Journal of Mechanical Engineering Research and Developments (JMERD)
DOI : http://doi.org/10.26480/jmerd.03.2018.67-73
ISSN: 1024-1752
CODEN : JERDFO

CONTROLLABLE VIBRATING SYSTEM TO ENHANCE THE PERFORMANCE OF HEAT PIPE EVACUATED TUBE SOLAR COLLECTOR

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ARTICLE DETAILS

Article History:

Received 23 May 2018
Accepted 24 September 2018
Available online 27 September 2018

ABSTRACT

Mechanical vibration is used to excite a heat pipe evacuated tube solar collector (HP-ETSC), where two (HP-ETSC's) are built identically to compare the performance of the solar collector with and without applying vibration. A controllable vibration system was designed and manufactured for increased the total collector efficiency. The vibration system consists of a motor with adjustable rotating unbalanced mass and a control circuit. The velocity (frequency) of the motor is controlled by mean of an Arduino circuit that applies the controlling signal in the form of pulses over a certain period of time. The vibration is applied on one of (HP-ETSC's) and the other is left in static condition under Iraq winter climatic conditions. The enhancement on the thermal performance at different frequency values (2, 4, 6, 8 and 10 Hz) and the three volumetric water flow rates are discussed. Results indicated that the evaporation and condensation heat transfer coefficients increased with vibrational frequencies, and the vibrational frequencies effectiveness depended on the water flow rate and the working conditions. The two heat transfer coefficients, hot water temperature and the total collector effectiveness of the HP-ETSC with controllable vibration system increased by 40%, 20%, and 22% during the test conditions.

KEYWORDS

Evacuated tube solar collector, Gravity-assisted heat pipe, low-frequency vibrations.

1. INTRODUCTION

Studying of vibration in structures and systems have been a fertile field because the existence of vibration plays a crucial role in the design of the engineering applications. In general, vibration occurs in the continuous system such as strings, membrane, and beams [1-3] and discrete systems [4]. Practically, most of the vibrations and oscillations phenomena are undesirable in industrial applications since repeated or cyclic motion causes failure or severe damages to the mechanical components. However, in some applications generating controlled vibration or forced excitation helps to achieve the application goal. For instance, in the medical application, the kidney stones can be disintegrated by using shock waves excitation [5].

On the other hand, controlled vibration is widely used in many engineering application such as thermal applications. Rong-Horng Chen et al [6, 7] conducted a study on a grooved cylindrical copper heat pipe where they applied horizontal longitudinal vibrations to improve the performance with different values of condensation section temperature, they stated that the longitudinal direction vibration caused reduction in thermal resistance of the heat pipe that was directly proportional to the input vibration energy. Moreover; the condensation region temperature has the major influence than that of the vibrations on the thermal performance. Huber and Bowman [8] presented an investigation about implementing of the bench-top shaker to excite a heat pipe with wrapped screen wick with various frequencies and amplitudes.

Huber and Bowman showed that applying longitudinal vibrations reduces the capillary limit of the wrapped screen wick copper water heat pipe, and hence they suggested further studies on different types of heat pipe since the topic of (vibration on heat pipe) is rarely presented in the literature [7]. Amir Alaei et al. [9] investigated experimentally the effect of using low-frequency vibrations on a gravity assist heat pipe. Their results showed that the vibration was strongly effective on the thermal performance (33.83%) and the optimal performance was achieved at the frequency 30 Hz. A similar observation was reported by Amir Alaei [10] where he implemented the same idea on an oscillating heat pipe (OHP) and the results showed a same similar trend in the enhancement of thermal performance of OHP.

Moreover, the vibration removed the “dry-out” at the lower filling ratio and maximum heat transfer rate. To the best of our knowledge, the research on using vibration with evacuated tube solar collectors is very little. The main objective of this work is to implement a vibration system that excites the structure of a heat pipe evacuated tube solar collector (HP-ETSC) to investigate the thermal performance, where the vibration to be applied in form of pulses over a period of time with different frequencies. A fully controlled vibration system is designed to run the experiment and the details of the control system are presented in section 2. In section 3, the design of the solar collector system is presented and the experiment rig is illustrated and the results are discussed in section 4.

2. EXPERIMENTAL RIG SETUP

The designed and manufactured experimental program included the heat pipe evacuated tube solar collector, vibrating actuation, and data measurement systems, with the integrated the control equipment. The diagram outline and photo of the experimental rig setup with integrated equipment are shown in Figure 1.

