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The Effect of Vibration Pulses on the Thermal Performance of Evacuated Tube Heat Pipe Solar Collector

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ABSTRACT: An experimental research has been performed to investigate and elicit a heat pipe evacuated tube solar collector (HPET-SC) that subjected to mechanical vibration. The voltage ranges used to generate vibration frequency are 6, 8, 10 and 12 Volts. For comparison, two HPET-SC's were built identically. This comparison has been made based on the solar collector effectiveness of in a presence and an absence of the vibration under Iraq's winter climatic conditions. In this study, a liquid of an Acetone was used as a working fluid inside the heat tube with 0.7 filling ratio. One of the outlet investigation results indicates that heat transfer coefficients of the evaporation and condensation increased with increasing of the vibrational frequencies. Another result, using the controllable vibration system led to increasing the two coefficients of heat transfer, the temperature of hot water and the total collector effectiveness by (25%), (15%), and (20%) respectively throughout the test conditions.

KEYWORDS: Vibration energy, Evacuated tube solar collector, Thermosyphone, Gravity-assisted heat pipe, ETHPSC

INTRODUCTION

The study of vibration in structures and systems was useful because the effect of vibration plays a crucial role in engineering applications. In the industrial applications, the bulk of the movements and oscillations are practically unfavourable because repetitive or cyclic movement leads mechanical components to a malfunction or severe damages [1-5]. Nonetheless, controlled vibration or induced excitation generation allows meeting the design target for specific applications. For example, kidney stones can disintegrate with shock wave excitation in a medical application. On the other side, in many engineering applications such as thermal systems, regulated vibration is commonly employed.

In a study on a grooved cylindrical copper heat pipe with horizontal longitudinal vibrations to increase efficiency with various condensation section's temperatures, Rong-Horng Chen et al.[6,7] reported that the longitudinal direction vibrator induced the thermal resistance of the heat pipe reduction which was directly related to the input vibration energy. The temperature of the condensation area has a significant impact on thermal efficiency than the vibrations. Bowman and Huber [8] proposed research into the use of the bench-top shaker to excite the heat pipe with a wrapped glass wick at different frequencies and amplitudes. Huber and Bowman have shown that longitudinal vibration decreases the capillary limits of the copper water heat pipe that wrapped screen wick, and consequently, further studies were suggested on various heat pipe types since the subject of (heat pipe vibration) is seldom discussed within the literature[7].

