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Experimental Investigation of an Evacuated Tube Heat Pipe Solar Collector Using Different Fluids

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Abstract : In the current work, the effect of four different fluids ethylene glycol, ethanol, methanol, and acetone as well as their aqua solutions on the performance of the thermosyphon evacuated tube heat pipe solar collector is investigated. Water is used as a heat transfer fluid with a volume flow rate of 1.95 l/min. Five modules each of three evacuated tube heat pipe solar collectors are used. The thermosyphon heat pipes are manufactured and charged with each working fluid and its aqua solution of volume concentration of 0, 0.25, 0.5, 0.75 and 1.0 respectively.

The performance of the systems is illustrated by the solar collector efficiency and the overall system efficiency. The results showed that pure water gives higher solar collector efficiencies than that of ethylene glycol, ethanol, methanol, and their solutions while acetone gives higher solar collector efficiency than the pure water. Correlation equations for solar collector efficiency in terms of (T_m-T_∞)/G and concentration are deduced. The current results are validated with the previously experimental published correlations.

Nomenclature:

Symbol	Description	Symbol	Description
a, b, η_o	Constants of Eq. (9)	Q_o	Output water energy rate, (kW)
a, b, c	Constants of Eq. (10)	T_i	Inlet or initial water temperature, (°C)
A_c	Solar collector area, (m^2)	T_m	Mean water temperature, (°C)
C_p	Specific heat of the water, (kJ/kg °C)	T_f	Final water temperature, (°C)
E_i	Input solar Energy, (kJ)	T_o	Outlet water temperature, (°C)
E_u	Useful stored energy, (kJ)	ETSWT	Evacuated Tube Solar Water Heater
F_R	Removal factor of the collector	T_∞	Ambient temperature (°C)
G	Solar radiation intensity (W/m^2)	t	Time, (s)
$\dot{m}$	Water (HTF) mass flow rate, (kg/s)	U_L	Overall heat loss factor
m_s	Mass of water in storage tank (kg)	V	Water volume flow rate, (m^3/s)
Q_i	Input solar energy rate (kW)	x	Volume concentration of heat pipe fluid
Greek Symbols		**abbreviation**	
ρ_w	Water density (kg/m^3)	HTF	Heat Transfer Fluid
η_c	Collector efficiency	THP	Thermosyphon Heap Pipe
η_s	System efficiency	THPECT	Thermosyphon Heap Pipe Evacuated Tube Collector

Introduction

Heat pipes are the most efficient means of transferring heat. They may transfer hundreds of times more energy between two bodies than a solid metal bar of the same dimensions and substance. This operation can be carried out with a working fluid such as water, which absorbs latent heat and evaporates in the hot part of the pipe (evaporator section), then condenses in the cool region to release the latent heat (condenser section). A heat pipe is simply a tube closed at one end and can be charged by the working fluid, occupying 5–30% of the volume of the pipe~~,~~ [1, 2]. As a result, a two-phase gas-liquid flow inside a heat pipe is prevailed.

For the heat to be transferred using a heat pipe, the working fluid should be in the liquid phase in the evaporator section of the pipe. As a result, a wick is frequently employed, which is put along the pipe's internal wall and for most of the pipe's length. The capillary action will let the liquid return from the condenser to the evaporator via this wick.

Thermosyphon Heat Pipe (THP) is a wickless heat pipe and the condensate return to its evaporator by gravity, the transfer of heat carried out through the phase change (evaporation and condensation) of the working fluid inside.

Unlike the classical type of heat pipe, which uses capillary force to return the liquid to the evaporator, a THP uses gravitational force to return the condensate [3]. THP offers several benefits, including a simpler structure, lower heat resistance, improved efficiency, and lower manufacturing costs. It also has no moving parts and requires no maintenance. All these advantages enable the THP to be widely used in a variety of industries, including heat recovery, electronic component cooling, turbine blade cooling, solar energy systems, permafrost preservation, road deicing, and so on [3]. THPs have the potential to operate at both low and high temperature drops at the same time. As a result, they are appropriate for use in evacuated tube solar collectors. A THPETC (thermosyphon heat pipe evacuated tube collector) is made comprised of a thermosyphon heat pipe encased in a vacuum-sealed glass tube. The vacuum envelope reduces the heat losses caused by convection and conduction heat transfer, so the collectors can be operated at higher temperatures than the flat plate collectors. Also, THPETC has higher efficiency at low incidence angles of solar radiation providing them day-long performance over FPC in [4].

The evacuation conservation of the pipes and the prevention of leakage are critical points in maintaining high performance for evacuated pipe solar energy collectors. There has been substantial research work in this area by different investigators. TRNSYS simulation model for the forced flow of the heat transfer fluid in solar water heating systems with either flat plate or heat pipe evacuated tube collectors was created by Ayompe et al. [5]. They validated the model by comparing it to experimental results for collector outlet fluid temperature. performed detailed investigation using data collected from a field trial installation over a year in Dublin, Ireland was performed by Ayompe and Duffy [6] to determine a solar water heating system's year-round thermal performance using a heat pipe evacuated tube collector. They reported the variation of the daily averaged collector and system efficiency all-round the year. Hayek et al. [7] experimentally studied the performance of water in glass and heat pipe designs of evacuated tube solar collectors. Their work was in the period (November to January) on the east coast of the Mediterranean. The results show that heat pipe collectors are 15 to 20 percent more efficient than glass water. Results for two types of solar collectors: single-phase open thermosyphon system and two-phase closed thermosyphon used for domestic water heating applications, reported by Chow et al. [8]. Their results were based on experimental data and statistical modeling to evaluate two types of performance. Their results show that the heat pipe type is slightly better than a single phase open thermosyphon, even if they are less economical. The thermal behavior of a solar heating system with evacuated tube heat pipe collector was evaluated by Daughigh and shafieian [9]. First, they presented a mathematical model utilizing the energy and exergy analysis to show the collector performance. Then the system was constructed. Xiaowu and Ben [10] analyzed the thermal performance of solar water heating system of a domestic scale based on exergy analysis. They showed that the exergy efficiency is small since the output exergy is of low quality. Large exergy destruction occurs in the storage tank. It is also required to carefully compromise between the exergy efficiency and cost.

