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Experimental investigation on the performance of evacuated tube solar collector with wickless heat pipe under Iraq climatic conditions

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ABSTRACT
A wickless heat pipe evacuated tube solar collector (HP-ETSC) is considered in this work. Where an experimental investigation is conducted to study the thermal performance for the (HP-ETSC). The proposed heat pipe is charged with distilled water as a working fluid, where different values of filling ratios and inclination angles are considered. Namely, five values of filling ratios (40, 50, 60, 70 and 80 %) and three inclination angle values (30°, 45° and 60°). The Gravity-assisted wickless heat pipe (GAHP) is made of a copper tube with outer diameter 0.016 m and the dimensions of the evaporator and condenser are 1.15 m and 0.2 m respectively. The core and wall temperatures are measured by means of thermocouples that are located in the center and at the wall of GAHP. This study aims to observe the thermal performance of the HP-ETSC when using different values of working fluid, filling ratio, inclination angle and hot water mass flow rate in Najaf city climate (Iraq: latitude 31 °N and longitude 44 °E) during clear weather days in February 2017. The results show that the optimal filling ratio and inclination angles are 70% and 45° it is recommended to implement ,respectively when compared with other values during the course of study. Hence, in Najaf city wickless heat pipe evacuated tube solar collector with filling ratio and inclination angles are 70% and 45° respectively to obtain the optimal thermal performance.

KEYWORDS: Gravity-assisted wickless heat pipe, evacuated tube solar collector, GAHP, Filling ratio, inclination angle.

INTRODUCTION

The unique physical characteristics of Gravity-assisted wickless heat pipes (GAHPs), encouraged the researchers and manufacturers to use it in many different applications and research fields. It has the simple design and ability to transfer heat even with very small temperature difference, hence GAHPs are widely used in waste heat and renewable energy applications [1] [2]. Where GAHPs is successfully implemented to increase the efficiency of conventional solar collectors [3] [4]. Also, GAHPs have several advantages when it is used in solar collectors, where in addition to its powerful ability to transfer heat with a comparison to small size finned conductors, GAHPs eliminate excessive heating and freezing disadvantage occurred in a wide range of solar water collectors.

