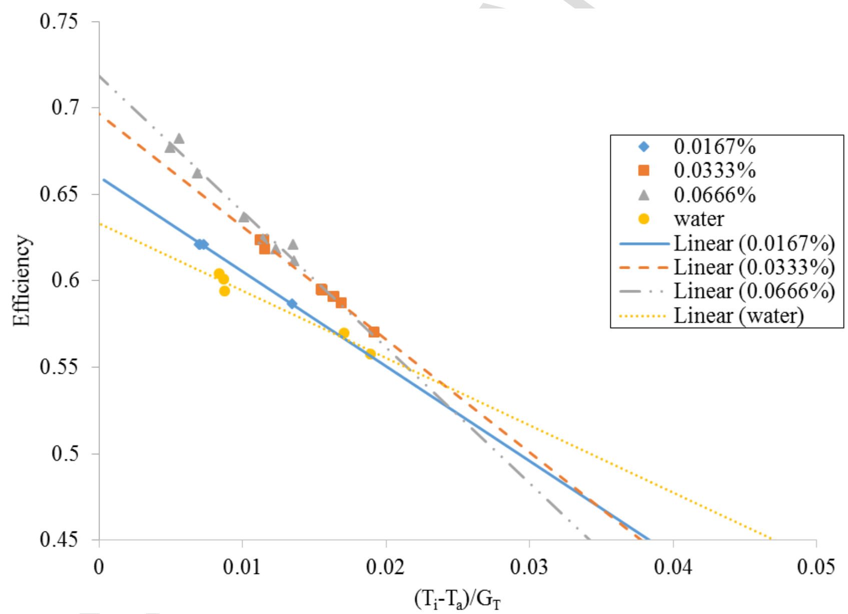

Figure 9. Efficiency of solar collector using WO3-water nanofluid and water for 0.0195 kg/s.m2 volume flow

Table 5. Intersections of nanofluids characteristics of water

Volume fraction φ%	Mass flux rates(kg/s.m^2)	Intersection $(T_i–T_a)/G_T$
0.0167	0.0156	0.0687
0.0167	0.0183	0.0165
0.0167	0.0195	0.0169
0.0333	0.0156	0.0244
0.0333	0.0183	0.022
0.0333	0.0195	0.0241
0.0666	0.0156	0.0244
0.0666	0.0183	0.0247
0.0666	0.0195	0.0215

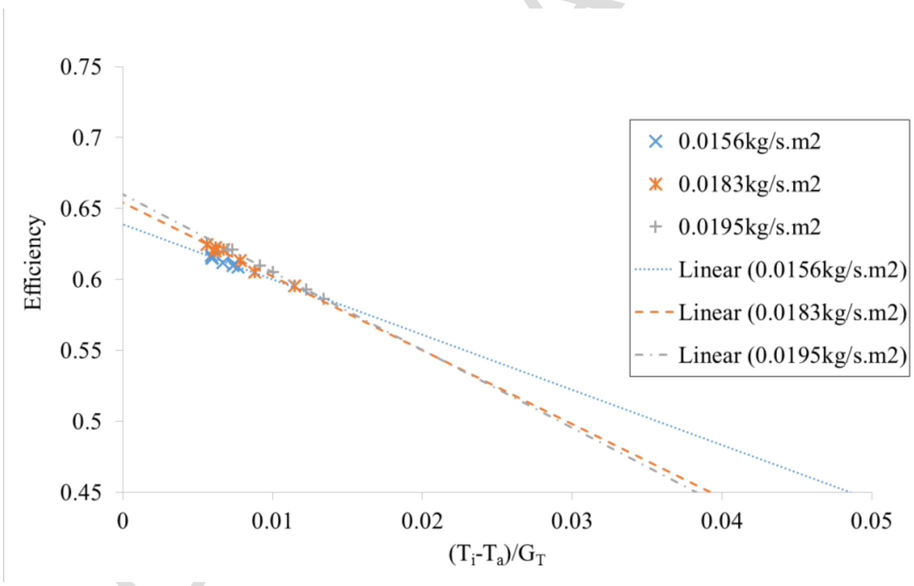

Figure 10. Efficiency of solar collector using φ=0.0167% of WO3-water with different mass flux rate