The working fluid in a heat pipe has a direct impact on the heat pipe's efficiency, overall heat transfer coefficient, and operational temperature range. Within the temperature range of solar energy collectors, water, ethanol, and methanol, as well as a mixture of these substances, are often employed as working fluids. Kang et al. [11] studied experimentally the closed loop type thermosyphon system for solar domestic heating water system using wickless heat pipe. They reported their results for water, ethanol and their solutions as working fluid and determined their influence on the heat pipe operating temperatures. In a different experiment, Savino et al. [12] tested whether an ethanol solution as a working fluid performs better in a heat pipe than pure water. Guo et al. [13] experimentally found that aqua-ethanol gives better performance than pure water when used as a working fluid in low diameter and low-capacity heat pipe. Experiments on evacuated tube solar energy collectors and simple flat plate solar collectors were undertaken by Zambolin and Col [14]. They discovered that, unlike the ordinary flat plate collector, the evacuated tube collector's performance was unaffected by the time of day. Furthermore, as compared to a standard flat plate collector, the evacuated tube collector had nearly constant efficiency throughout the day and a higher collector outlet temperature. Arab and Abbas [15] developed a completely integrated theoretical model for a grooved type of evacuated tube solar water heater, which they validated with experimental data. They demonstrated the impacts of several working fluids on a normal day of operation and determined that water is the optimum working fluid. Jahanbakhsh et al. [16] built and tested an evacuated tube solar collector with a thermosyphon heat pipe, using ethanol and water solutions as the working fluid at various tilt degrees and concentrations. The results indicated that at low heat flux, ethanol in the solution improves the heat pipe performance, and that concentrations of 50% and 75% showed the highest performance characteristics in the heat transmission process with an efficiency of about 52%. They also found that evacuating a heat pipe or employing a wick had little effect on improving heat pipe performance, and that the collector's heat transfer coefficient had the highest value at a tilt angle of 35°. Ersoz [17] applied the energy and exergy analysis to investigate the effect of six different fluids in thermosyphon heat pipe evacuated tube solar collector under three different velocities 2, 3 and 4 m/s of air as a heat transfer fluid. The highest energy efficiency takes place when using THPETC-Acetone at air velocity of 2 and 3 m/s and when using THPETC-Chloroform at air velocity of 4 m/s. The best exergy efficiency takes place in the THPETC-Acetone at air velocity of 2 m/s and in the case of Chloroform at air velocity of 3 and 4 m/s. Modified coaxial heat pipes were designed and manufactured by Kabeel et al. [19]. Heat pipes were made up of two concentric copper tubes so that the annulus volume area between the concentric tubes was charged with refrigerant. Furthermore, they used the air used as a working fluid which flows through the system at four distinct mass flow rates of 0.0051, 0.0062, 0.007, and 0.009 kg/s in the heat pipe's inner tube to the flow via the annulus between the heat pipe and the evacuated glass solar tubes. The effect of the evacuated tube's tilt angle on the thermal performance and, the optimal tilt angle for the solar collector was investigated. Also, experiments were done on the effect of filling ratio for the two types of refrigerant R22 and R 134a on the thermal efficiency of the coaxial heat pipe solar collector at filling ratios ranging from 30% to 60%. At a mass flow rate of 0.009 kg/s, the maximum increase in thermal efficiency was 67 percent, compared to when heat pipes were not used. Similar results for the two refrigerants were observed. Eidan et al. [20] conducted two groups of experiments, the first one studied the effect of filling ratio and the tilt angle for acetone as working fluid inside thermosyphon heat pipe solar collector. Experiments for filling ratio ranged from 40% - 80% as well as tilt angle of 30°, 45°, and 60° were conducted. In the second group, they employed two nanofluids Al_2O_3 and CuO/acetone-based with concentration of 0.25% and 0.5% vol. for the optimal conditions of the first group. The results showed thermal performance enhancement of (20-54%) and efficiency (15-38%) due to the use of nanofluids. Fallahzadeh et al. [21] used water and ethanol at three different filling ratios for a pyramid-shaped solar still integrated with heat pipe solar collector. Their results showed augmentation for the hourly and accumulated yield.

From the literature survey carried out in this study, little work has been conducted on the effect of the working fluids and their aqua solutions on the performance of the solar collector, so our current study is aimed to experimentally investigate the most effective working fluid that gives the highest performance on the solar collector, so this will enable to construct a good heat pipe operated solar energy collector.

2. Experimental Test Setup

The current experimental test facility was designed and installed to investigate the effect of the working fluid on the thermal characteristics of thermosyphon heat pipe evacuated tube solar collector. The experimental runs are carried out on the roof of the west part of the main building of the Faculty of Engineering at Shoubra, Benha University, in Cairo, Egypt (Latitude; 30.1° N, Longitude; 31.4° E). The setup consists of 5 identical modules as shown photographically in Fig. (1a). Each module is schematically illustrated in Fig. (1b). It is a closed loop circuit, where the water is pulled and pumped from the storage tank to a manifold in which the three condenser parts of the three heat pipes are inserted by using a circulating pump.