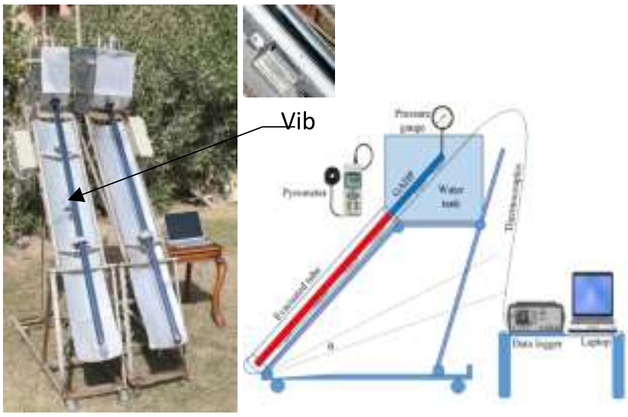

Figure 1: Experimental rig setup and schematic diagram for HP-ETSC with and without vibrator.

2.1 Vibration System

The vibration effect is to be applied in form of pulses for a specific period of time during the course of the experiment. Thus, a controllable vibration system needs to be designed. In this work a vibration system is designed from different components as follows:

2.1.1 DC Motor

A small DC motor is used to generate the vibration by mean of unbalanced load as shown in Fig (2). Where the eccentric mass can be set to different radii and mass values. A plastic drum is made to hold an adjustable screw (which represents eccentric mass) and the screw mass can be increased by adding more nuts. The motor is to be mounted on the heat pipe evacuated tube solar collector (HP-ETSC) to provide an excitation with different amplitudes and frequencies by mean of controlling circuit. The base of the motor is covered with elastic layer to smooth out the vibration transmitted to the heat pipe evacuated tube solar collector (HP-ETSC).

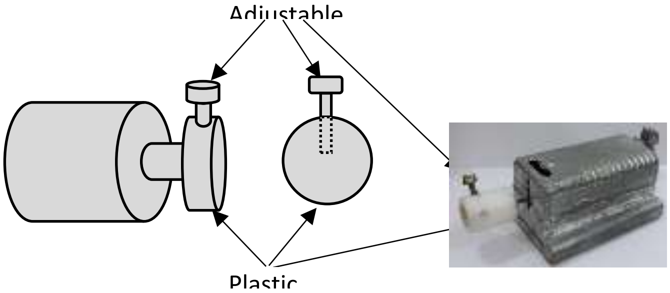

Figure 2: DC motor and rotating unbalanced mechanism.

2.1.2 Control System

The control system consists of DC power supply (0-12 V), and an Arduino UNO system which is used to control the signal provided to the vibrating motor to vibrate the heat pipe evacuated tube solar collector (HP-ETSC), where the Arduino is a programmable device that is able to provide the desired output based on a code generated by the user. The Arduino provides data signal within 0-5 V, in addition to 5 V as maximum voltage and this voltage is not enough to run the DC motor. Hence, a relay circuit is needed to switch the vibrating motor on/off (with voltage > 5 V) based on the data signal provided by the Arduino, the Arduino and relay are shown in Figure. 3. Also, a variable resistor is implemented to control the voltage provided to the motor and hence the frequency is controlled as a result, the control circuit scheme is shown in Figure 4.

