Simulation and Analysis of Experimental Photovoltaic Thermal (PVT) Solar Water Heater and Comparison of Turbulence Models

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Abstract— **In order to clean the environment, by producing and assessing the solar water heater and by applying the analytical study of an experimental model by turbulence models with use of ANSYS in Islamic Azad University Central Tehran Branch during six years, we achieved considerable results that can be beneficial in its development. By increasing the temperature of solar panel surface, the thermal and electrical efficiency of solar panel will be increased and declined respectively and the solar cells will deteriorate in high temperature of solar plates by passing time. We can solve it by inserting water pool below the Photovoltaic-Thermal solar panel in this project. On the other hand, the decline of thermal efficiency can be compensated by inserting solar collector in the cycle. So the increase of electrical efficiency is more important and that is why we have chosen this issue as the aim of our research. By sunrise and increasing the heat flux from zero to 1250W/m^2, the interior and exterior levels of panel will be different to 20°C in average. Then voltage and amperage input (production) will be increased from 80% to 91% and from 71% to 84% respectively. The average water temperature from input to output will be also increased to 76°C.**

Keywords— Photovoltaic-Thermal (PV/T) solar water heater, solar panel cooling, thermal and electrical efficiency, simulation of experimental model and analytical study, turbulence models

I. INTRODUCTION

Aiming to maintain the environment unpolluted, the global community has driven itself toward the use of clean and renewable energies among which solar energy has received the most attention due to its extensive usage and special requirements. In addition, the science of working with solar energy is in its early time and a considerable body of research and studies is required to benefit the most from the maximum efficiency of solar equipment or improve it. In solar panels, each cell's voltage and current are basically quite limited. Therefore, a large number of solar cells are usually put together and connected in series so the generated electricity can be used for various applications [1, 2]. In a standard photovoltaic module, a small fraction of solar radiation is converted to electricity, while most of it is converted to heat and wasted in exchange with the environment. This physical effect directly depends on the amount of the band gap energy between the bands of semiconducting materials used in solar cells and on the energy of the photons received. In fact, two major phenomena can possibly occur; if the photon's energy is less than the band gap energy between the cell's band, the current-carrying electron is not generated and the entire energy of the photon is transmitted to the environment in form of heat. If the photon's energy is more than the band gap energy between the cell's bands, a part of this energy is spent on generating current while the rest is transferred to the crystal structure in form of heat [3]. The thermal photovoltaic module can collect solar energy in various wavelengths, thus increasing energy and exergy efficiency. Colleges and Zhang suggest that with a similar absorption area to a solar collector and panel, a thermal photovoltaic module can collect and convert a larger amount of solar energy, which will result in the high-efficient and low-cost generation of heat and power [4] with a shorter time for return on investment comparing to collector and photovoltaic systems [3, 5]. Some of the major issues in photovoltaic panels include a decrease in the life span of solar cells and the reduction in their electrical efficiency due to the increase in the temperature of the surface of these panels [6] and their electrical efficiency is the topic of competition among manufacturers. The increase in the temperature of the exterior surface of photovoltaic panels should be prevented to increase their electrical efficiency. To do so, a fluid can be flowed around the panel to decrease its temperature. Accordingly, a new generation of equipment is manufactured in the Iranian Islamic Azad University, Central Tehran Branch, leading to some considerable results. In this university's manufactured equipment, while the solar panel is cooled using a direct-contact water tub and the given problem is solved, the panel's absorbed heat can be used elsewhere to avoid wasting it, and this is how a type of solar water heater was invented. In the following sections of the present study, ANSYS software is used for structureless simulation and analysis, confirming the results of the experimental model. In comparison to nanofluid-based solar panel cooling [13-14], the advantage of this method is that its outputting warm water is not detrimental to the environment and can be directly used domestically and industrially. Additionally, compared to using gases instead of liquids [15], the other advantage is that storing and using gases is much more difficult and dangerous than storing and using liquids.

II. Methods and Principles

As shown in Fig. 1, a frame and an iron tub of about 1m × 2m × 6cm are prepared for a thermal photovoltaic solar panel of about 1m×2m. To reduce and control the pressure of the flowing fluid, Styrofoam is used to cover about 60% of the tub's volume, making it reach a volume of about 38.6 liters. In addition, an iron structure is made and attached to the back of the panel so that its weight force can neutralize some of the pressure force of water. In addition, an iron box is prepared and attached to the panel to prevent the panel's external electrical wires from getting wet. Furthermore, several types of glue and rubber are used to waterproof the frame. The panel should be placed at an angle of almost 45°, and there are several pipers for the inlet and outlet of water below the frame [7 – 12]. As shown in Fig. 2, the geometry of the experimental model is modeled using software, and electrical wiring, nuts, and bolts are removed for simplification purposes.