Fig. (1b) shows the schematic diagram for the evacuated tube heat pipe. All heat pipes are of the thermosyphon type and are equipped with a charging valve to permit change of its working fluid. The geometrical dimensions of the evacuated tube and the heat pipe are illustrated in Table (1). Fig. (2) illustrates schematic diagram for the heat pipe used. They are designed and manufactured in the current study. The air inside the thermosyphon heat pipe THP is drawn, and the pipe is evacuated to 15 Pa, using a vacuum pump. Then the volume of 24 ml of ethylene-glycol, ethanol, methanol, and acetone, as well as their aqua solutions is charged evenly into each of the THPs. The charge volume represents 42% of the evaporator section and about 30% of the pipe volume. The evaporator section of each pipe was located concentrically inside the evacuated tube, whereas the condenser section of each pipe is fitted in a manifold that manufactured to fit only three pipes. The manifold is depicted in Fig. (3). Three calibrated type T thermocouples are used to measure the inlet and outlet water of the manifold as well as the water tank temperature for each module as well as the ambient temperature. The water flow rate is controlled using a gate valve. The valve position is calibrated to get the water flow rate. Four groups of experiments are carried out to illustrate the effect of heat pipe working fluid on the collector efficiency. A laptop and a data acquisition card having the following specifications (NI USB-6210, 32-inputs, resolution of 16-bit and scanning rate of 250 kS/s) are used for temperatures measurement through the use of thermocouples. The temperature readings at inlet, outlet of the collector manifold and tank temperature were recorded each second. The solar irradiance was measured by a solar power meter which was mounted on a surface parallel to the collector plane, which was inclined to the horizontal by 45^{o}, and its readings were taken manually each 30 minutes. Also, all the experiments are performed at constant volume flow rate of 1.95 l/min the circulating water (heat transfer fluid).

Fig. (1): a) Photograph for the test rig

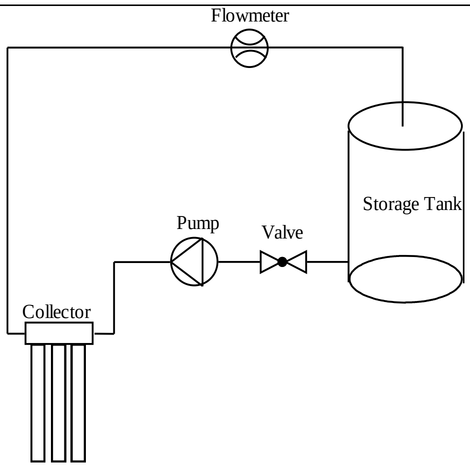


Fig. (1): b) Schematic diagram for the test rig

Table 1 Evacuated Tube and Heat Pipe Dimensions

Details of Evacuated Tube Solar collector	
Item	**Size**
Tube length	1800 mm
Outer tube dimensions	ϕ 58 mm x 2 mm
Inner tube dimension	ϕ 47 mm x 2 mm
Tube material	Borosilicate glass
Details of Heat Pipe	
Item	**Size**
Heat pipe material	Copper
Evaporator length	1650 mm
Evaporator diameter	ϕ8 mm
Adiabatic section length	100 mm
Condenser length	60 mm
Condenser diameter	ϕ24 mm

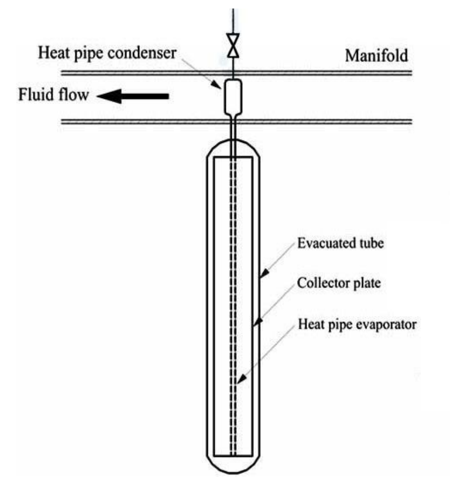


Fig. (2) Schematic diagram of the heat pipe

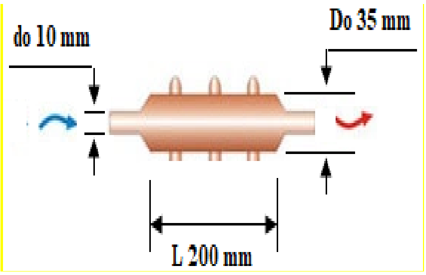


Fig. (3) heat pipe manifold

3.Data Reduction

The heat gained (output) by the water in the collector manifold is given by:

$$Qo = \dot{m}\ cp\ (T_o - T_i) \qquad (1)$$

Where; m·, T_o, and T_i are the water mass flow rate, water temperature at collector outlet, and water temperature at collector inlet, respectively.

The water mass flow rate can be calculated from:

$$\dot{m} = \rho\ V \qquad (2)$$

Where ρ is the water density and V is measured water volume flow rate.

