The Influence of Exciting Vibrational Force on the Performance of Evacuated Tube Heat Pipe Solar Collector

Sarah H. Ali¹, Adel A. Eidan²*, Assaad Al Sahmani¹, Ali Mohammed Hayder²
¹Engineering Technical College of Al-Najaf, Al-Furat Al-Awsat Technical University (AUT), Iraq.
²Technical Institute of Al-Najaf, Al-Furat Al-Awsat Technical University (AUT), Iraq.

*Corresponding author: inj.adel@atu.edu.iq

Abstract. In this research paper, it examined the effect of excitation vibration force on the thermal performance of the heat pipe evacuated tube solar collector (HPET-SC). The main target of this work is to predict the temperatures of the water when applied different values of excitation vibration force (frequency). In order to achieve these tasks, it was designed and implemented a new test rig (HPET-SC) from scratch, that containing the vibration unit to generate the excitation vibration force. We added a control board to regulate the magnitude of frequency of the excitation vibration force. The range of the vibration frequency is from 6 to 14 V. All results were compared with the reference case study (static case). All tests were done in Iraq during the winter season. It was found based on the obtained results, that the vibration has a influence on the performance of the heat pipe evacuated tube solar collector, especially when applied the vibration force with high frequency.

1. Introduction
Many common uses in the world, certainly needs energy as a basic component. Consequently, energy is utilized in different applications, such as electric power production, manufacturing, transportation, and so forth, etc. Fossil fuels have helped to cater for all different human needs of energy. This huge utilization of fossil fuels to produce energy results in a lot of negative effects on the atmosphere and occurring of danger on the humanity due to the melting of snow in the Northern and Southern Poles of the earth. Therefore, it can be considered that the renewable energy is necessary as complementary or alternative element of energy supply sooner or later. Clean environment needs clean energy production, so there is no effect on human. The renewable energy may be of different kinds: solar energy, wind energy, geothermal energy, bio energy and hydropower energy. The solar energy is considered the backbone for all other kinds of renewable energy. The solar energy is available all around the year, but it is not continuous. Because of this limitation, researches are required to treat this problem [1-10]. Therefore, there are many researcher’s around the world tried to challenge and overcome these problems and find suitable solutions to produce a clean energy.

One of the solutions that achieved by scientists is using the nanofluids to enhance the overall performance of the evacuated tube solar collector. Where, the main aim is to supply the users/Beneficiaries with sufficient quantity of hot water. It selected the angle between 30° to 60° in order to
obtain the best results, while the filling ratios was between 40 to 80%. It was found that the results of the developed test rig are very promising [11].

One of the proposed solutions is using the vibration force to enhance the behaviour and performance of the thermal systems such as heat pipe-evacuated tube solar collectors. Eidan et al. [12-15] applied the excitation vibration force with low level of frequency (2 Hz to 10 Hz) to improve the behaviour and performance of a heat pipe-evacuated tube solar collector. They achieved an optimization process to find the optimal values of excitation vibration force and frequency to obtain the highest efficiency of the system. They found based on their results that the coefficients of heat transfer (evaporation and condensation) grown when applied to vibration. The highest values of the heat transfer coefficients occurred when applied the vibration with frequency of 10 Hz.

The main goal of this research paper is to explore the effect of the vibration excitation force on the overall behaviour of heat pipe-evacuated tube solar collector. a new test rig heat pipe-evacuated tube solar collector was built and a new vibrational system was added to generate the excitation force with different values od frequencies. It was studied how can benefit practically of the hot water in the winter period using the new thermal system.

2. Experimental Work
A new experimental test rig of the heat pipe evacuated tube solar collector was designed and implemented to investigate the effect of the excitation vibration force. It was applied the excitation vibration force with different values of frequency which are: static condition (0V), 6V, 8V, 10V, 12V and 14V. It was assumed when the system under the static condition is the reference cases study.

It can be seen from the above details, different cases were investigated. In order to obtain the results, a new evacuated tube heat pipe-solar collector was constructed. The experimental work was executed in the winter period (January, February and March), and the location of the work was in the Al-Furat Al-Awsat Technical University - Engineering Technical College of Al-Najaf.

The Experimental test rig included a heat pipe evacuated tube solar collector, vibrating actuation, and measured data systems, with the control system that integrated the control equipment and amusement systems. The schematic representation and description of the experimental rig setup with auxiliary equipment are shown in Figure 1. The new experimental rig consists of a new structure that contains iron stand, evacuated glass tube, thermosyphon, water storage tank, and other accessories. The new test rig of the heat pipe evacuated tube solar collector that included the vibrating actuation is shown in figure 1(A).