The GAHPs basically works with aid of small charging of vaporizable fluid in a sealed evacuated tubular container where the evaporation occurs at one end and the condensation occurs at the other end and, hence, the fluid circulates continuously as long as there is temperatures difference. A various number of investigations have been conducted to address the full understanding of the parameters (working fluids, inclination angle, heat input, and filling ratio.. etc) that might affect the performance of GAHPs especially in solar water heater applications. For instance, Mustafa Ali Ersoz [5] studied the effect of six different working fluids on the thermal performance of evacuated tube solar collectors with GAHP, where the air velocity is considered in three different values (and the results showed that the maximum energy transfer is associated with THPETC-Acetone). Mobin Arab and Ali Abbas [6] concluded that the water is the best working fluid when they investigated the effect of using many working fluids on the performance of a semi-dynamic model of a concentric (evacuated tube solar water heater (ETSWH) located in Sydney, Australia. A similar study on (ETSWH) was conducted by Redpath et al. [7], where experimental data were collected from (ETSWH) in the Climate of Northern Maritime. They implemented two identical models of the manifold chamber of a thermosyphon heat-pipe ETSWH in the laboratory where the two models are built with same dimensions to observe and compare the behavior of the two models when exposed to the same similar rates of heat input. Hayek et al. [8] used water-in-glass and heat pipe collectors models to investigate the overall performance under Mediterranean weather conditions. They showed that the heat pipe based collectors are more efficient than water-in-glass collectors where its efficiency is almost 15-20% higher, and they stated that the initial cost of heat pipe based collectors still a challenge to be considered as local markets items. Nkwetta et al. [9] presented a study on the internal low-concentrating evacuated tube heat pipe solar collector where they used optical method for the evaluation and analysis. The design was performed to enhance the collection of solar radiation where they tested different transverse angles and implemented ray trace techniques which determine flux distribution, optical efficiencies and related optical losses. Similar work on concentrated evacuated tube heat pipe solar collectors was presented by Nkwetta and Smyth [10] where they compared two profiles of single-sided and double-sided absorbers. Where the proposed design was tested at a tilt angle of 60 to the horizon. And under indoor conditions with five transverse angles (0-40^{o}) with an increment of 10^{o}, they compared heat loss coefficients, energy collection rates, and collection efficiency. In Southeast University, China, Du et al. [11] conducted an experimental study to implement a platform to test solar collectors where a heat pipe is used to transfer heat to the water by means of the designed flat form and the performance of an evacuated heat pipe solar collector is investigated. The main aim of their study is to observe the instantaneous efficiency and its correlations with the receiver and absorber areas, the incidence angle modifier, pressure drop, and the effective heat capacity. Also, they presented the theoretical analysis of the solar collector for these parameters. Arab and Abbas [12] investigated using different working fluids, during a typical day of operation, namely acetone, water, ammonia, pentane, and methanol on the performance of the fully integrated model for a grooved type evacuated tube solar water heater, and they found that the water is the best-working fluid. Another study was conducted by Jahanbakhsh et al [13], where they built and tested evacuated tube solar collector with thermosyphon heat pipe and two fluids were used, namely water and ethanol. The data were collected for different tilt angles and concentrations. The results showed that the heat pipe performance at low heat flux is enhanced when they used ethanol, also, the performance of transferring the heat reached its best level when concentrations are of 50% and 75% where the efficiency of the heat pipe was about 52%. This investigation came to conclude that adding wick or evacuating of the heat pipe do not affect significantly on the heat pipe performance and the optimal tilt angle of maximum heat transfer coefficient is 35^{o}. Jalal M. Jalil et al [14] worked on increasing the condenser lengths (0.15, 0.20 and 0.30 m) numerically and experimentally to improve the performance of solar collector heat pipe. The results showed that the water tank temperature is increased by 17% for a filling ratio of 30% and inclination angle 45º when the condenser length is increased by 25%.

One can see that most of the experimental studies above dealt with the performance of wickless heat pipe evacuated tube solar collector (HP-ETSC) where the performance depends on a number of parameters such as the type of working fluid, filling ratio, inclination angle, and operating conditions. However, for each heat pipe setup, dimensions, working fluid and condition, there are specific optimal filling ratio and inclination angle and it differs from heat pipe to another. Moreover, there is no good way of linking all parameters together and predict the change in heat pipe performance when one or more parameters are changed. In this work, we conducted an experimental study to address a wide range of parameters changes namely five values of filling ratios along with three different inclination angles to evaluate the performance of GAHP solar collector using water as working fluid, where the data are collected during February 2016 in Najaf city- Iraq climate; (latitude 31 ^{o}N and longitude 44 ^{o}E).

I. *Experimental rig setup, procedure and uncertainty:*

A. *Experimental rig setup:*

The primary objective of the experimental section is to study the effect of some parameters on the heat pipe evacuated tube solar collector (HP-ETSC) thermal performance in terms of temperature distribution, the Evaporation, Condensation heat transfer coefficient and thermal resistance. The considered parameters are solar intensity, a filling ratio (amount of liquid charge in evaporator section in GAHP) and inclination angle by using distilled water as working fluid. The schematic diagram and a photo of experimental set up of HP-ETSC that was used in this research are illustrated in Fig. 1. The details of the HP-ETSC that were used in this experiment are shown in Table 1. The measurements were performed during sunny days in February 2017 between 8 Am and 4 Pm. The GAHP and the water tank temperature were monitored during the period of the experiment by using twenty-four K-type thermocouples, positioned at different levels and locations inside the HP-ETSC, and the increase in internal energy of the system could be calculated. In order to study the boiling and condensation phenomena inside the heat pipe at the core for both evaporator and condenser sections, five K-type thermocouples were used; three in the evaporator region at the center of the tube and two others in the condenser region. The thermocouple readings' data by Data Acquisition system type Lab-Jack (T7 Series) were recorded at 5 s intervals in the experiment work. Thermocouple location is shown in Fig. 2.