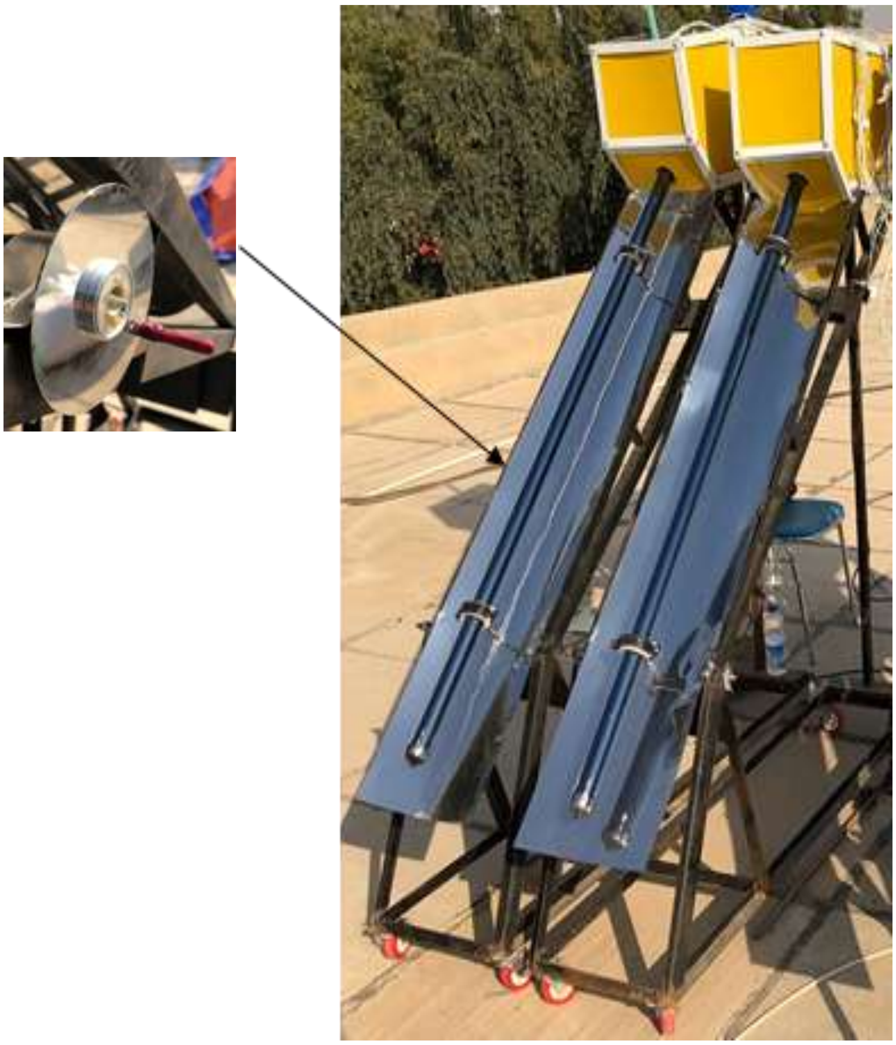
Amir Alaei et al. [9] experimentally researched the effect of the use of low-frequency vibration on a gravitational support heat pipe. They demonstrated that thermal efficiency is highly responsible for the vibration (33.83%); the optimum value of efficiency was achieved at frequency 30 Hz. Amir Alei [10] reported a similar experiment in which he put the same concept into action on an oscillating heat pipe, and the results show a similar trend in thermal efficiency enhancement in the oscillating heat pipe. Furthermore, the "dry-out" at the lower filling rate and the maximum heat transfer rate are eliminated by vibration. To our best knowledge, there is very little research on the use of vibration with evacuated solar heat pipe collector's. The main aim of the current work is to establish a vibration system that will trigger the heat pipe evacuated tube solar collector structure to study thermal efficiency, where the vibration to be delivered as pulses with different frequencies over some time. The experiment is carried out by a fully controlled vibration system, and descriptions of the designed control system are shown in section 2. Section 3 presents the construction of the solar collector system. The test model is shown in section 4.

EXPERIMENTAL RIG SETUP

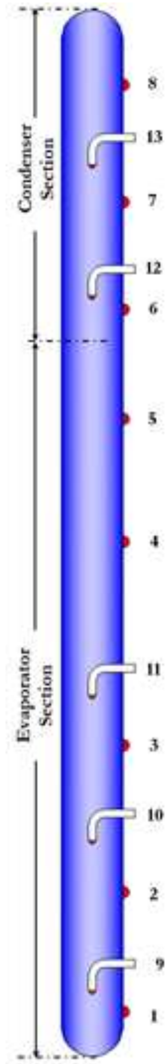
An (HPET-SC), vibrating actuation, and data measurement systems, are the main components of the designed and manufactured experimental program. Fig.1 (A) and (B) shows the diagram and photograph of the experimental rig with integrated equipment.

System of Vibration

For a specified period during the experiment, the vibrational effect implemented in the form of pulses by means of a designed controllable vibration system. A vibration system of various components has been built as follow.