The solar energy is energy source, and the solar irradiance, G, is the input power that received by the collector surface then it is absorbed and then transmitted to the heat transfer working fluid (pure water).

$$Q_i = G.\ Ac \qquad (3)$$

The efficiency of the solar collector is calculated as:

$$\eta_c = \frac{Q_o}{Q_i} = \frac{\dot{m} c_p (T_o - T_i)}{G A_c} \qquad (4)$$

Considering the useful energy and the heat accumulated in the storage tank, so the system efficiency can be calculated. Useful energy can be calculated using the following equation:

$$Eu = m_{st}\ cp\ (T(t) - T_{intial}) \qquad (5)$$

The input energy by solar irradiance can be calculated as:

$$E_i = \int_{t=0}^{t} G A_c dt \qquad (6)$$

The system efficiency can be given by:

$$\eta_s = \frac{E_u}{E_i} \qquad (7)$$

Also, the net power output can be written an input power minus the power lost due to heat loss [18]

$$Q = A_c F_R [G - U_L(T_m - T_\infty)] \qquad (8)$$

Where F_R is removal factor of the collector and U_L is the overall heat loss coefficient and Tm is the mean temperature of the heat transfer working fluid flowing inside the collector, generally it is the average between the inlet and the outlet temperatures of the collector manifold. Using Eq. (4) and Eq. (8) and noting that UL is a function of temperature, gives the following expression:

$$\eta = \eta_o - a\frac{(T_m - T_\infty)}{G} - b\left(\frac{(T_m - T_\infty)}{G}\right)^2 \qquad (9)$$

In which η_o, a, and b are constants to be determined either analytically or experimentally. The maximum uncertainties in measuring parameters under investigation are presented in Table (2).

Table (2): Uncertainties of the measured and derived quantities

Quantity	Uncertainty %
Ac	1.779
G	1.667
T	2.85
$\dot{m}$	2.22
Q_i	1.667
Q_o	12
η_c	12.834

Results and Discussions

Developing an empirical correlation is the first step of the collector testing process. The current experimental data is utilized to obtain average coefficients for Eq. (9) and compared with some correlations used for predicting the thermal efficiency of the heat pipe solar collector under consideration are listed in Table (3), [7]. Also, these correlations are graphically represented in Fig. (4).

Table (3): Experimental coefficients of efficiency correlation for heat pipe collectors

Correlation	η_o	a	b	Source
Teknikum	0.84	2.02	0.0046	Teknikum Rapperswill [7]
Florida	0.81	1.23	0.0122	FSEC [7]
Present Work	0.87	1.559	40.07	Avg. for all working fluids

Due to the difficulty of performing the required experimental work at the time, so each experimental run for each of the tested working fluid was conducted in one day (7 July, 15 Aug, 2 & 10 Sept.). The weather data represented by the ambient temperature and the solar irradiance respectively for the four days in which the current experimental work is carried out are illustrated in Fig. (5a, b). The figure shows peaks of the ambient temperature at 13.0 PM whereas the peaks of solar irradiance at about 12.0 PM.

Figure (6) illustrates the variation of the solar collector efficiency with (T_m-T_∞)/G for different heat pipe working fluids at different concentrations of their aqua solutions. Figure (6a) shows the collector efficiency for ethylene glycol. As the value of (T_m-T_∞)/G increases which means that increasing the heat loss form the collector or decreasing the received irradiance by the collector, the collector efficiency decreases. It is observed that the pure water gives higher values of collector efficiency and as the value of ethylene glycol concentration increases the collector efficiency decreases and this may be due to the increased heat losses by the collector through the decrease in the thermal resistance of the collector. The same pattern of variation is observed in Fig. (6b-c) for Ethanol and Methanol while the pattern is reversed in Fig. (6d) for Acetone. The data in Fig. (6) is utilized to obtain correlation equations if the form of:

$$\eta_c = a.\left(\frac{(T_m - T_\infty)}{G}\right)^b x^c \qquad (10)$$

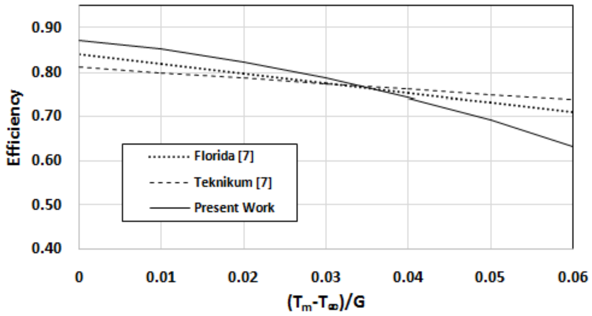


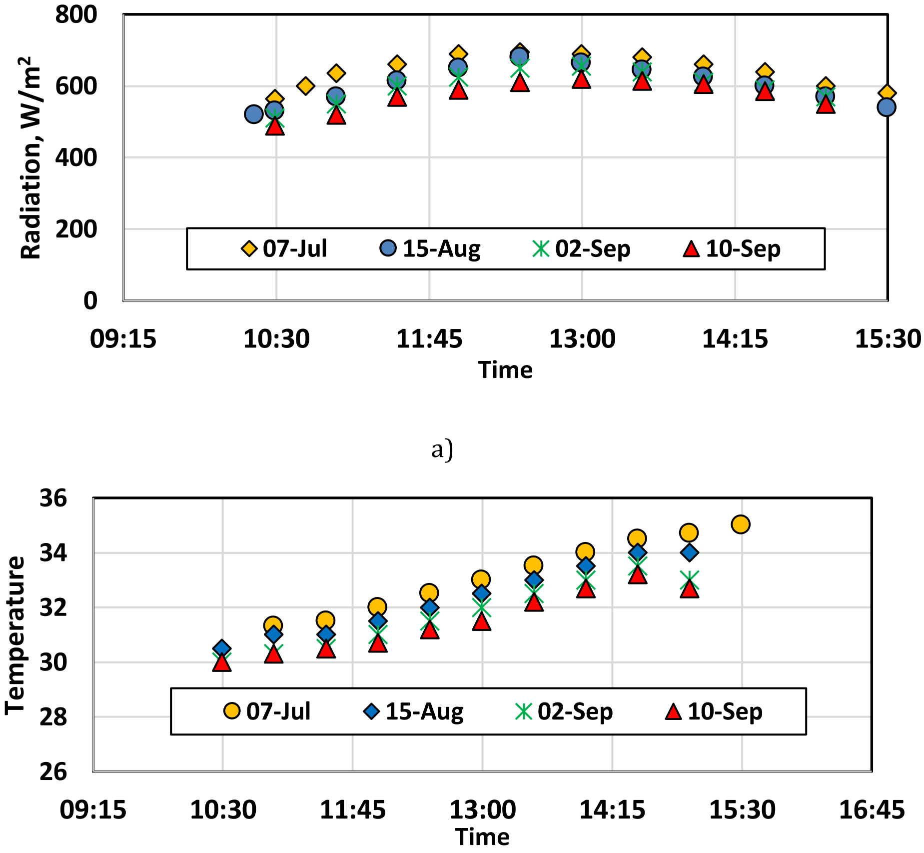
Fig. (4) Empirical correlations of the present work against those of [7]