Fig. 1. The study's experimental model.

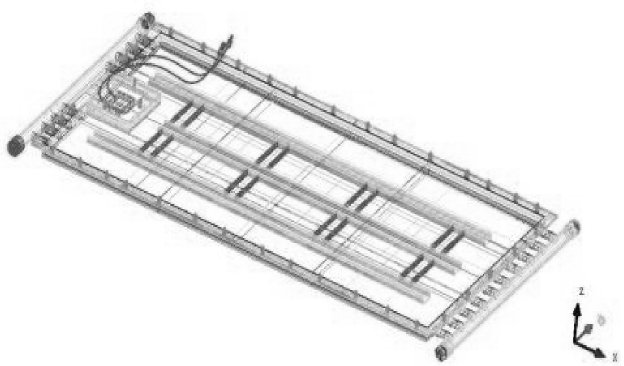


Fig. 2. The study's geometrical design using CATIA Software.

The study's geometry meshes in seven different sizes (from approximately 5.7 million elements to approximately 25.4 million elements) using ICEM-CFD Software with a structureless method, and after the analysis, the mesh with 9810487 elements became the network-independent mesh, as partly shown in Fig. 3. It should be noted that to create a structureless mesh, the Patch Independent, Delaunay, and Linear methods were used to create the surface, volume, and boundary layer meshes, respectively.

Since the volumetric flow rate is known from the experimental model [7 – 9] as 0.7 l/min, the Reynolds number is calculated from Eq. 1 to be 5336.752.

$$Re = \rho VD/\mu \tag{1}$$

Therefore, the flow is turbulent in a lower bound of the Reynolds number. The study's geometry is analyzed for a 950 W/m2 heat flux using K-Omega, BSL EARSM, RNG K-Epsilon, and hear Stress Transport methods in CFX Software, which is suitable for this type of geometry, to introduce the best and most accurate method among these four analytical methods. In Diagrams 1 and 2, the average temperatures of the exterior surface of the solar panel and the output water are compared among four analytical methods, respectively.

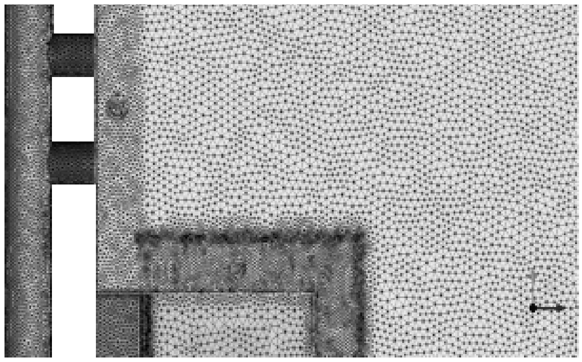
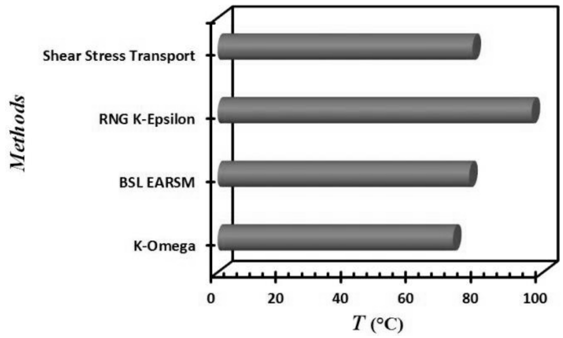
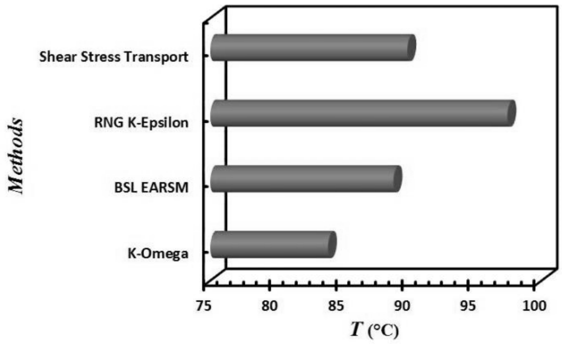


Fig. 3. A part of the study's geometrical network-independent mesh with 9810487 elements.