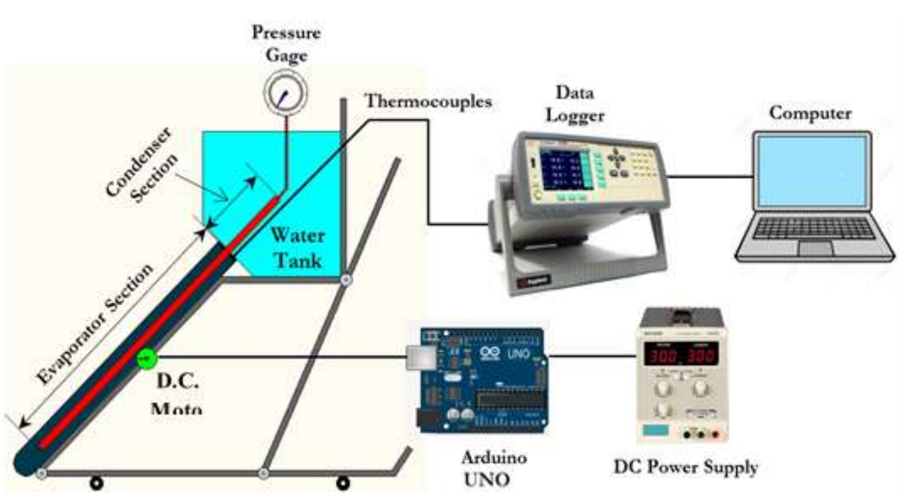


(A)



(B)

Thermo. No.	Position (mm)
1	10
2	250
3	500
4	750
5	1000
6	1160
7	1230
8	1280
9	30
10	565
11	1100
12	1230
13	1280



(C)

Figure 1. (A and B) Setup and schematic diagram of the experimental rig for HPET-SC with and without a vibrator, (C) GA-HP thermocouple positions (surface wall and core)

DC Rotating Motor

A small DC motor has been used to produce the vibration with an unbalanced load, as illustrated in Fig.1. Where different radii and mass values can be defined by using the eccentric mass. An aluminium disc is produced to hold a screw (eccentric mass) with a constant mass of 15 grams. The DC motor shall be mounted to the structure of the solar tube collector evacuated heat pipe (HPET-SC) to produce excitation through the control circuit with various amplitudes and frequencies. The motor's base is shielded by an elastic sheet, which smoothes out the generated vibration in the heat pipe evacuated tube solar collector. The supplied signal to the vibrating motor has been controlled by using a system includes DC power supply and an Arduino UNO system where the Arduino is a programmable instrument capable of delivering the required output using software code. The variable resistor regulates the variable voltage delivered to the motor, and as a consequence, the frequency is controlled. The diagram of the circuit of control is illustrated in Figure 2.

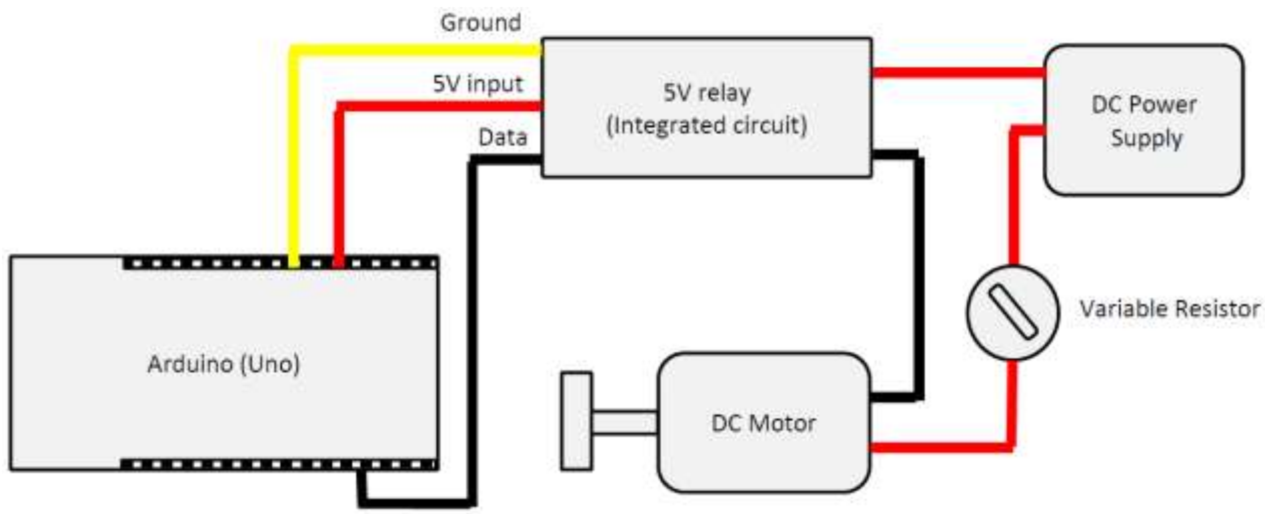


Figure 2. The circuit of the control

Heat Pipe Evacuated Tube Solar Collector (HPET-SC)

