International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 6, Issue 8, pp 53-60, August-2022

https://doi.org/10.47001/IRJIET/2022.608008

Simulation of U Tube Heat Exchanger Immersed in Oil inside Solar Evacuated Tube

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Abstract **- A numerical simulation using finite difference method, transient and 3D for the water flow within the U-tube heat exchanger which is immersed in oil inside evacuated tube solar collector. This simulation process starts from the heat gained from the solar radiation and ends with the outlet temperature of the water to be heated by the U-tube heat exchanger. The characteristics of the used materials such as glass, water, copper and the used oil were entered to the simulation software. The vacuumed space between the two glass tubes was replaced with Aerogel being the most appropriate solution instead of the vacuum part because it is difficult to represent in the mesh part. The solar load model was used to track the radiation in this simulation, where the solar radiation heat flux is solved using the fair weather condition of the radiation equations, then the solar radiation load is considered as the term source in the energy equation tube according to geographical location, date and hour of the day. The performance of the solar evacuated tube (SET) was studied under the continuous water circulation and exposing the collector to the solar radiation, i.e. heating the oil and water together at a speed of 0.08 m/sec and where the flow that is laminar. The simulation results showed a clear effect of solar radiation in the contours of temperature charts and water circulation inside the solar collector, where the highest oil temperatures are at the top opened end of the SET collector and the lowest at the bottom closed end of the SET.**

Keywords: U-Tube, Hear Exchanger, Immersed Oil, Solar Evacuated Tube.

I. INTRODUCTION

The recommendations of the climate conference in "Glasgow 2021" confirm Iraq's commitment to environmental determinants, as Iraq must take advanced steps to reduce emissions and protect the environment and the climate by reducing the use of fossil fuel .The excessive use of fossil fuels in the civil and industrial sectors causes air pollution and raises the proportion of carbon dioxide, and thus the occurrence of global warming, which encourage the use of solar energy, which is considered renewable and environmentally friendly energy and is one of the most important alternative energy sources.[1]

In most engineering applications of solar energy, the received solar energy is converted into photovoltaic energy or thermal energy. In all thermal applications of solar energy, solar energy is captured using different types of solar collectors that convert solar radiation energy into thermal energy. Solar heat is obtained by intercepting solar radiation by a well-absorbing opaque receiver. The collected thermal energy can then be used to power many applications, such as a solar water heating system or hot air supply for various purposes, driving thermal electric power plants, water distillation and purification systems, solar drying and solar cooling systems [2]

Solar Water Heating (SWH) is the conversion of solar energy into heat for heating water using a solar thermal collector. This solar energy conversion uses heat energy transfer mechanisms (conduction, convection &radiation).

The main components of most solar water heating systems are:- The collector, which capture and retain heat from the sun rays and use it to heat the working fluid or the heat transfer medium. The circulating pump, which forces the water to circulate through the system, some types of heating systems work without a pump. The thermal insulation, special measures must be taken to prevent the leakage of the captured heat to the outside environment. Thermally insulated storage tank, which stores the heated water coming from the solar collectors. The transfer medium, which is the working fluid that acquires heat and transfers it to the place of use or storage until use. Tubes transfer the working fluid between the parts of the collector system. Structure to which all the parts of the solar collector are attached, [3].

1.1 Solar Collectors

In general, there are several techniques for collecting thermal energy from solar radiation, and solar collectors can be defined as a special type of heat exchanger that converts solar radiation into heat energy through a carrier medium

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which transmits heat to the place of storage or use. Solar collectors are the main component of any solar system[1].

There are two types of solar collectors: - the first is non-concentrating solar radiation. The second is concentrating solar radiation.

A non-concentrating fixed collector has the same area to intercept and absorb solar radiation, while a concentrating solar collector that tracks the sun, to maintain a high concentration ratio, usually has concave reflecting surfaces to intercept and focus the sun's radiation beam on a smaller receiving area, thus increasing intensity of solar radiation. Concentrating collectors are suitable for high temperature applications (>100°C), [4].

Common types of non-concentrating solar collectors are:

- **Flat plate solar collector**

Flat plate collectors operate efficiently at temperatures as low as (100°C) which limits their applications for domestic water heating and air heating. Higher temperatures can be achieved by developing solar collectors by using the space between the glass cover and the absorber plate to reduce or eliminate convective losses,[5]

- **Evacuated tube solar collector (SET)**

Vacuum tube collectors are also used in water heating systems, evacuated tube collectors are often devices with significantly higher performance than regular flat plate collectors. This hypothesis is true for the specific operating conditions of the collector when the ambient temperature is very low and the solar radiation decreases at a level close to that of the collector, [6].