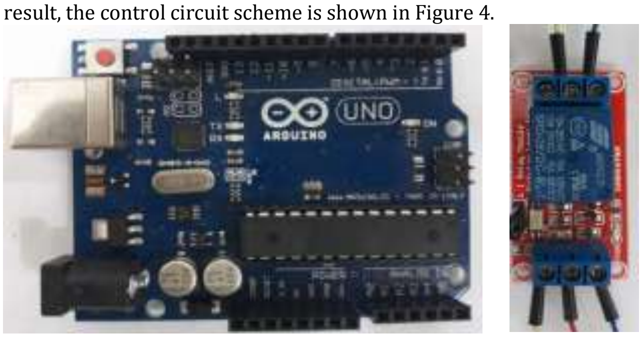

Figure 3: The Arduino and Relay system

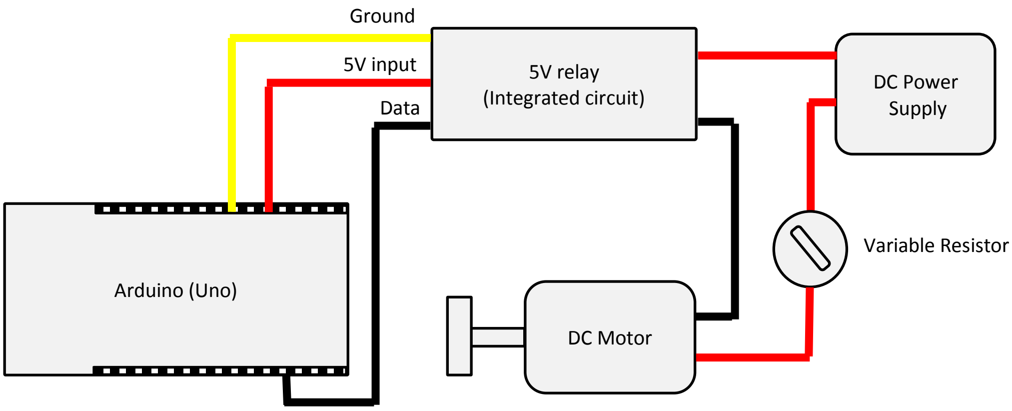

Figure 4: The Control circuit

2.2 Heat pipe Evacuated tube solar collector system

In this section, we experimentally verify the efficacy of applying vibration to investigate the thermal performance of heat pipe evacuated tube solar collector (HP-ETSC). Basically, the investigation includes the recorded results for thermal resistance, the condensation, and evaporation heat transfer coefficient in addition to the temperature distribution. Two identical rig setups are implemented to compare the outputs results for (HP-ETSC) with and without using of vibration and both rig setups are shown in Figure. 1 along with the diagram that shows the setup outlines. Moreover the specifications and data regarding the experiment are listed in Table 1 [11]. Where a set of 24 K-type thermocouples is used to record the water tank temperature and GAHP temperature during the course of the experiment.

The temperature sensor probes are spread inside the HP-ETSC with different positions and levels to ensure direct and accurate calculation of the internal energy content. Five temperature sensor probes are used to record the temperatures inside evaporator section (three thermocouples centered in the tube) and condenser sections (two thermocouples) as shown in Figure 5. Recording temperatures in the core of evaporator and condenser sections allows studying the boiling and condensation phenomena in GAHP. The entire readings from all thermocouples, during the course of the experiment, are collected by a digital data acquisition system (T7 Series Lab-Jack type), where each reading is collected every five seconds during the experiment.

The water tank has a capacity of 6 liters and the solar collector is inclined by an angle of 15 to 90° with an increment of 15°, where the inclination angle is measured from the horizontal. The location of the experiment is Najaf city, Iraq (latitude 31 °N and longitude 44 °E) [12] and the data is collected during sunny days in January 2018 between 8 AM and 4 PM. The global solar radiation is instantaneously measured by a pyrometer (Model-DWR 8101, Make-DynaLab) and the mass flow rate of hot water is measured by mean of a stopwatch, a rotameter and measuring glass bottle. Figure 1 shows the experimental rig for two identical heat pipe evacuated tube solar collector (HP-ETSC), one is provided with vibrator (left) and the other one without vibrator (right).

Table 1: Details of the design specifications of the HP-ETSC system [11].

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

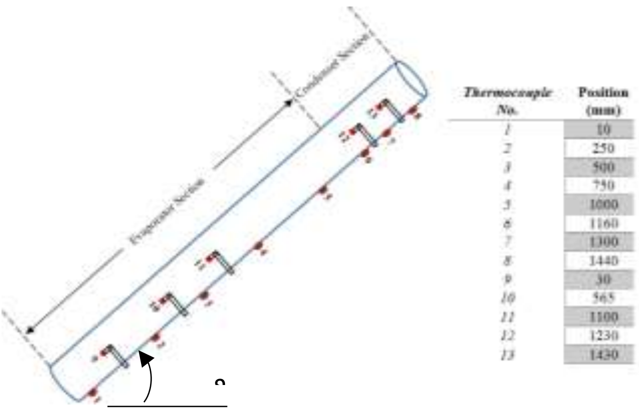

Figure 5: GAHP thermocouples positions (core and wall surface)