Correlation equations are deduced for each working fluid and the constants a, b and c for each fluid is given in Table (4), and theses correlation equations are illustrated graphically with their maximum deviations in Fig. (7) for the experiment ranges $0.25 \leq x \leq 1.0$ and (T_m-T_∞)/G as depicted in the figure.

Table (4) Correlation coefficients for different working fluid

Working Fluid	a	b	c
Ethylene glycol	0.4931	-9.293E-02	-8.062E-02
Methanol	0.5137	-1.069E-01	-1.857E-02
Ethanol	0.4239	-1.412E-02	-4.610E-02
Acetone	0.5880	-7.916E-02	6.039E-02

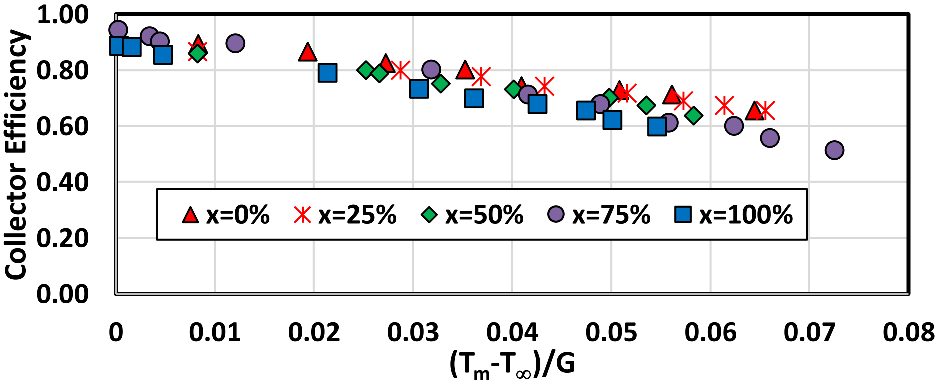
Also, the overall performance of the system is measured by the system energy efficiency given by Eq. (7). The timewise variation of the system efficiency for different heat pipe's working fluid and their aqua solution are depicted in Fig. (8). The figure illustrates great differences between the collector efficiency and the system efficiency which indicates that the amount of heat losses from the piping and the storage tank is large. The collector and system efficiencies for different working fluids are illustrated in Fig. (9a-b) respectively. Fig. (9a) shows that acetone gives the highest solar collector efficiency, followed by methanol, ethylene glycol, and ethanol, respectively with daily average collector efficiency of 76%, 74%, 73%, and 70% respectively; whereas the most higher system efficiency obtained in case of using methanol followed by acetone, ethanol, and ethylene glycol with daily average system efficiency of 36%, 32.5%, 21%, and 20.7% respectively.



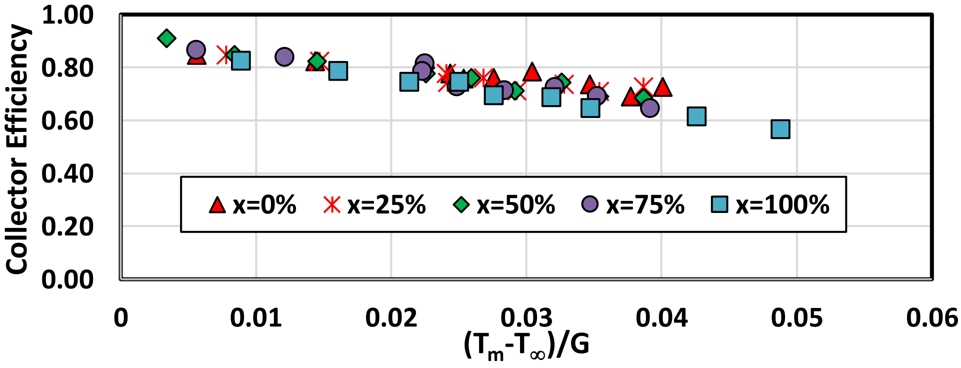
a)

b)