The modern solar evacuated tube consists (SET) of two interlaced concentric glass tubes, one inner tube and the other outer tube. The inner tube is coated with selective opaque coating but the outer tube is transparent. The solar rays pass through the transparent outer tube and reach the surface of the inner tube to be absorbed later by the inner tube. Thus, the inner tube is heated as a result of the passage of sunlight through the outer tube. To maintain the collected heat inside the inner tube an air vacuum in the annular field created between the two glass tubes, which allows the passage of solar radiation and prevent the heat convection. The vacuum is created by welding the two tubes together at the top end and the air trapped in the annular field is drawn out. In this way, the heat energy gained from solar radiation remains inside the inner tubes and thus these vacuum tubes collect the solar radiation energy efficiently. Therefore, the vacuum tube collector is the most effective solar thermal collector,[7].

1.2 Classification of Evacuated Tube Solar Water Heating Systems (ETSWHS)

One of the most important problems in designing solar evacuated tubes is the difficulty of extracting heat from the absorbent film that extends along the length of the tube. The most important ways to extract heat are: -

- The heat pipe consists: in this type of collectors a heat pipe equipped with cylindrical fins is inserted into the SET in such a way that the fin comes in close contact with the inner glass tube. The evacuated tube absorbs solar radiation and converts it into heat energy. The heat energy is then transferred to the refrigerant located inside the heat pipe. This refrigerant working fluid evaporates and rapidly rises to the condenser part of the heat pipe which transfers energy to the cold water to be heated, which flows around the condenser. There is no direct mixing between the refrigerant working fluid in the heat pipe and the heated water[8].
- Direct contact with the water to be heated in what is known as water-in-glass (all glass) solar collector. In such collectors, the top open ends of several SETs are placed in the heated/cold water storage tank such that the water flows from the tank into the solar tubes where it is heated by the solar radiation, Hot water rises back into the tank and is replaced by cold water, heat is transferred in the system only by the natural circulation of water [9].
- The U-tube exchanger: in this type of collectors a U shaped metallic tube fitted to a cylindrical fins is inserted into the SET in such a way that the fin comes in close contact with the inner glass tube. The collected heat energy is transferred to the fin and then by conduction to the U-tube, and from there to the working fluid running inside the U-tube by convection[10].

The researcher Budihardjoet al.,[9]studied vacuum solar energy tubes, where he found that their performance is better than flat solar collectors in obtaining temperatures due to reducing losses caused by convection due to the presence of vacuum and as a result, solar water heaters that are used flat plate collectors are more common in warm climate regions, while evacuated tube collectors are increasingly adopted in north Asia and European countries, where vacuum collectors perform better than flat plate collectors due to lower heat loss in producing higher temperatures in cold climates.

The researcher Gao, et al., [11]compared the energy performance of the water-in-glass evacuated solar collector and the U-tube evacuated solar collector, where it was found that the average thermal efficiency of the water-in-glass evacuated solar collector is less than the average thermal efficiency of the U-tube evacuated solar collector. They also

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found that the flow rate also affects the thermal performance of the system. A higher flow rate will reduce the energy collection performance as the U-tube vacuum solar collector has a small improved flow rate range of 20-40 kg/h m2 compared to 20- 60 kg/h m2 for water-in-glass vacuum solar collector.

1.3 The main factors affecting the thermal energy gain by solar evacuated tube collector studied in literatures are:

Tilt angle: The researcher Thant et al., [12] conducted a numerical study of the temperature distribution along the length of the vacuum tubes of the solar water heating system, where he used the CFD package from the ANSYS program using the finite volume method. For tubes, the researcher concluded that there is no noticeable change in the temperature distribution when changing the angle of inclination because the rounded shape of solar tubes makes it capable of receiving the largest amount of solar radiation, in addition to the fact that the amount of heat lost is small.

Flow rate and solar radiation intensity: The researcher Dileep and his group [13]carried out an analytical study based on CFD from the ANSYS program to heat water using a solar collector. The buoyant force helps raise the temperature of the water inside the tank, and the researcher concluded that at the lowest flow rate and the highest solar radiation, the highest temperature was obtained.

Natural flow and forced circulation: Harender et al., [14]performed a computational analysis of the vacuum tube solar collector for active and passive flow, and to ensure that the system receives the maximum useful heat gain, the optimum mass flow rate was analyzed using ANSYS Fluent CFD. The researcher concluded that the thermal efficiency of the passive tube system is higher than that of the active tube system and that the useful heat gain is relatively higher in the passive tube system. It is preferred to use passive flow because active flow is more expensive and have lower thermal efficiency compared to passive piping systems.