2.3 Experimental procedure and uncertainty

The experiments in this work are performed on two identical HP-ETSC's to study the performance of each HP-ETSC with and without the use of vibration when both HP-ETSC's operates together in same conditions. The optimal operating conditions of the best performance for the HP-ETSC are obtained as 70% filling ratio and 45° tilted angle when fixing the water flow rate to the desired value [11]. The result from one of the two HP-ETSC systems is assumed to be a reference since it operates without vibration effect. And the other HP-ETSC is subjected to vibration effect represented as periodic pulses which are applied as off-on manner (10 seconds on - 60 seconds off) during the course of the experiment. The vibration is applied in five different frequencies (2, 4, 6, 8 and 10 Hz), and it is well known that in rotating unbalanced, the amplitude is related to the motor r.p.m (Amplitude $\propto mr\omega^2$) where m is mass rotating unbalanced which is screw weight, r is the distance from the drum center to the nut and ω is the angular velocity of the motor. Also, three hot water flow rates (0, 1, and 2 l/h) are considered to be tested. Using an inclination angle of 45° to maintain the highest performance level for HP-ETSC system with single gravity assist heat pipe (GAHP), the experiment procedure steps are:

1. The heat pipe in the two systems have been charged with distilled water at 70% as a filling ratio from the evaporator section.

2. The volumetric flow rate of the hot water was set to the desired value, that is, to 0 l/h, 1 l/h, or 2 l/h.

3. The control system is set to provide a vibration pulse that lasts for 10 second and to be repeated every 60 second. The frequency is to be set accordingly for every run, where the desired vibration amplitude is adjusted.

4. The surface and core temperatures were measured and recorded for every five second over the period of (8AM to 4PM).

5. Changing frequency value and repeat to step 3-4.

6. Changing flow rate value and repeat steps 3-5.

The main uncertainties for the instrumentation used in this work are represented in thermal resistance, evaporation and condensation heat transfer coefficient, total efficiency and vibration energy, are in the range (1.25 - 3.2) depending on the test conditions. The total uncertainties can be evaluated by using the Root-Sum-Squares (RSS) method [13] from the equation:

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

2.3.1 Theory relevant

1- GAHP performance calculations: The amount of solar energy input (I in w/m2) transfers from the evaporator GAHP to the condenser then to be dissipated through the water tank. To calculate the overall thermal resistance (Rexp) for the solar collector, we use the following formula [11, 14]:

$$R_{\exp} = \frac{\left(\overline{T}_E - \overline{T}_C\right)}{2\pi r_o l_E \mathrm{I}} \quad (2.2)$$

Where $\overline{T}_E$ and $\overline{T}_C$ are the average wall temperatures at the condenser and evaporator regions which are measured by sensors located at eight different positions on the surface as shown in Figure 2. On the other hand, the heat transfer coefficients EHTC and CHTC (condensation and evaporation) for both GAHP sections are calculated as follows [14].

$$EHTC = \frac{I}{\left(\overline{T}_E - \overline{T}_v\right)} \quad (2.3)$$

$$CHTC = \frac{I\left({l_E}/{l_C}\right)}{\left(\bar{T}_v - \bar{T}_C\right)} \quad (2.4)$$

Where $\bar{T}_v$ is the mean saturated temperature measured by core temperature sensors at the center of the GAHP, shown in Figure (5).

2.3.2 Efficiency calculations

There are many different factors that interfere with the operation of heat pipe evacuated tube solar collector (HP-ETSC). Main factors are, filling ratio, radiation intensity, inclination angle, the type of heat pipe, the type of working fluid, hot water conditions (mass flow rate and inlet water temperature), in addition to the ambient conditions (clear or cloudy sky, the speed of wind and ambient temperature) [14-16]. The efficiency of HP-ETSC is studied under steady-state conditions; where the data are collected over a period of 8 hours (8 AM - 4 PM) during a sunny day in January 2018. Three different volumetric flow rate values (0, 1, and 2 l/h) are considered when measuring the inlet and outlet water temperatures. The calculation of the efficiency shows a noticeable fluctuating value since many factors affect the efficiency as it was mentioned before. However, the efficiency can be calculated using the following relation [16]:

$$\eta = \frac{Q_u}{Q_{in}} \quad (2.5)$$

$$\eta = \frac{\dot{m}C_P\left(T_{wo} - T_{wi}\right)}{A_c I} \quad (2.6)$$

3. RESULTS AND DISCUSSION

In the following sections, we investigate the effect of using different frequencies of vibration on the thermal performance of gravity assist heat pipe and HP-ETSC system. Initially, the thermal resistance for GAHP was studied with respect to the solar radiation during the sunny day (from sunrise to sunset). The influence of vibrational frequencies on thermal performance was further evaluated. Finally, the respective influences of different vibration frequencies and the hot water flow rate on the performance of HP-ETSC were investigated.