Dia.1. The average temperature of the exterior surface of the solar panel in K-Omega, BSL EARSM, RNG K-Epsilon, and hear Stress Transport methods for a 950 W/m2 heat flux.



Dia.2. The average temperature of the output water in K-Omega, BSL EARSM, RNG K-Epsilon, and hear Stress Transport methods for a 950 W/m2 heat flux.

Since the average temperatures of the exterior surface of the solar panel and the output water for a 950 W/m2 heat flux are 70 to 75 and 74 °C, respectively, the K-Omega method which is designed for turbulent flows with a low Reynolds number is closed to the solutions of the experimental model, and consequently, it is more appropriate for analysis compared to other methods. The server of the Computing Center of the Amirkabir University of Technology, and it should be noted that each file took about 2 to 6 days to execute on the servers of this university.

III. Results

In the selected K-Omega method, if the number corresponding to y+ is less than 5 in CFX Software after the analysis, it is implied that the boundary layer meshes are small enough, and the software can easily check the changes in the given zone. As shown in Fig. 4, the dimensionless number of y+ ranges between 0 and 3.962 which shows the suitability of the size of boundary layer meshes. In addition, the flow lines and the movement of the fluid in the solar water heater are shown in Figs. 5 and 6.

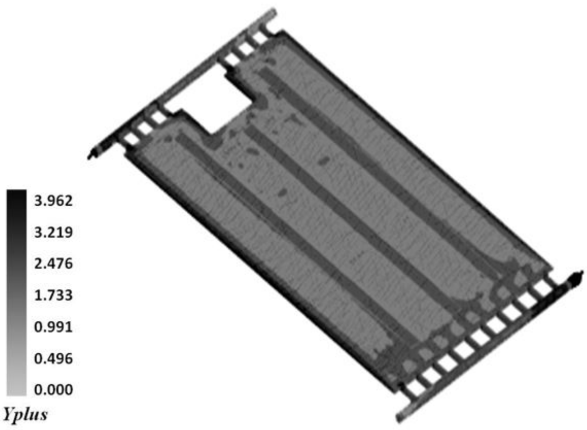


Fig. 4. The y+ contour for fluid parts of the solar water heater.

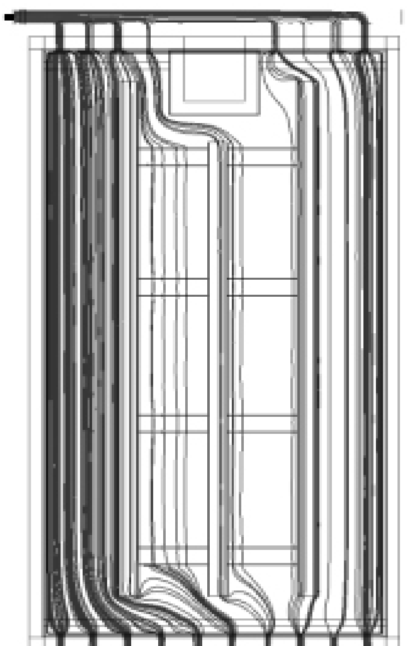


Fig. 5. Flow lines of the solar water heater.

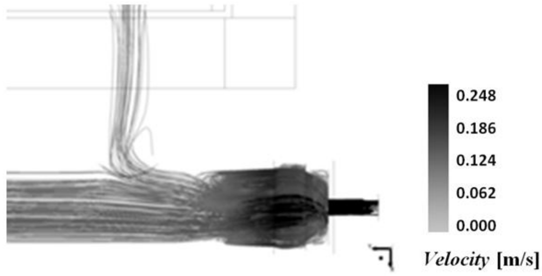


Fig. 6. Flow lines of the solar water heater.

As shown in Fig. 5, the fluid has more tendency to move from the left side of the solar water heater which is due to the configuration of the piping network. Therefore, the left side of the solar water heater is expected to have a lower temperature, as shown in Fig. 7. In addition, due to the sudden increase and decrease in the input and output cross-section of the solar water heater, the fluid creates a vortex and this sudden change in the cross-section leads to the sudden increase and decrease in the fluid's velocity, which is completely logical, and as shown in Fig. 6, it follows the laws of converging and diverging nozzles.