The experimental part was conducted under Najaf city climate; (Iraq latitude 31 ^{o}N and longitude 44 ^{o}E). The title angle of solar collector change within the range (30 to 60^{o}) measured from horizontal, capacity of the water tank is 6 liters. The instantaneous value of global solar radiation intensity was measured by using the pyrometer (Model-DWR 8101, Make-DynaLab) [15]. The mass flow rate of cooling water was measured by using a rotameter and also measured by using a stopwatch and by using a measuring glass bottle.

B. Experimental rig setup

The experiment procedure for the heat pipe evacuated tube solar collector (HP-ETSC) steps are:

Fix the tilted angle and water mass flow at the recommended value.

1. Choose the filling ratio (FR) for the distilled water (40, 50, 60, 70 and 80 %).
2. The surface and core temperatures along the GAHPs as well as the water tank temperatures are measured and recorded at each quasi-steady state condition.
3. Change the FR to a new value and repeat step 2.
4. Change water mass flow and repeat steps 1-3.
5. Change solar collector tilted angle and repeat steps 1- 4.

During each experiment, the amount of solar energy input (1 in w/m2) at evaporator region of GAHP is transferred to the condenser region and removed by the condenser, and the overall thermal resistance (R_{exp})for the solar collector were calculated as follows[16]:

$$R_{exp} = \frac{(T_{evap} - T_{cond})}{2\pi r_o l_{evap} \mathrm{I}} \quad (1)$$

Where $\bar{T}_{evap}$ and $\bar{T}_{cond}$ are the average wall temperatures at the evaporator and condenser regions measured by the surface temperature thermocouples in eight different locations as shown in Fig. 2.

C. Uncertainty:

The effect of uncertainty for the present work is an accumulation of the effect of the uncertainties for each element used in the set-up. Abernethy and Thompson [17] method is used in this work to combine uncertainties for all elements. The main inherited and calculated uncertainties in this work are summarized in Table 2.

Table 1: Details of the design specifications of the HP-ETSC system

Part	Item	Specification
Solar collector	Type	Evacuated tube heat pipe
	Collector area	0.06912m2
Gravity assisted wickless heat pipe	Material	Copper
	Outer diameter	16 mm
	Inner diameter	14 mm
	Evaporator length	1150 mm
	Condenser length	200 mm
	Working fluid	DI water
Glass envelope	Material	Pyrex glass
	Length	1200mm
	Outer diameter	50mm
	Inner diameter	45mm
	Wall thickness	2.5mm
	Vacuum	10-4 torr
	Transmittance	93 %
Flat reflector	Material	Aluminum sheet foil
	Area	1250*300mm
Storage tank	Material	Galvanized steel 0.6mm thickness
	Capacity	6L
	Insulation	Glass wool 25mm thickness
	Outer shell	Sheet of 1mm aluminum

Table 2: Uncertainty for experimental results.

Specification	Mean value	Total Uncertainty value	Total Uncertainty (%)
Measured parameters			
Temperature, °C	45	±0.41	±0.91
Pyrometer, W/m2	400	±0.5	±1.6
Volumetric flow rate, l/h	1	±0.4	±1.4
Calculated parameters			
Thermal resistance (Rexp), m2.K /W	0.198	±0.8	±2.3