We test the feasibility of the use of vibration to analyze the thermal performance of (HPET-SC). In addition to the temperature distribution, this work includes the investigated thermal resistance, condensation and evaporation heat transfer coefficients. To compare the performance of (HPET-SC) with or without using of vibration; two similar rig configurations are identically constructed, and these are shown in Fig.1. together with the schematic diagram showing the setup outlines. Also, the experimental parameters and data are illustrated in Tab.1. Where the water tank temperature and GA-HP temperature are measured by a series of 24 (K-type) thermocouples throughout the experiment. The temperature sensors inside the HPET-SC are placed in different positions and levels to ensure that the internal energy content is measured explicitly and reliably. To measure the temperatures inside the evaporator and condenser sections; five temperature sensor probes are positioned in the centre of the cross-section with various parts, three are in the evaporator section, and the rest is in the condenser section as shown in Fig.5. Temperature recording in the centre of evaporator and condenser sections enables researching the phenomenon of boiling and condensation inside GA-HP. The full readings from all thermocouples, during the study, are obtained using a digital data acquisition system (U6-PRO Series Lab-Jack type). Where every reading during the experiment is taken every five seconds. The volume of the water tank is 6 litres, and The inclination of the solar collector's angle is 45˚. The experiment is located in Najaf city, Iraq (latitude 31 ^{o}N and longitude 44 ^{o}E) and the data was obtained from 8 AM to 4 PM on sunny days in January 2018. A pyrometer measurement was used to detect global solar radiation instantly. A stopwatch, a rotameter, and measuring glass bottle were used to measure the mass flow rate of hot water. Figure 1 illustrates the test rig for two similar heat pipe evacuated tube solar collector (HPET-SC), one is equipped with a vibrator (left) and the other vibrator-free (right).

Experimental Procedure and Uncertainty

Two similar HPET-SC rigs were conducted to determine the performance of each HPET-SC in the same conditions with a presence and an absence of the vibration. When setting the water flow rate to the desired value, the ideal working conditions for the HPET-SC were reached by a filling ratio of 70% and a tilted angle of 45˚ [11]. As one of two HPET-SC systems operates with the absence of vibration effect, it has been considered to be a reference. The other HPET-SC was exposed to a vibrational effect that is expressed as regularly periodic on-off pulses (20 seconds on – 120 seconds off) throughout the course of the experiment. The voltage ranges used to generate vibration frequency are 6, 8, 10 and 12 Volts. Using a 45 ° angle of inclination to achieve the highest performance for the single-gravity assist of HPET-SC system. The procedural steps of the experiment are:

1. The heat pipe in both two rigs has been supplied with pure acetone at a filling ratio of 70% from the evaporator portion.
2. The control system is adjusted to provide a 20-second vibrating pulse and repeated for every 120 seconds.
3. Throughout 8 AM to 4 PM, the surface and core temperatures were estimated and reported in every five seconds.
4. Change the value of the frequency and repeat to step 3-4.

Based on the test situation, the most critical uncertainties for the instrumentation used in this study are (1.25-3.2), which is represented in thermal resistance, evaporation/condensation coefficients of heat transfer and vibration energy. Using the Root-Sum-Squares (RSS) method, total uncertainty can be calculated by the equation:

$$U_{RSS} = \sqrt{\sum_{i=1}^{i=n} \left(\frac{\partial R}{\partial X_i}\ \Delta X_i\right)^2} \tag{2.1}$$

Table 1: Details of HPET-SC's design specifications [11].