As shown in Fig. 7, when there is no heat flux, the overall temperature of the panel is equal to the temperature of the input fluid and about 302 K. When the sun rises and the heat flux increases, the panel's temperature rises, and Diagram 3 shows the comparison between the average temperatures of the exterior and interior surface of the panel of the solar water heater from 0 to 1250 W/m2 heat flux over a 24h period for an average ambient temperature of 35.65 °C in Summer, the input municipal water temperature of 29 °C, and average ambient pressure of 846.2 Hecto Pascal (hPa) (Note: a unit of hPa equals 0.1 kPa).

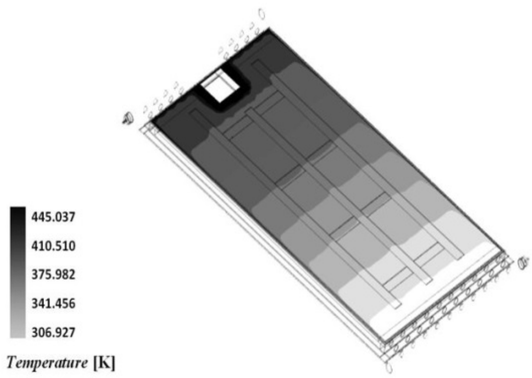
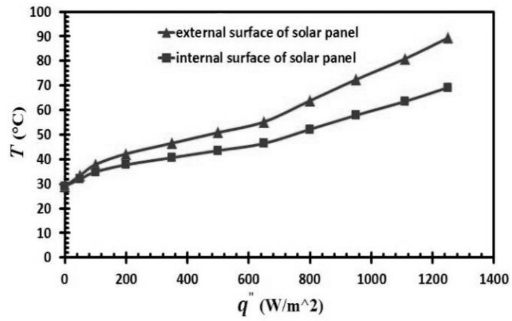


Fig. 7. The temperature contour of the interior surface of the solar panel for a 950 W/m2 heat flux.



Dia.3. The comparison between the average temperatures of the interior and exterior surfaces of the panel of the solar water heater from 0 to 1250 W/m2 heat flux.

As shown in Diagram 3, when the sun rises and the heat flux increases from 0 to 1250 W/m2, the average temperature of the exterior surface of the solar panel increases from about 29 °C to about 89 °C, and the average temperature of the interior surface of the solar panel increases from 29 °C to about 69 °C. Furthermore, it can be seen that the diagram does not have a consistent gradient, meaning for each unit of increase in the heat flux, the temperature change is not necessarily constant, and a host of factors influence the thermal efficiency. When the solar water heater is working, the interior and exterior surface of the solar panel can have an average of 20 °C difference in temperature. This difference creates a significant conductive heat transfer as the solar panel is quite thin. In fact, the radiation heat transfer from the solar radiation warms up the exterior surface, this heat is transferred to the interior surface of the solar panel through conduction heat transfer, and then, it is absorbed and moved out through convection heat transfer from the fluid's movement in the tub. Since the amount of solar radiation cannot be adjusted, if we can control the temperature of the input fluid and its velocity, the amount of conduction and convection heat transfer can be increased as the main issue in increasing the electrical efficiency. In the experimental model [7 – 9], we had about an 18 to 23 °C decrease in temperature from the top to the bottom of the solar panel after cooling. In addition, there was a 14 °C decrease in temperature in the analytical model which is directly related to the solar panel's voltage and amperage and increases the electrical efficiency. Therefore, cooling the panel can increase the electrical efficiency, and the generated warm water can be used as a prewarming fluid or applied directly.

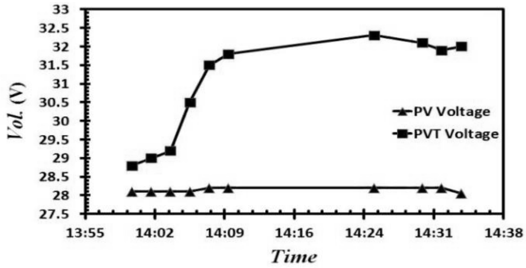
The changes in voltage and amperage are as follows:

- In case of no cooling, the solar panel's voltage is fixed and about 28v, while it increases to 32v after cooling. According to the maximum voltage for the maximum power of this model of solar panel which is about 35v, the voltage generation has increased from 80 to 91% by cooling the panel.
- In case of no cooling, the solar panel's amperage is fixed and about 5.65A, while it increases to about 6.68A after cooling. According to the maximum amperage for the maximum power of this model of solar panel which is about 7.95A, the amperage generation has increased from 71 to 84% by cooling the panel.