The volume of the water tank is 5.25 L (dimensions: 27.5 cm*27.5 cm*7 cm). The storage water tank made of Aluminium sheet [16] (thickness = 1mm). The reasons to use the Aluminum in such applications are low price, good thermal conductivity, and high resistance against wear. It was glued with a thermal substance and put five thermocouples inside the tank to calculate the temperature of the water in different levels and contains an opening on the top to add water and open it at the bottom to drainage the water in the event of a problem and isolation by glass wool and the use of Alekopond to increase the insulation. One of the lower corners of the tank was cut down with 45° to facilitate the process of assembling of thermosyphon. Figure 1 demonstrates the shape of the storage tank.

Several vibration frequencies in form of pulses with fix time value in the measurements work. These vibration frequencies were controlled in manufactured by control unit, which designed as follows:

1. DC Motor: A small DC motor has been used to produce vibration with an unbalanced load, as illustrated in Figure 1. Where different radii and mass values can be defined by using the eccentric mass. The aluminum disc is produced to hold a screw (eccentric mass) with a constant mass of 15 grams. The DC motor was mounted to the structure of the solar tube collector evacuated heat pipe (HPET-SC) to produce excitation force through the control circuit with various amplitudes and frequencies. The motor’s base is shielded by an elastic sheet, which smooth out the generated vibration in the heat pipe evacuated tube solar collector. The supplied signal to the vibrating motor has been controlled by using the control
unit 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.

2. A control unit with its components, voltage power supply and Arduino UNO system responsible to generate the excitation vibration force in the HP-ETSC. The DC motor will work at 0-5V signal and 5V (controlled by variable resister) provided by the Arduino, the Arduino and relay are shown in Figure 3.

In order to reduce the heat losses, the tank was insulated with glass wool with (thickness= 5cm). The insulation process was performed by pasting the on the outer walls of the tank. The storage system was folded with Alekopond sheet (thickness= 3 mm). The new system was supplied with pure acetone, where the filling ratio was 70% of the evaporator portion and a tilted angle of 45° [14], the vibrational effect was applied as regularly periodic on-off pulses (20 seconds on - 120 seconds off) during the period of experiment. The values of voltage that used to generate vibration frequency are 6, 8, 10, 12 and 14 Volts. The experimental work started from 8 am to 10 pm, and the surface and core temperatures were estimated and reported at every five seconds.

It can be written the equation to find the experimental thermal resistance \( R_{exp} \) of the solar collector as [17, 18],

\[
R_{exp} = \frac{(\bar{T}_E - \bar{T}_C)}{2\pi r_o l_E} 
\]

Where \( \bar{T}_E \) and \( \bar{T}_C \) are the average wall temperatures [°C] at the evaporator and condenser regions which are measured by sensors, and \( I \) is the input solar power [W/m²] transfers from the evaporator GAHP to the condenser then to be dissipated through the water tank. \( r_o \) and \( l_E \) are outer radius and length of GAHP in (m). The heat transfer coefficients for the evaporation (EHTC) and condensation (CHTC) for both GAHP sections are [18],

\[
EHTC = \frac{1}{(\bar{T}_E - \bar{T}_v)} 
\]

\[
CHTC = \frac{I (l_E/l_C)}{\bar{T}_v - \bar{T}_C} 
\]

Where \( l_E \) and \( l_C \) are the evaporator length and the condenser length in (m). \( \bar{T}_v \) [°C] is the mean saturated temperature measured by core temperature sensors at the center of the GAHP.

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 [18]:

\[
\eta = \frac{Q_u}{Q_{in}} = \frac{m C_p (T_{wo} - T_{win})}{I A_C} 
\]

Where \( T_{win} \) and \( T_{wo} \) [°C] are the inlet and outlet temperature of the water. \( m \) is mass (kg) and \( C_p \) is the specific heat.
Figure 1. (A and B) Setup and schematic diagram of the experimental rig for HPET-SC, (C) GAHP thermocouple positions (surface wall and core).

Figure 2. The circuit of the control unit
Figure 3. The Arduino board and Relay devise.

3. Results and Discussions
The variations of the average temperature of water in tank with time when applied different values of vibration are investigated. Six different cases were studied in details which are: static condition, applying 6, 8, 10, 12 and 14 V as excitation vibration force.

Figure 4 shows the variation of water temperature in the storage tank with time. It can be noticed that the values of temperature increased when the excitation vibration force increased too. The minimum level of temperature appeared in the static condition (excitation vibration force=0), and the highest level of temperature appeared when applied 14 V. It can be noticed that the temperature decreased very quickly after time=3 pm (15:00).