Part	Item	specification
Solar collector	Type	Evacuated tube heat pipe
	Collector area	0.06912 m^2
GA-HP	Material	Copper
	Outer diameter	16 mm
	Inner diameter	14 mm
	Evaporator length	1150 mm
	Condenser length	200 mm
	Working fluid	Pure Acetone
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	Aluminium sheet foil
	Area	1250*300mm
Storage tank	Material	Aluminium 1 mm thickness
	Capacity	5L
	Insulation	5mm Fiber Glass+3 mm Silicon+ Layer of Glass Wool
	Outer shell	Sheet of 3mm Alicabond

Theory relevant

The solar energy source (I in W/m^2) converts to the condenser from the GA-HP evaporator and then is dissipated by the water tank. We employ the below equation for calculating the overall solar collector's thermal resistance (Rexp) [11, 12]:

$$R_{ex} = \frac{\bar{T}_E - \bar{T}_C}{2\pi r_o l_E I} \tag{2.2}$$

Where : r_o and l_E are the outer diameter and the length of GA-HP, respectively.

RESULTS AND DISCUSSION

In the following sections, the effect on the thermal performance of GA-HP and HPET-SC is examined using different vibration frequencies. The GA-HP thermal resistance for sunny days (from sunrise to sunset) has initially been analyzed with solar radiation. An analysis was made of the influence of vibrational frequencies on thermal efficiency. Finally, the influences of the HPET-SC performance from different vibration frequencies were studied. Enhanced the Condensation process in all types of heat pipe increased the amount heat transferred by converting a vapour working fluid into a liquid and film back flowing to the evaporator section by capillary effect or gravity assist because of the diversity mode of the condensation process (homogeneous, dropwise, film-wise and direct contact). As it is seen for different vibration frequencies, the surface evaporator temperature decreases with the increase of the vibration frequency, as shown in Fig.3. Also, for the same reason, we notice that as the vibration frequency increases the surface condenser temperature decreases as illustrated in Fig.4.

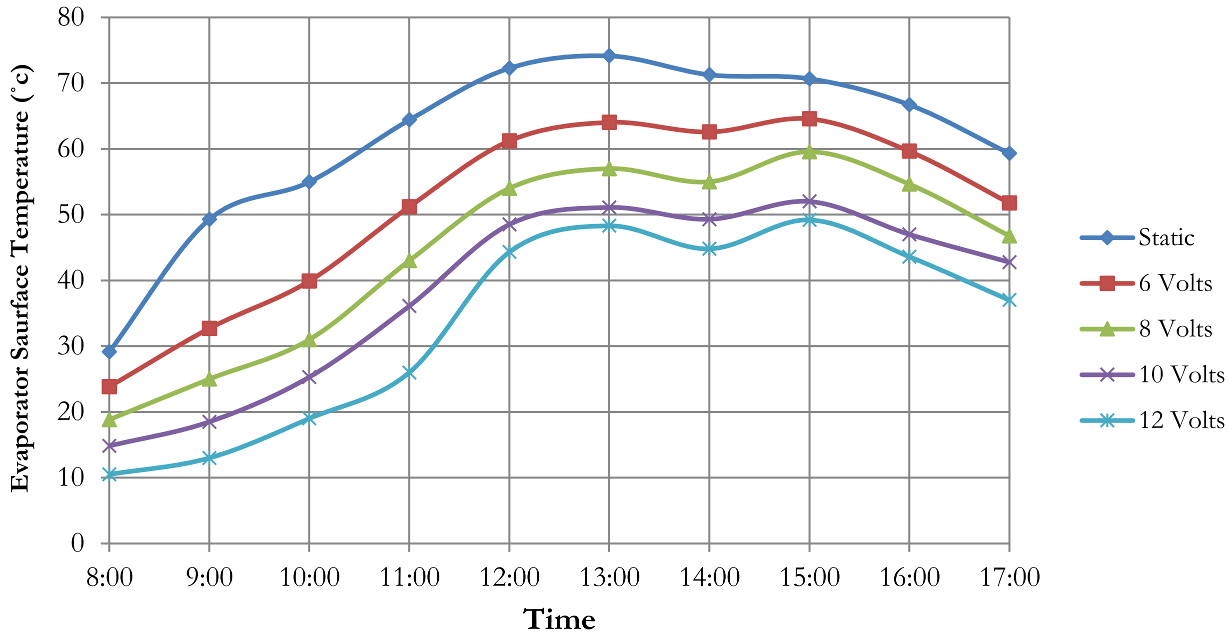


Figure 3. Mean surface Temperature of Evaporator Section of GA-HP at various voltages