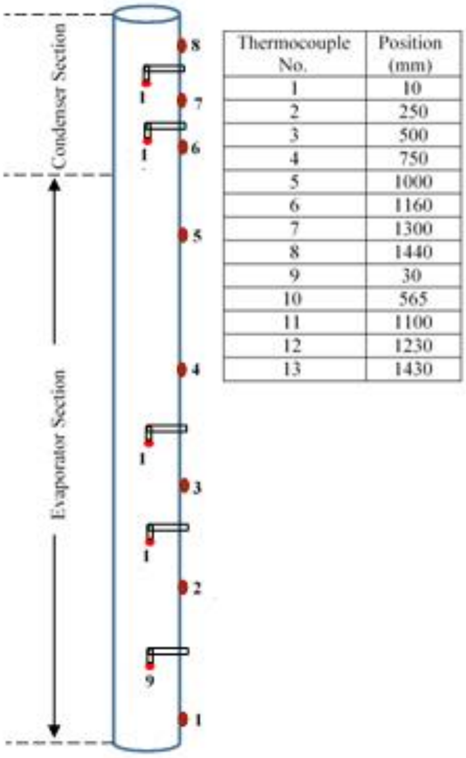


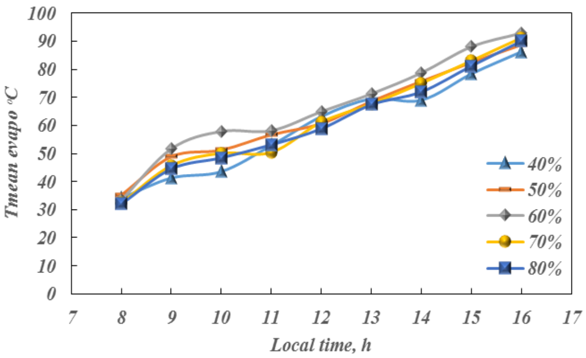
Fig. 1: The schematic diagram and a photo of experimental set up of HP-ETSC.
Fig. 2: GAHP thermocouple positions (surface wall and core)

RESULTS AND DISCUSSION

For the twenty nine days during February month in 2016 of experiments, Figs. 3–5 show the instantaneous variation during each day of the solar time, filling ratio, inclination angle and the hot water mass flow rate of the wickless heat pipe evacuated tube solar collector (HP-ETSC).

D. Effects of the fluid filling ratios on evaporator surface temperature:

Figures. 3 through 5 show the effect of the working fluid filling ratio on the evaporator mean surface temperature at the three nominated title angles for HP-ETSC. These figures indicated that the mean evaporator wall temperature decreases from its maximum value at fill ratio 40% to the minimum value at 70% then increases again to a certain value at fill ratios 80%. However, at a low solar intensity in the morning before the solar noon (from 8.00 to 10.00 in the morning), there is a slight change in mean evaporator wall temperature between the five tested filling ratios. Therefore, the effect of filling ratio on mean evaporator wall temperature is clearer at the relatively high solar intensity. Decreased fill charge ratio causes an increase in the mean evaporator surface temperature for all inclination angle, which reduces the thermal resistance to heat flux resulting in a lower evaporator wall temperature. This result was obtained for all experimental heat pipes with all fluids. This behavior is due to the hydrodynamic stratification of the liquid film flowing downwards along the inner evaporator surface at small filling ratios, this phenomenon was named the geyser effect by Casarosa et al. [18], The reason behind increasing the surface wall temperature in the evaporator section at highest filling ratio (80%) is attributed to the fact that the thermal resistance of liquid film in the evaporator increases as liquid height increase (fill ratio) above the optimum value. These Figs. indicate that a filling ratio of 70% gives the higher performance (lower thermal resistance) where it has a small evaporator mean temperature throughout the day this result was supported by the results obtained by Mahdy [19], Aljboory [20] and Jalal M. etal[14] where an optimum distilled water filling ratio in the range of 50–70% was obtained.



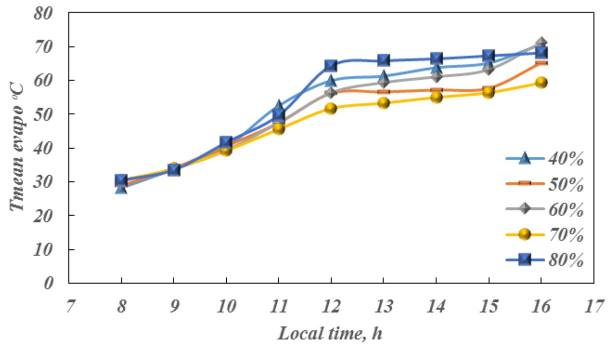
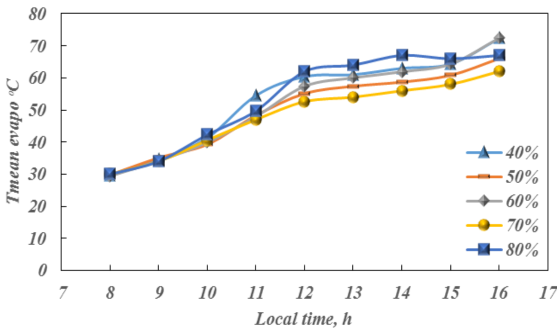