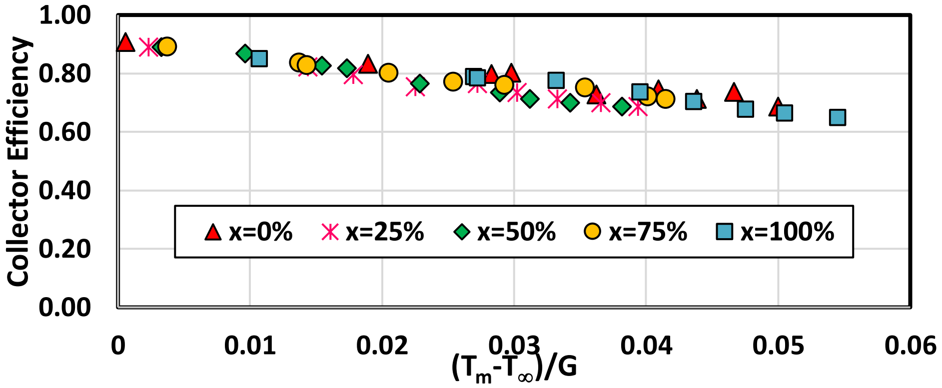
Fig. (5) Solar irradiance and ambient temperature for experiments' days



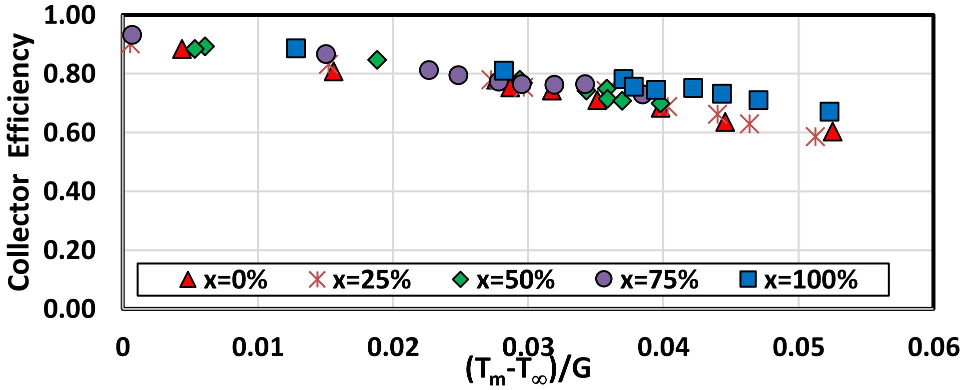
a) Ethylene glycol



b) Ethanol

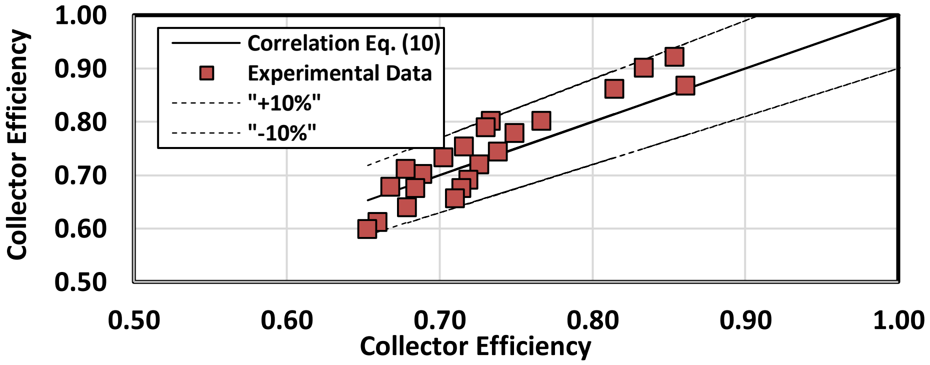


c) Methanol

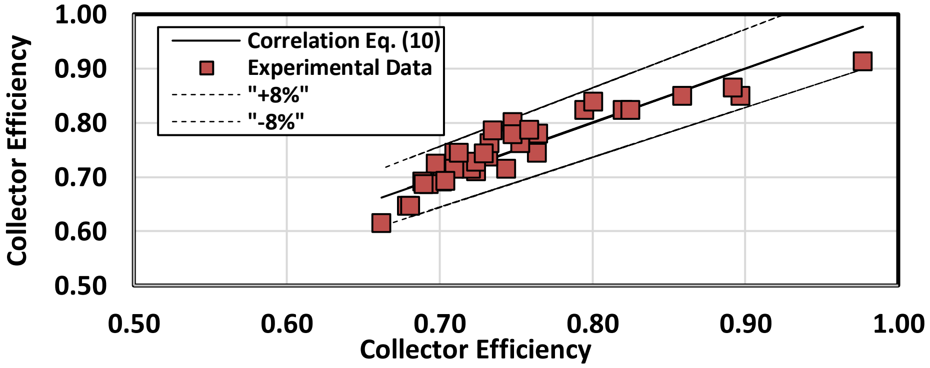


d) Acetone

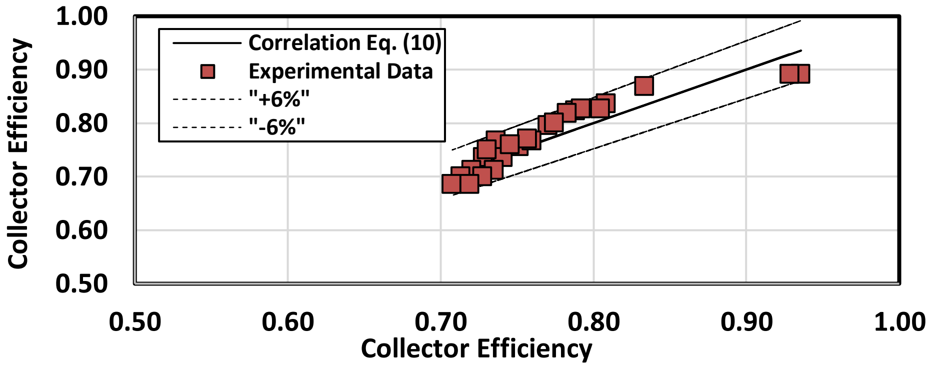
Fig. (6) Collector efficiency for different heat pipe's working fluid and its aqua solution