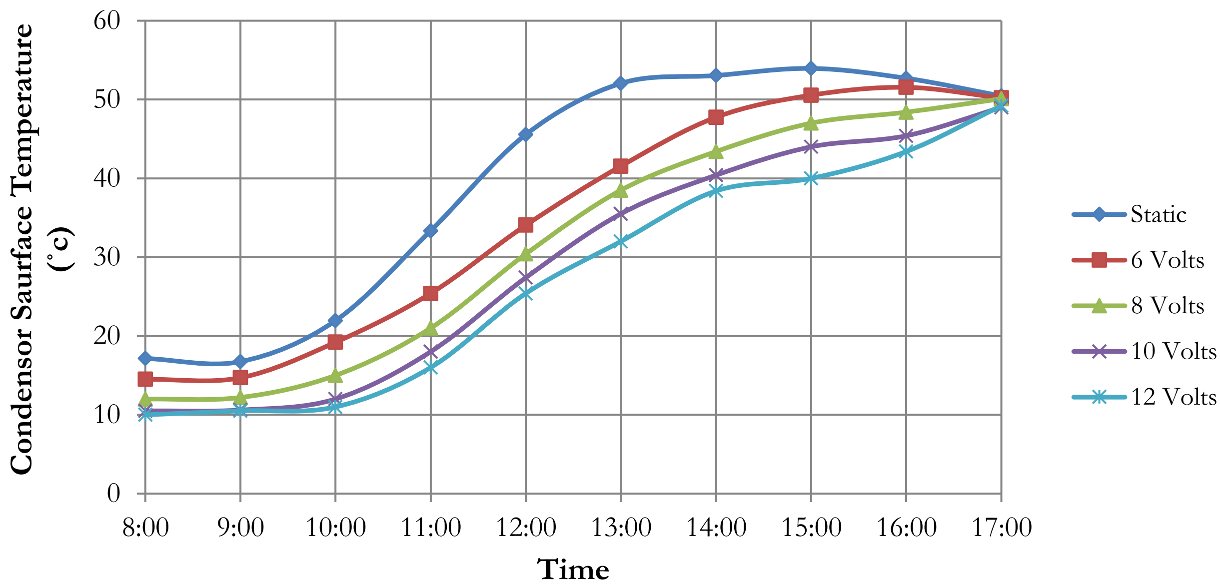


Figure 4. Mean surface Temperature of the condenser section of GA-HP at various voltages

One main parameter of all forms of solar water heater systems like HPET-SC is the temperature of the tank. In this research, in order to calculate the enhancement of system storage and internal energy of the HP-ETSC system, the water tank temperature has a significant impact on the performance of GAHP, which is the condenser cooling fluid temperature (when it decreases, the thermal resistance decreases) [11,14]. Five K-type thermocouples are mounted inside the tank on different levels (right, left, top, bottom and centre) to determine the water tank temperature. A higher tank temperature leads to higher collector efficiency of HPET-SC and the best output with similar solar radiation input due to two effects. The first one is that the quantity of useful two-phase heat transmitted through GAHP is equivalent to radiation input, that is the best working fluid and lowest thermal resistance. The second reason is that the homogenous temperature distribution in a water tank by the reduction in the viscosity of water because the temperature rises and the thermosyphon over the surface of GA-HP condenser section are affected by the change in density of the warmed water. So, as shown in Fig.5 the increasing the voltage used to generate the vibrational frequency the increasing the mean water tank temperature.