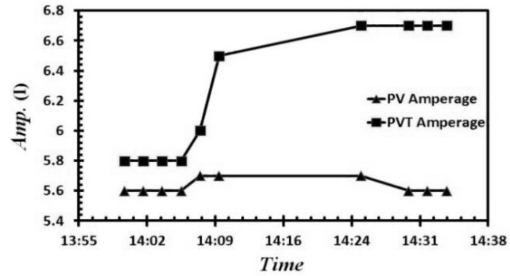
Diagrams 4 and 5 show the voltage and amperage diagrams in the experimental model, respectively. On the interior surface of the solar panel which is in contact with water, the average Nusselt number which is a criterion of heat transfer is obtained from Eq. 2:

$$\overline{Nu} = \frac{\bar{h}\,D}{k} = \frac{\overline{q''}\,D}{k\,(\bar{T}_s - \bar{T}_{bulk})} \qquad (2)$$

where $\overline{T_{bulk}}$ is the average temperature of the fluid in the water tub, and D is the cube root of the water tub's volume.



Dia.4. The voltage changes of the panels in terms of time in the experimental model.



Dia.5. The amperage changes of the panels in terms of time in the experimental model.

For this particular geometry and water as fluid:

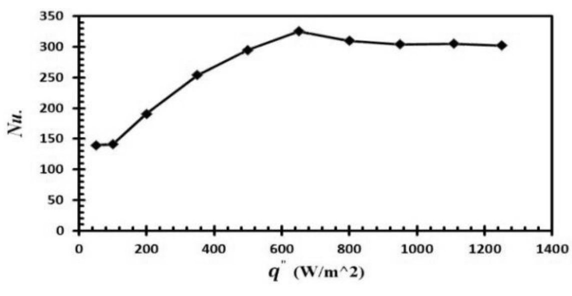
$$D = (1.940 * 0.995 * 0.014)^{\frac{1}{3}} = 0.3m \qquad (3)$$

$$k_{water} = 0.6069\ \frac{W}{mK}$$

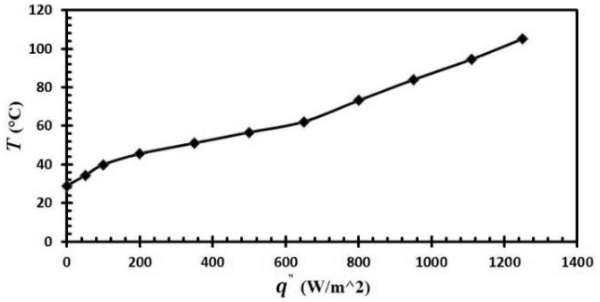
Therefore, Diagram 6 shows the average Nusselt number in different heat fluxes for the interior surface of the solar panel which is in contact with water. As it can be seen, the Nusselt number of this study changes between approximately 140 and 326.

In addition, Diagram 7 shows the average temperature of the output water of the solar water heater from 0 to 1250 W/m2 heat fluxes over a 24h period of an average ambient temperature of 35.65 °C in Summer, the input municipal water temperature of 29 °C, and average ambient pressure of 846.2 hPa.

As shown in Diagram 7, depending on the intensity of solar radiation, the temperature of the output water of the solar water heater can increase from 29 °C to about 105 °C, and it can be used as a prewarming fluid for another system or applied directly. It should be noted that if this water is to be used domestically or in sensitive industrial equipment, the sanitation and the percentage of its composing elements should be studied and tested several times.

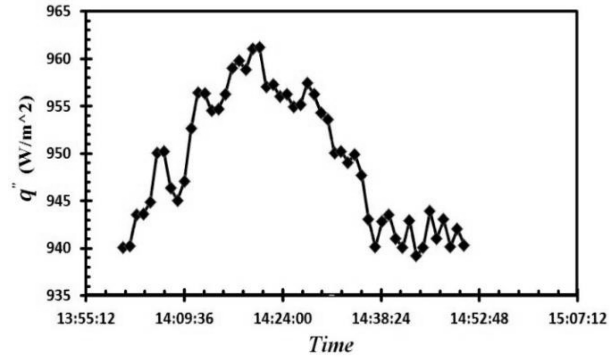


Dia.6. The Nusselt number in different heat fluxes.

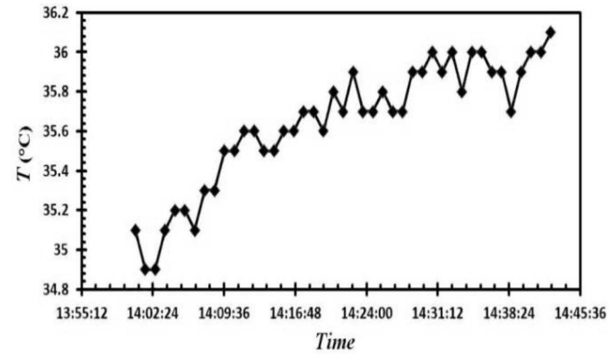


Dia.7. The average temperature of the output water of the solar water heater from 0 to 1250 W/m2 heat fluxes.