Fig. 3: Variation of mean wall temperature of evaporator with fill ratio during solar time at title angle 30°
Fig. 4: Variation of mean wall temperature of evaporator with fill ratio during solar time at title angle 45°



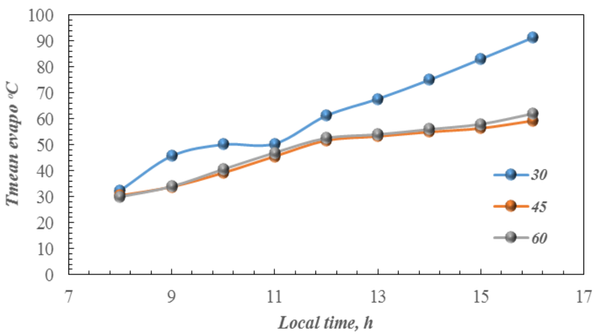


Fig. 5: Variation of mean wall temperature of evaporator with fill ratio during solar time at title angle 60°.
Fig. 6: Variation of mean wall temperature of evaporator at different inclination angles for optimal fill ratio 70%.

E. Effects of inclination angle on evaporator surface temperature:

The effect of inclination angle at optimum filling charged (70%) according to the above results on the mean surface temperature of the evaporator section during the solar time is illustrated in Fig. 6. It can be seen that the evaporator temperature increases as the inclination angle decreases toward the horizontal orientation for all solar intensity and this increase is higher when the solar intensity is higher. However, at angles of 30° and 60° the value of the evaporator mean surface temperatures are greater than that at angle 45° for both closed and withdraw systems. Therefore, the effectiveness of the HP-ETSC is better at 45° than that at other inclination value (similar conclusions were reported by [21]).

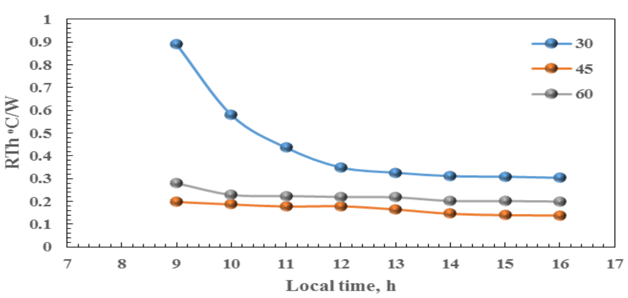
F. Effects of inclination angle on thermal resistance:

Figure 7 shows the effect of inclination angles on thermal resistance for optimal filling ratio. It is seen that the thermal resistance decreases with increasing solar time for all inclination angles. A higher thermal resistance is observed at 30° due to the fact that the working fluid covers part of the internal space of the evaporator whereas is has a lower value at 45° during the sunny day (similar trend was obtained by [22]). However, a lower difference in thermal resistance between the inclination angles is seen at the period of after noon, especially, between 45° and 60°. Thus, the best inclination angles is 45° and this is a similar conclusion as those were concluded by [14, 20 and 22].

G. Effects of inclination angle on the wall surface temperature distribution along GAHP:

A precise experimental determination of the thermal performance of the wickless heat pipe evacuated tube solar collector (HP-ETSC) requires accurate measurements of the temperatures in the condenser and evaporator regions in addition to the inclination angle. The each measuring location point, the final temperature reading is obtained by averaging of the readings over the measuring period of time. Figures 6-8 show the temperature distribution over the wall surface of GAHP associated with the optimal filling ratio 70% from the results which are illustrated in figs. 3-5. In figures 7 and 8, one can see the behavior of temperature distribution which is nearly isothermal over the evaporator section. This behavior is because of the existence of fluid lining that covers the internal surface of the evaporator. In GAHPs with low tilt angle, the liquid film (hydrodynamic stratification of the liquid flow downwards to the liquid pool in the evaporator) does not touch the entire wall surface of the evaporator section.