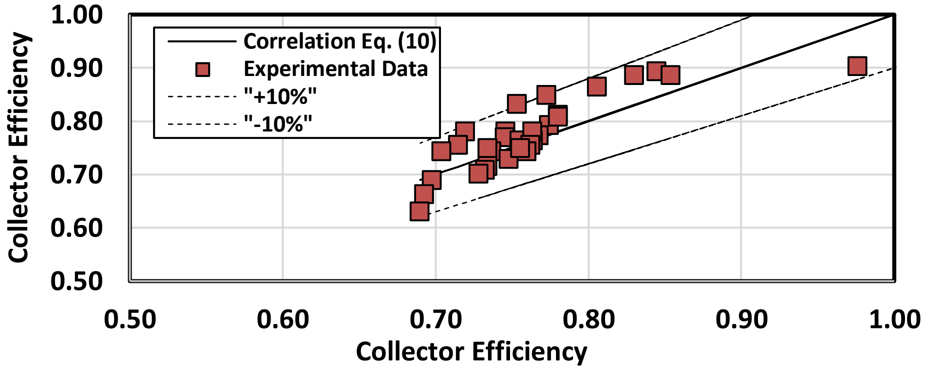
a) Ethylene-glycol



b) Ethanol

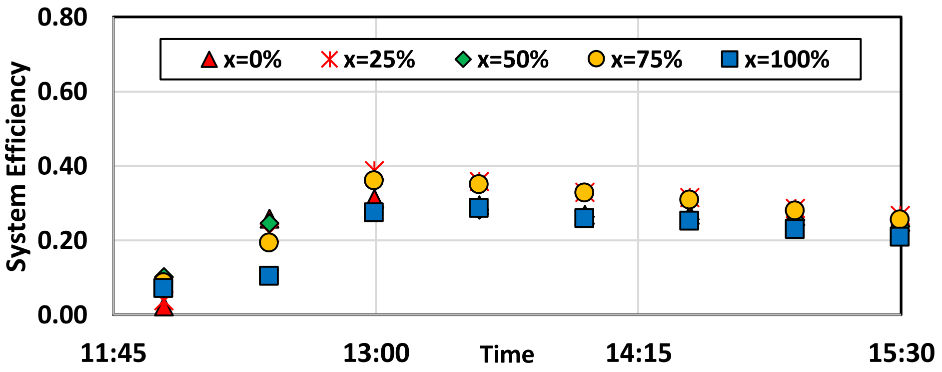


c) Methanol

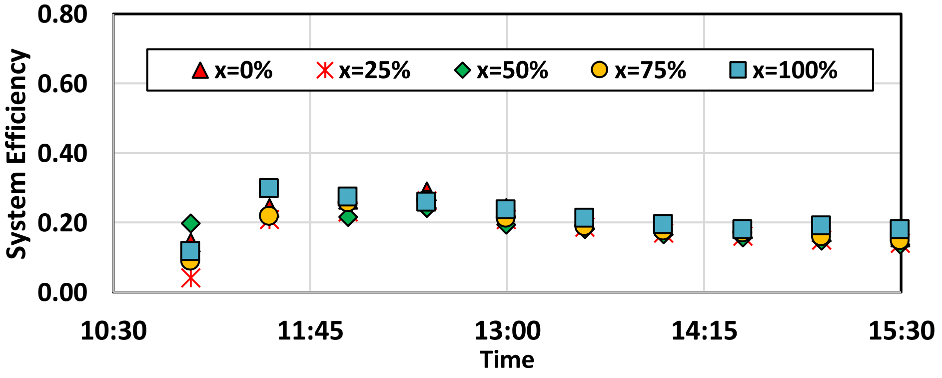


d) Acetone

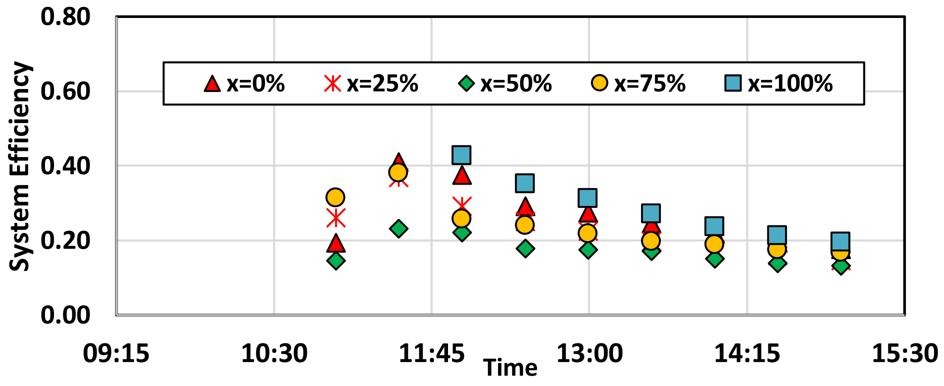
Fig. (7) Correlation equation of the collector efficiency for different heat pipe's working fluid and its aqua solution