3.1 Effect of vibration frequencies on GAHP Thermal Performance

Figure 6 shows the thermal resistance of the GAHP under a wide range of vibration conditions. It should be noted, as shown in all cases of Figure. 6, that the thermal resistance (Rexp) decreases with the increase in solar radiation and eventually varies greatly. The Rexp varies more slightly for all vibration frequencies values than the static condition due to many reasons, firstly enhance the ball boiling in the evaporate section by agitating the bubbles generation in the bottom and covering the internal wall surface which causes a reduction in the average evaporator temperature and increases the evaporation heat transfer coefficient [17]. Secondly, cracking the film layer which covers the internal surface of the condenser section and changing the type of condensation phenomena from film wise to dropwise method which leads to enhancing in heat transfer between the working fluid and water tank and continues providing liquid back flowing to the evaporation from the condensation section [18,19]. Moreover, the vibration causes uniform temperature distribution for the water tank by peeling the boundary layer over the condenser section of GAHP.

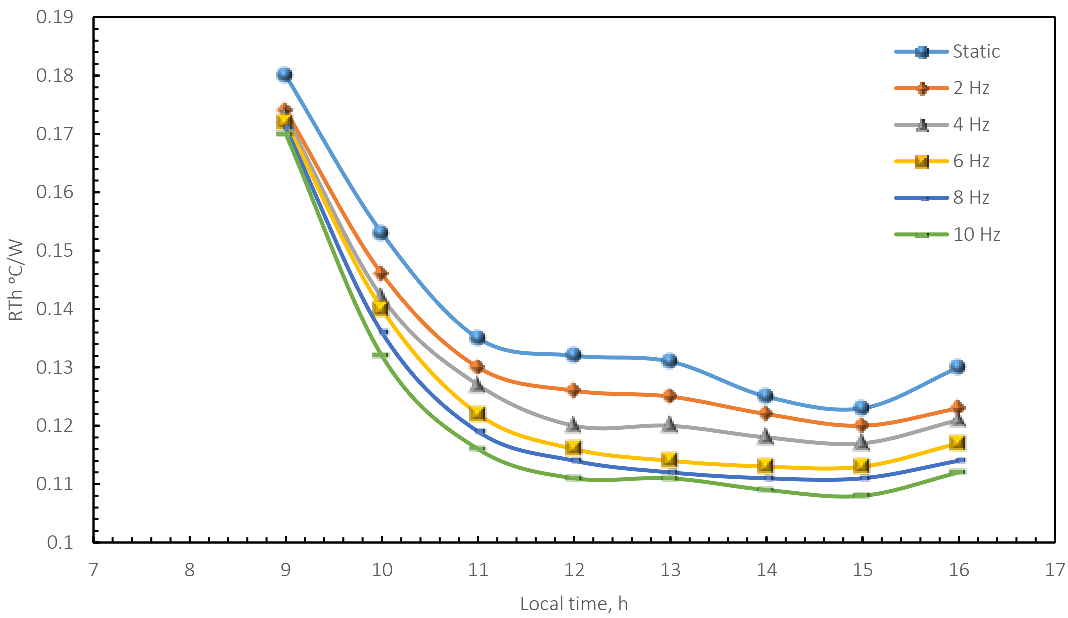

Figure 6: Effect of the vibrational frequencies on GAHP thermal resistance at filling ratio 70% and 45° inclination angle.

3.2 Performance HP-ETSC with vibrational frequencies Results

3.2.1 Effect of vibrational frequencies on evaporation heat transfer coefficient

The evaporation heat transfer coefficient (EHTC) in a partially filled gravity assist is the sum of two evaporation heat transfer coefficients calculated for two internal liquids contents. First liquid part is the liquid pool region at the bottom of the evaporator section and the second part is the uninterrupted liquid film back flowing from the condenser that extends from the liquid pool surface to the lower end of the condenser [14,20]. Figure 7 shows a comparison between the evaporation heat transfer coefficients in the HP-ETSC systems, where both systems use distilled water during a sunny day and 45° inclination angle at 70% as a filling ratio in the heat pipe, but one system without vibration and the other with vibration effect.