Moreover, with high solar intensity after noon time and lower tilt angle 30°, the liquid film covers the upper half from the evaporator causing the internal evaporator wall surface to dry-out (Geyser effect) [1,18] at the upper location, resulting in a sudden rise in the evaporator surface temperature. As shown in Fig. 6 the GAHP operates at a higher wall temperature with 30°. It is clear from Fig. 6 that the temperature has a trend of starting with sharp gradient behavior between the two regions of GAHP and slightly the trend becomes isothermal for the rest of condenser section. This trend is expected to because of the absence of adiabatic section in GAHP.



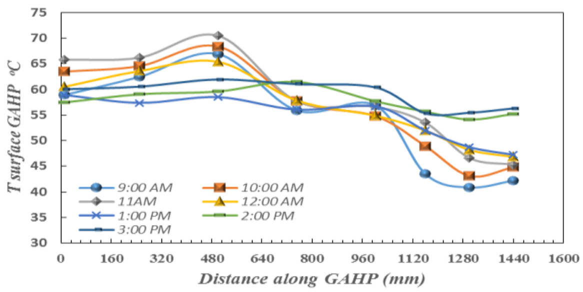
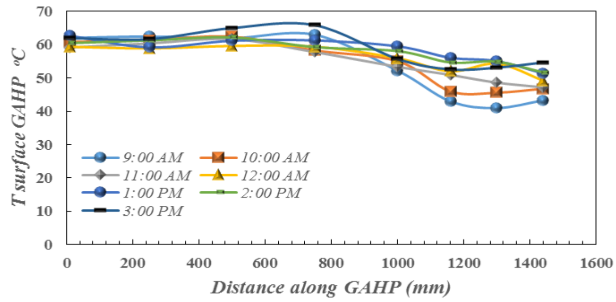


Fig. 7: Variation of GAHP thermal resistance for the three angles at optimal filling ratio 70%.

Fig. 8: Variation of temperature with the distance along the wall of GAHP at optimal fill ratio 70% during solar time at title angle 30°.



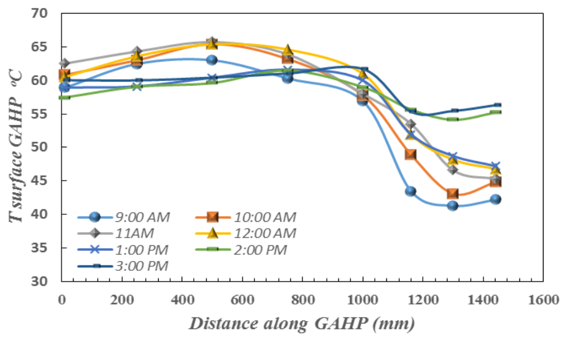


Fig. 9: Variation of temperature with the distance along the wall of GAHP at optimal fill ratio 70% during solar time at title angle 45°.

Fig. 10: Variation of temperature with the distance along the wall of GAHP at optimal fill ratio 70% during solar time at title angle 60°.

Conclusions:

Use From the present experimental investigation on HP-ETSC with different values of filling ratio, inclination angles, hot water mass flow rate and wide range of solar intensity, it is concluded that:

1. The optimum working fluid filling ratio of the HP-ETSC is 70%.
2. In evaporator section, the vapor core temperature was less than surface temperature, whereas in condenser section the behavior was opposite.
3. The best performance can be achieved with no closed system (zero water mass flow rate).
4. The minimum thermal resistance at 45^{o} as a tilt angle.
5. More experimental studies are needed to investigate the optimum filling ratio of different working fluids and different cross-sectional geometries on the performance of HP-ETSC.

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