Generally, it was observed that the average temperature of the tank increased when the frequency of the vibration increased too. The results gave a clear picture about the influence of vibration on the behavior and performance of the evacuated tube heat pipe solar collector system (ETHPSC). It can be found that the values of temperatures are proportional to the magnitude of excitation vibration force. The reason for increasing the values of temperature with increasing the magnitude of excitation vibration force is the growing in the amount of heat exchange between water tank and the surface of condenser during the process. When the vibration increased from 0 V (static condition) to 14 V, the average percentage increases in temperature is approximately 13% for time after 1 PM.

Figure 5 shows the variation of the thermal resistance of the GAHP applying different values of vibration frequencies (from 0 V to 14 V). It can be seen for all cases that the thermal resistance decreased with the increasing of the solar radiation. Also, it can be observed that the thermal resistance decreased with increasing the magnitude of the excitation vibration force (frequency). There are many advantages of applying the excitation vibration force in such systems. Firstly, improving the boiling ball in the section of evaporation by exciting to generate the bubbles in the bottom and enclosure the surface of internal wall. This will lead to decrease the average temperature of evaporator, where the value of evaporation heat transfer coefficient will increase [17]. Secondly, the breaking in the film layer that encloses the surface of internal wall of the condenser section. Where this kind of condensation phenomena is changed from film wise to dropwise that yields to improve the operation of heat transfer that occurred between the water tank and the working fluid, where the process will be continued the flowing of the fluid back to the section of evaporation that came from the section of condensation [18, 19]. Furthermore, applying the excitation vibration force will change the distribution of temperature of water tank form non-uniform to be more uniform via exfoliation layers that covered the condensation section of gravity that assist heat pipe (GAHP).
Generally, it can be noticed that the values of the thermal resistance decreased when the excitation vibration force (frequency) increased for all cases. The average percentage reduction in the thermal resistance for all cases, when the vibration frequency change from (0 V to 14 V) is found 27%.

It can be divided the evaporation heat transfer coefficient (EHTC) into two kinds of the internal liquids. The first one is the region of pool liquid that located at bottom side in the evaporator section. While, the second one is the continuous film liquid that flow back from the condenser section. This flowing expands from the surface of liquid pool to the lower end of condenser [14,20]. The sum of the two coefficients is equal to the evaporation heat transfer coefficient (EHTC).

Figure 6 displays the variation of evaporator heat transfer coefficient (EHTC) with time when applied different values of the excitation vibration force (frequency). It can be noticed that the values of evaporator heat transfer coefficient (EHTC) significantly increased when the values of excitation vibration force increased too. The average percentage increment in the evaporator heat transfer coefficients for all cases when the vibration frequency changed from (0 to 14V) is found approximately 30% at the peak value occurred (t= 12:00).

It can be considered the growth in the heat transfer coefficients is the main key to enhance the performance of the all types of heat pipe systems. Therefore, a proper approach should be used to achieve the enhancement in the system as applying the excitation vibration force.

Figure 7 demonstrates the variation of the condenser heat transfer coefficient under different conditions of vibration. Based on the results, it can be seen that the behavior for all cases are similar during the experiment time. However, it can be seen a significant increment in the values of condenser heat transfer coefficient (CHTC) when the excitation vibration force increased as well. The maximum values of the CHTC occurred at time 12:00 for all cases. The average percentage increment in the condenser heat transfer coefficients for cases, when the vibration frequency changed from (0 v to 14V) is found approximately 25% when the peak value occurred (12:00).

Figures 8 exhibits the variation of efficiency of system (ETHPSC) during the period of experimental work when applied the same range of frequencies (from 0 to 14 V). It was found that the lowest values of efficiency occurred early in the morning where the minimum values of the solar radiation occurred. The highest values of the efficiency occurred at the noontime during the whole test period. The reason behind such results is the peak values of the solar radiation that occurred at this time. Where, this led to increase the amount of absorbed heat in the section of evaporation (GAHP) compared with the remaining time of the tests.

Generally, it can be observed the enhancement in the values of efficiency when applied the excitation vibration force on the system. Where, the values of the efficiency increased when the vibration frequency increased as well. The maximum values of the efficiency occurred at time 1 pm (13:00). The efficiency of the system when using PCM increased from 57% to 76% at 1 pm when the influence of vibration frequency changed from (0 to 14 V).