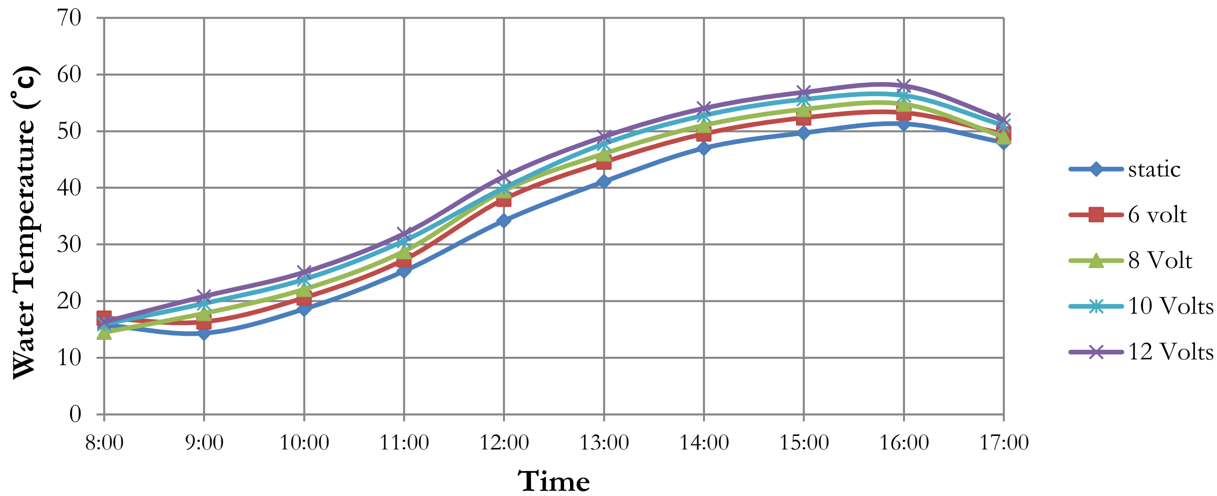


Figure 5. Mean water tank Temperature at various voltages

Also, because of the excitation by using a vibrational system with HPET-SC leads to enhance of the condensation process, the amount of heat transferred increased by converting a vapour working fluid into a liquid and film back flowing to the evaporator section by capillary effect or gravity assist because of the diversity mode of the condensation process. Figures (6) and (7) clearly indicated that the average temperatures along the HP-GA in the case of absence of the vibration is highly greater than that in case of presence of the vibration.