Diagrams 8, 9, and 10 show the intensity of solar radiation, ambient temperature, and ambient pressure during the time of the experiment in the experimental model, respectively [7 – 9]; the data logger is used to measure the data.



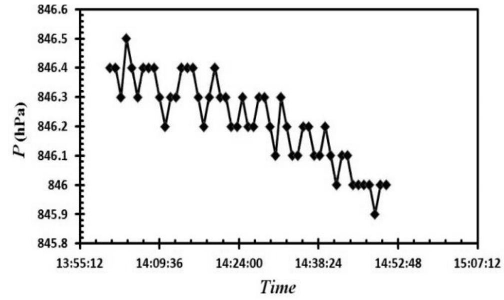
Dia.8. The intensity of solar radiation during the experiment in the experimental model



Dia.9. The ambient temperature during the experiment in the experimental model

In the experimental model, the water heater had a high temperature as it was placed on the roof of a building on the campus of Islamic Azad University, Central Tehran Branch for several days before the experiment, and its status became normal after a few minutes of working. Therefore,

- The temperature of the input water decreased from about 37 °C to about 29 °C.
- The temperature of the output water was about 99 °C when the tub was being filled, and it reduced to about 54 to 74 °C afterward.

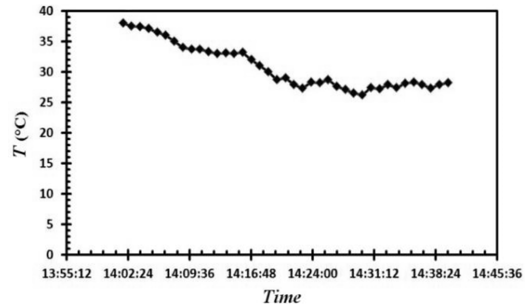


Dia.10. The ambient pressure during the experiment in the experimental model.

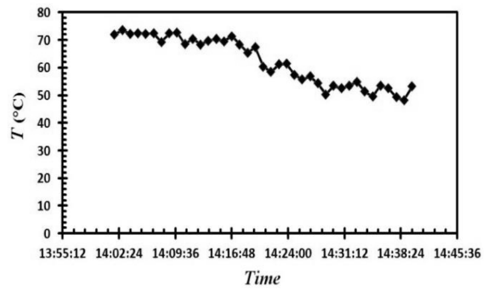
Therefore, as shown in Diagrams 11 and 12, there was about 25 to 45 °C temperature increase from input to output [7 –12].

In the analysis of the present research, the temperature of the input water was considered to be 29 °C. The temperature of the output water also increased up to about 83 °C for a 950 W/m2 heat flux. Therefore, the maximum temperature increase is 54 °C from the input to the output of the solar water heater. The present research shows that cooling photovoltaic solar panels significantly increases their electrical efficiency. Of the several methods used for cooling this type of panel, the method selected by the present research (direct-contact water tub) is implemented in the world for the first time, and it resulted in the world's highest efficiency in power generation for this model of solar panel, which is a subject worth highlighting. In addition, in this cooling process, the solar panel has simultaneously become a solar water heater, and the generated heat can be used. Preventing the loss of energy is also another important result of this research.

To extend the scope of this research, the interested readers are recommended to disperse cold water to the back of the solar panel using injectors. The results of this research and other works can hopefully serve the international community and play a crucial role in providing a pollution-free environment.



Dia.10. The temperature of the input water in terms of time in the experimental model.



Dia.12. The temperature of the output water in terms of time in the experimental model

IV. NOMENCLATURE

$Amp.$	Amperage (I)
D	Characteristic length
h	Convection heat transfer coefficient
k	Conduction heat transfer coefficient
Nu	The Nusselt number
$q^{"}$	Heat flux
Re	The Reynolds number
T	Temperature (°C)
V	Velocity (ms-1)
$Vol.$	Voltage (V)
Greek symbols	
μ	Dynamic viscosity (kgm-1s-1)
ρ	Density (kgm-3)
Superscripts	
$-$	Average value
Subscripts	
$bulk$	Fluid
S	The interior surface of the solar panel

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