It can be seen clearly that the EHTC depends strongly on the vibrational frequencies compared to the static condition. The experimental results illustrated that, for constant amplitude value, water flow rate, the vibrational frequency values have major effect on the EHTC of the HP-ETSC (2 Hz (260-1240) W/m2.ºC, 4 Hz (305-1280) W/m2.ºC, 6 Hz (325-1350) W/m2.ºC, 8 Hz (338-1445) W/m2.ºC and for 10 Hz (343-1490) W/m2.ºC). The EHTC of the HP-ETSC was lower for static condition (230-1200) W/m2.ºC at the same operating conditions.

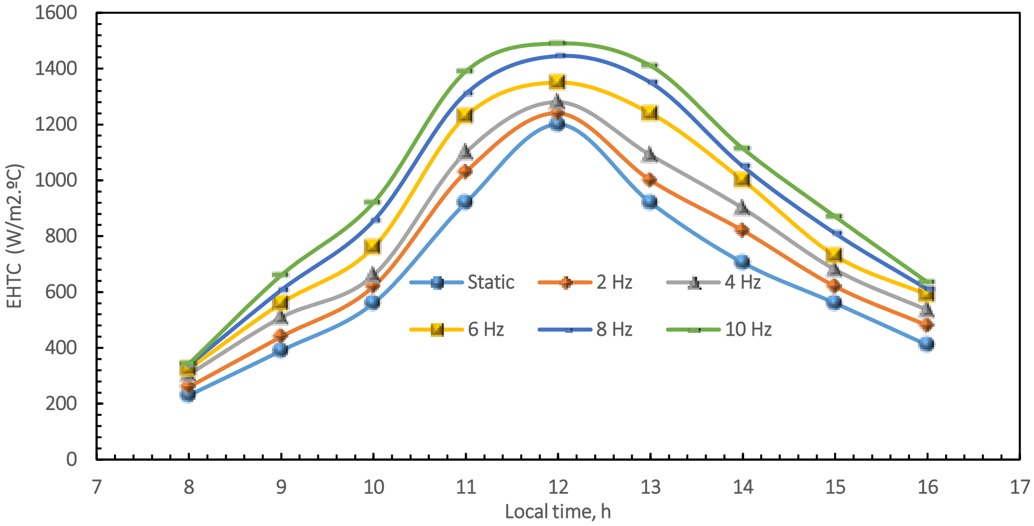

Figure 7: A comparison between the EHTCs in the HP-ETSC with different vibrational frequenciey and a flow rate at 2 l/h.

3.2.2 Effect of vibrational frequencies on condensation heat transfer coefficient

Enhanced the Condensation process in all types of heat pipe increased the amount heat transferred by convert a vapor working fluid into a liquid and film back flowing to the evaporator section by capliray effect or gravity assist. In view of diversity mode of condensation process (homogeneous, drop wise, film wise and direct contact).

The most efficient heat transfer mode for the condensation is the dropwise. Since it provides higher condensation rates than filmwise condensation [20]. It is common in industries, the surface is made such that it is non-wetting by promoters (e.g., coating with long-chain fatty acids). Then the droplets form and rapidly grow, then the gravity removes the larger ones (or vapor shear does) and the process resumes. However, maintaining the non-wetting surface characteristics is a hard task since the condensed liquid removes the promoters after a period of time.

Moreover, a liquid film can be formed due to the accumulation of droplets on a surface, therefore using vibration ensures the dropwise condensation permanently even with the rough surfaces. The effect of different vibration frequencies values on the condensation heat transfer coefficient (CHTC) in the GAHP during the sunny day and 45° inclination angles at 70% as a filling ratio is demonstrated in Figure (8). As it is seen for different vibration frequencies, the condensation heat transfer coefficient increases with the increase of the vibration frequency and same behavior in evaporation heat transfer coefficient shown in Figure (7). Also, it is clear that using the vibration enhances the CHTC compared to the static condition.