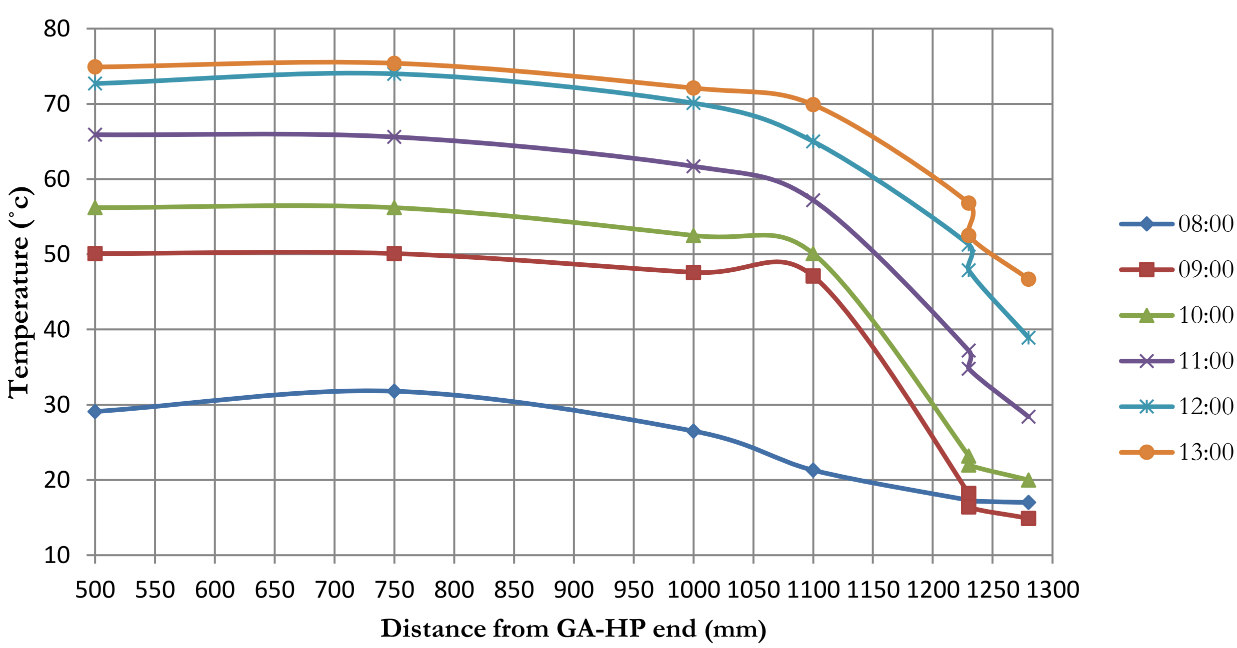


Figure 6. Temperature distribution along GA-HP without vibration

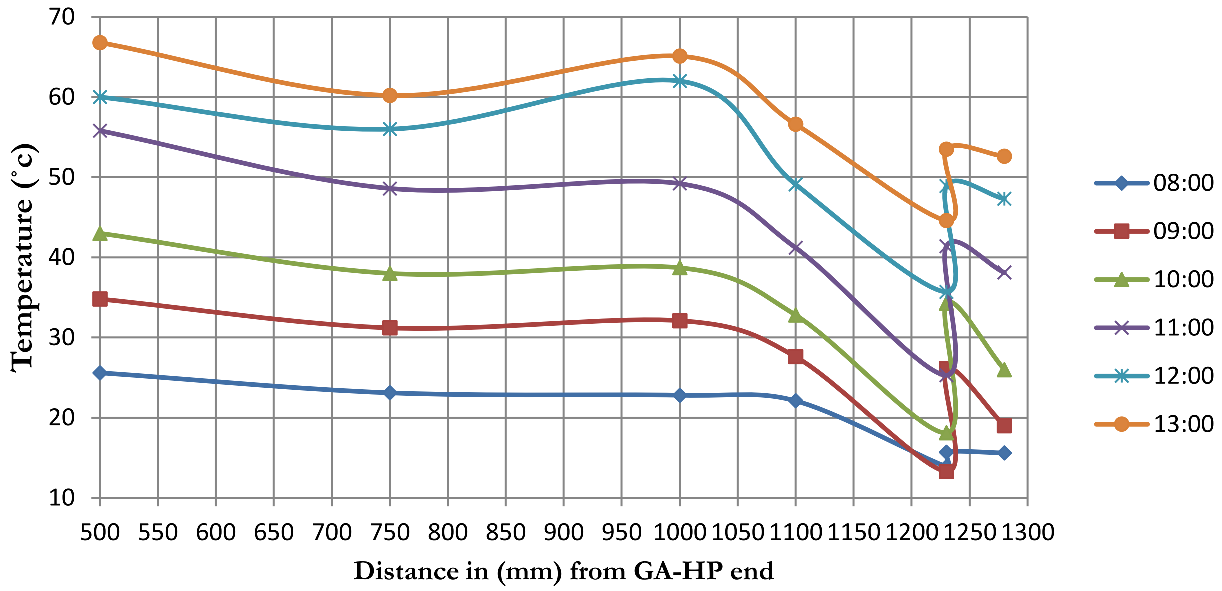


Figure 7. Temperature distribution along GA-HP with vibration

CONCLUSION

This research is carried out with a controllable vibration system to improve the heat transfer efficiency of GA-HP and HPET-SC systems. The testing rig consists of two key parts. The first part is the vibrating system consisting of the motor that controls the vibration with adjustable rotating unbalance mass and electrical control circuits. The second part is the HPET-SC, where two HPET-SC's were built identically for comparison purpose. This comparison has been made based on the solar collector effectiveness of in a presence and an absence of the vibration under Iraq's winter climatic. A liquid of an acetone was used as a working fluid inside the heat tube with 0.7 filling ratio. The findings for the performance of the GA-HP showed that as the voltage used to generate the vibration increased from 6 to 12 volts, the thermal resistance in all test conditions was reduced and it has a lower value at 12 volts. However, the results showed that the temperatures of evaporator and condenser decreased with increased voltage levels. Moreover, the results showed that the increase of vibration through increasing the voltage levels lead to an increase of the water tank temperatures so it can be implemented in many different solar applications to enhance the thermal performance.

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