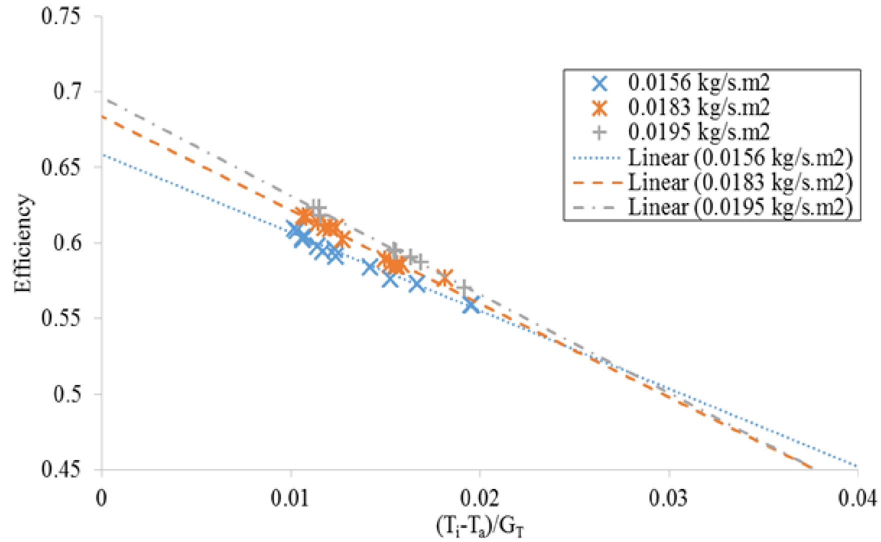

Figure 11. Efficiency of solar collector using φ=0.0333% of WO_3-water with different mass flux rate

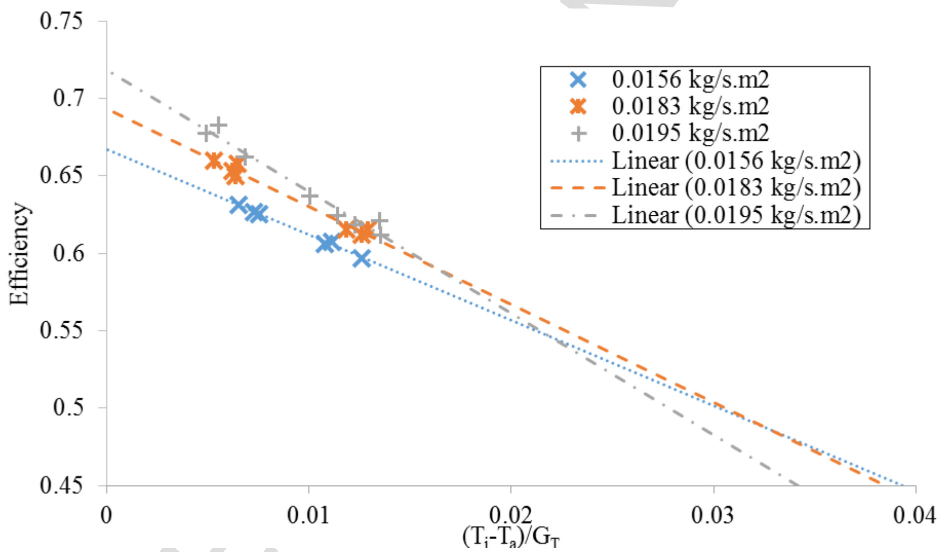

Figure 12. Efficiency of solar collector using φ=0.0666% of WO3-water with different mass flux rate