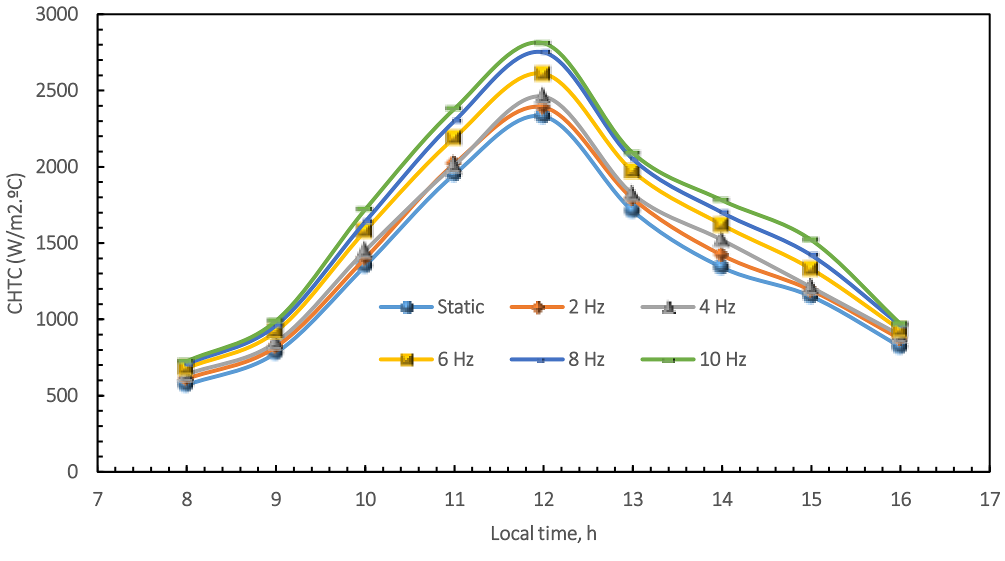

Figure 8: A comparison between the CHTCs in the HP-ETSC with different vibrational frequenciey and a flow rate at 2 l/h.

3.2.3 Thermal storage tank temperature

The water tank temperature has been one of the important parameters in all types of hot water solar collector systems, including HP-ETSC. 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 major impact on the performance of GAHP, which is the condenser cooling fluid temperature (when it decreases, the thermal resistance decreases) [11,16]. The temperature of the water tank is measured by using three K type thermocouples placed inside the tank at three levels (top, middle, and bottom). In HP-ETSC, a greater water tank temperature leads to higher collector efficiency as well as the best performance with similar solar radiation input as a result of two effects. First, the amount of useful heat transferred by the two-phase flow through the GAHP similar ray radiation input, which means the best working fluid and lowest thermal resistance as discussed in section (3.1) . Second, the homogenous temperature distribution in a water tank due to the reduction in the viscosity of water as the temperature rises and the thermosyphon over the surface of GAHP condenser section is affected by the change in density of the warmed water.Figure. 9 shows that the vibration frequency at the highest value (10 Hz) has higher hot water temperature compared to the static condition for all flow rate values (0, 1 and 2 L/h). In addition, at zero loads (0 l/h), the mean water tank temperature is indeed higher for all vibration frequency values due to the increase in heat exchange time between the condenser surface of the GAHP and water inside the tank.

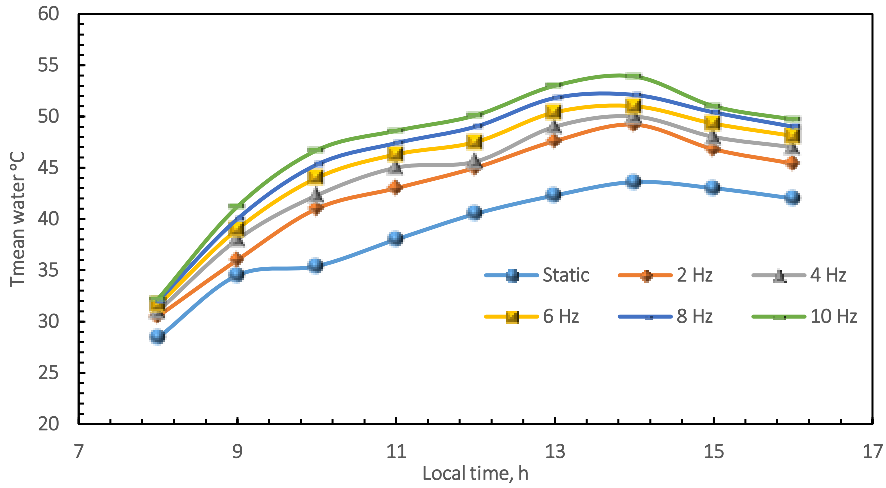

Figure 9: The mean temperature of water tank for vibrational frequencies with a flow rate at 2 l/h.