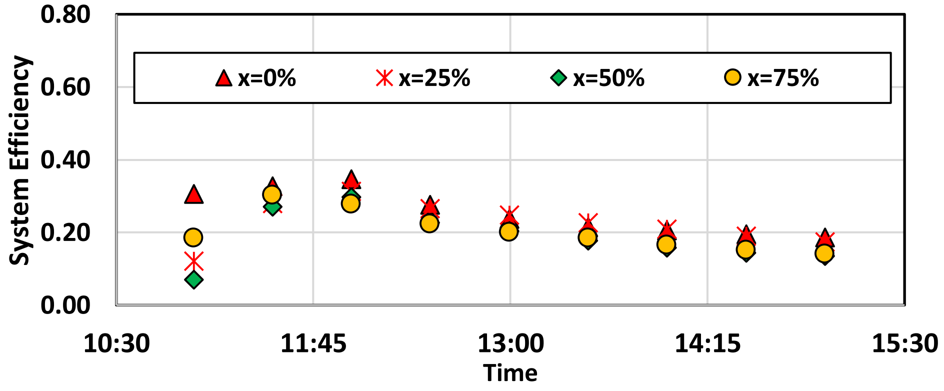
a) Ethylene glycol



b) Ethanol

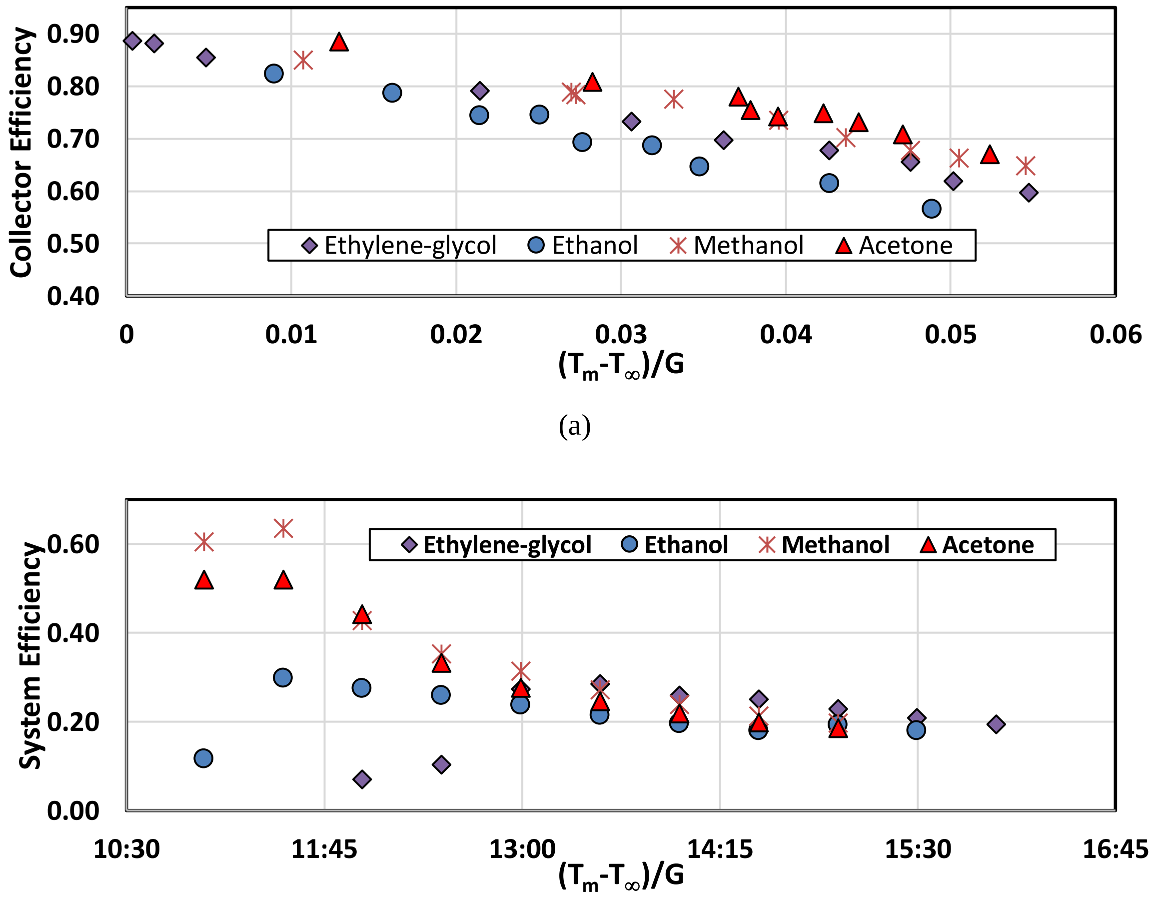


c) Methanol



d) Acetone

Fig. (8) Timewise variation of the system efficiency for different heat pipe's working fluid and its aqua solution



(a)

(b)

Fig. (9) Collector and system efficiency for different heat pipe' working fluid

Conclusions

In this work, the effect of using different heat pipe working fluid at a filling ratio of 30% of acetone, methanol, ethanol, and ethylene glycol at constant flow rate of 1.95 l/min for water as the heat transfer fluid on the collector and system efficiencies of the THPETCs and inclination angle of 45° under the climatic conditions of Cairo, Egypt in the outdoor test rig located at Faculty of Engineering at Shoubra, have been investigated experimentally. The results showed that pure water gives higher collector efficiency of methanol, ethylene glycol, and ethanol whereas acetone gives higher efficiency than pure water. Also, results showed that acetone gives the higher solar collector efficiency, followed by methanol, ethylene glycol, and ethanol, respectively with daily average collector efficiency of 76%, 74%, 73%, and 70% respectively; whereas the most higher system efficiency obtained in case of using methanol followed by acetone, ethanol, and ethylene glycol with daily average system efficiency of 36%, 32.5%, 21%, and 20.7% respectively. Empirical correlations for the collector efficiency in terms of $(T_m-T_\infty)/G$ and concentration are deduced.

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