Tables 1-3 list the values of thermal resistance, evaporator and condenser heat transfer coefficients when applied different vibrational frequencies (0, 6, 8, 10, 12 and 14 V).
Table 1. The values of thermal resistance when applied different vibrational frequencies.

| Time (Hr) | 0 V  | 6v   | 8V   | 10 V | 12 V | 14V   |
|-----------|------|------|------|------|------|-------|
| 8         | 0.193| 0.185| 0.181| 0.179| 0.176| 0.173 |
| 9         | 0.165| 0.157| 0.149| 0.141| 0.133| 0.125 |
| 10        | 0.136| 0.128| 0.12 | 0.112| 0.104| 0.096 |
| 11        | 0.1285| 0.1205| 0.1125| 0.1045| 0.0965| 0.0885 |
| 12        | 0.1245| 0.1165| 0.1085| 0.1005| 0.0925| 0.0845 |
| 13        | 0.121| 0.113| 0.105| 0.097| 0.089| 0.081 |
| 14        | 0.12| 0.112| 0.104| 0.096| 0.088| 0.08 |
| 15        | 0.1195| 0.1115| 0.1035| 0.0955| 0.0875| 0.0795 |
| 16        | 0.125| 0.117| 0.109| 0.101| 0.093| 0.085 |

Table 2. The values of evaporator heat transfer coefficient when applied different vibrational frequencies.

| Time (Hr) | 0 V | 6v | 8V | 10 V | 12 V | 14V |
|-----------|-----|----|----|------|------|-----|
| 8         | 235 | 320| 335| 350  | 365  | 380 |
| 9         | 370 | 560| 600| 640  | 680  | 720 |
| 10        | 555 | 820| 860| 895  | 1026 | 1125 |
| 11        | 910 | 1230| 1260| 1296 | 1360 | 1450 |
| 12        | 1185| 1355| 1408| 1461 | 1514 | 1567 |
| 13        | 915 | 1232| 1256| 1289 | 1320 | 1420 |
| 14        | 705 | 1005| 1027| 1040 | 1115 | 1185 |
| 15        | 555 | 733 | 757| 819  | 827  | 905 |
| 16        | 402 | 592 | 605| 618  | 631  | 644 |

Table 3. The values of condenser heat transfer coefficient when applied different vibrational frequencies.

| Time (Hr) | 0 V | 6v | 8V | 10 V | 12 V | 14V |
|-----------|-----|----|----|------|------|-----|
| 8         | 580 | 680| 692| 705  | 718  | 731 |
| 9         | 785 | 905| 945| 975  | 1005 | 1035 |
| 10        | 1352| 1555| 1633| 1722 | 1811 | 1900 |
| 11        | 1965| 2195| 2290| 2385 | 2480 | 2575 |
| 12        | 2320| 2610| 2733| 2805 | 2877 | 2949 |
| 13        | 1610| 1870| 2065| 2190 | 2119 | 2230 |
| 14        | 1361| 1601| 1700| 1794 | 1810 | 1910 |
| 15        | 1135| 1280| 1420| 1520 | 1540 | 1570 |
| 16        | 806 | 908 | 933| 982  | 1031 | 1080 |
Figure 4. The mean water temperature.

Figure 5. Variation of the thermal resistance when applied different vibrational frequencies.
Figure 6. Variation of evaporator heat transfer coefficient with time when applied different vibrational frequencies.

Figure 7. Variation of condenser heat transfer coefficient with time when applied different vibrational frequencies.
4. Conclusions
In this experimental work, it was proposed to use the influence of excitation vibration force to enhance the thermal performance and efficiency of the heat pipe evacuated tube solar collector (HPET-SC). Excitation vibration force was applied with a wide range of frequencies (between 6 to 14 V) and compared the results with static working condition. For this purpose, a new system of evacuated tube solar collector that included a developed unit to generate the excitation vibration force.

It was found that the excitation vibration force has a positive significant influence on the performance and efficiency of the heat pipe evacuated tube solar collector (HPET-SC). The results showed that the mean water temperature increased when applied the vibrational force. Also, the evaporator and condenser heat transfer coefficients and efficiency increased when applied the vibration. While the thermal resistance decreased when applied the vibration. The maximum effect occurred when applied the excitation vibration force that has highest frequency (14 V), and the minimum effect occurred when applied the excitation vibration force that has lowest frequency (6 V).

List of symbols
Rexp: The overall experimental thermal resistance for solar collector [°C/W].
\( \bar{T}_E \): The average wall temperatures at the evaporator [°C].
\( \bar{T}_C \): The average wall temperatures at the condenser [°C].
I : The solar energy source [W/m²].
ro: The external radius [m].
LE : The length of GAHP [m].
IE: The lengths of the evaporator [m].
IC: The lengths of the condenser [m].
\( \bar{T}_v \): The mean saturated Temperature [°C].
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