3.2.4 Efficiency of the HP-ETSC water heater

Figure 10 illustrates the efficiency of HP-ETSC for different types of working fluids and mass flow rates of 2 l/h during the day in the experimental work. During the period of the experimental test, the best and most stable data is chosen. From the experimental results, it was clearly observed that the efficiency slowly increases as the mass flow rate increases. Moreover, the minimum efficiency for the HP-TSC is mostly reported in the morning because of the minimum value of global solar irradiation compared to other times during the test. The maximum efficiency is found to be at noontime in the entire test period because the amount of solar radiation is at its peak value and the heat absorbed by the evaporator section in GAHP increased faster than the other times.

Figure 10 shows that the HP- ETSC efficiency is always better with vibration effect compared to static condition at the same test conditions. This is because; at vibration frequency, the GAHP works with lowest thermal resistance and the mean evaporator temperature. As a result of these two factors, the GAHP transfers more heat gained by the two-phase flow phenomena [20] as discussed in section (3.2.1 and 3.2.2),

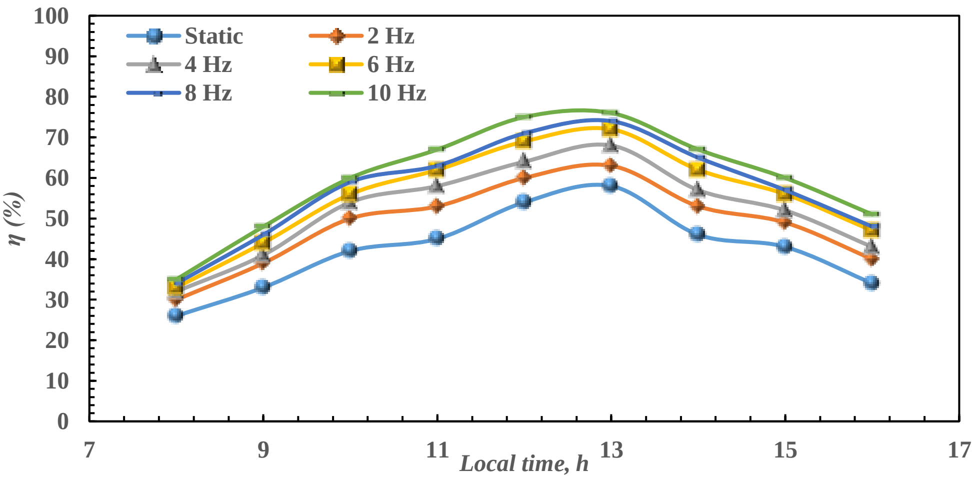

Figure 10: Efficiency of HP-ETSC for vibrational frequenciey with a flow rate at 2 l/h.

4. CONCLUSION

A controllable vibration system is implemented in this study to enhance the heat transfer performance of GAHP and HP-ETSC systems. The experimental rig consists of two main parts. The first part is the vibrating system which consists of a motor with adjustable rotating unbalance mass and electrical control circuit to control the vibration in which the system provides pulses with various frequencies and amplitudes over a period of time. The second part is the heat pipe evacuated tube solar collector (HP-ETSC) where two identical HP-ETSC's are used to compare the thermal efficiency for the HP-ETSC with and without the effect of vibration. In the experiments, we used 70% filling ratio working fluid of distilled water and the vibration frequencies of (2, 4, 6, 8, and 10 Hz) were experimentally tested.

The results for the GAHP performance showed that the thermal resistance for all test conditions was decreased with the increase of the frequency vibration from 2 to 10 Hz and the lowest value at 10 Hz. The results also showed an increase in the evaporation and condensation heat transfer coefficients with the increase of the vibration frequency. Moreover, the HP- ETSC efficiency is always better with vibration effect compared to static condition at the same test conditions. The vibration system showed its efficacy when it is used in the experiment and it can be implemented in many different solar applications to enhance the thermal performance.

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