Factors affecting the increase in heat transfer to the working fluid-carrying tubes

There are several factors that affect the increase in heat transfer to the absorbent tubes carrying fluid in the evacuated tube solar collector, as mentioned below:

Effect of tube shape: The researcher Kim [15]studied the thermal performance comparisons of the evacuated glass tube solar collectors with different shapes of the absorber tube. The researcher noticed that the performance of the solar collector is affected by the shape of the absorbing tube, and the angle of incidence of solar radiation.

Using more than one U-tube: The researcher Soheil and his group [16]carried out a study that included a two-dimensional numerical simulation of the vacuum tube solar collector by the finite element method to simulate radiative heat transfer, two models of vacuum tube solar collectors were studied and analyzed, the first model contains one tube with a U-type and the second model contains two U-type tubes. Simulation results show an increase in collector efficiency due to an increase in the number of U-type tubes in evacuated tube solar collectors.

Effect of a metal type of U-shaped tube: The researcher Naik and his group [17]carried out a three-dimensional numerical study to evaluate the performance of a vacuum solar collector containing a U-shaped tube by using the finite element. Where the researcher used three types of metals for the U-shaped tube (aluminum, copper and brass alloy), where the researcher found that the highest efficiency of the collector was obtained when using a tube made of copper, then copper ingot, then aluminum.

Effect of using the filling inside SET: Liang [18] conducted a theoretical and experimental analytical study of the U-tube type solar collector, which is filled with a selected filling. To reduce the effect of thermal resistance between the absorber tube and the copper fin of a conventional vacuum solar collector. The filled layer has a cylindrical configuration with two cavities for inserting a U tube, which can be made of a high thermal conductivity material, such as a compressed graphite component to be tightly fixed to the inner wall of the absorber tube. The results of the research showed that the evacuated tube of the type filled with U tube has good thermal performance, and the efficiency of the evacuated tube of the type filled with U tube is 12% times higher of evacuated tube is U-shaped with copper fin.

Naik et al.,[17] conducted a work in which different fillings were used between the inner wall of the glass and the U-shaped tube. The filling material were magnesium oxide, aluminum oxide and graphite filler. Where the researchers concluded in their study that the highest efficiency of the collector was in the case of using graphite filler, where the combined efficiency increased by 15.3 %.

The researcher Abokerssh et al [19]studied the on-demand operation of a compact solar water heater based on a vacuum tube solar collector containing a U-shaped tube along with the phase change material PCM. A new solar collector was presented U-tube built-in paraffin wax (ALEX WAX 600) for energy storage. This PCM is an organic phase change chemical with an average melting temperature of 60°C and a thermal conductivity of 0.21 W/m K. The main issue of the

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developed system is storing energy in the vacuum tube itself through the use of paraffin wax.

The researcher Papadimitratos and his group [20]studied the vacuum tube solar collectors combined with phase change materials packed in small bags, whereby under this method, the heat tube is immersed inside the phase change material, where the heat was collected effectively and stored for a long period of time due to the thermal insulation of the evacuated tubes.

Also, silicone oil was injected into the tubes between the spaces between the bags of phase change materials. Silicone oil increases convective heat transfer (stirring effect) resulting in uniform melting inside Erythritol bags and prevents tube breakage or failure. The benefit of this method includes improving functionality by delaying heat loss, thus providing hot water during hours of high demand or when solar energy intensity is insufficient.

The researcher Kim et al.,[21]simulated the performance of an all-glass solar collector with a coaxial channel inside. By conducting a numerical analytical study of the water heating system using evacuated tubes, where the water is heated when passing through the coaxial channel, which is inserted into each SET of the collector. The space between the outer part of the coaxial channel and the inner glass tube is filled with antifreeze fluid to facilitate heat transfer from the solar absorber surface to the water and to prevent problems caused by freezing in sub zero weather conditions.

The researcher Abd-Elhady and his group [22]conducted an experimental study to improve the performance of evacuated heat pipe assemblies using oil and foam metals. The introduction of thermal oil into the evacuated tube in order to improve the heat transfer rate, so that the mode of heat transfer from the inner surface of the evacuated tube to the heat tube, by convection through the oil, as well as the conduction through which the installed fin is.

The finned surface was replaced with foamed copper. They found that the heating efficiency of the evacuated heat pipe increases if oil is introduced into the evacuated tube and the cylindrical fin is replaced with foamed copper, and the thermal oil acts as a heat store.

1.4 Summary of previous research and studies

Previous research and studies focused on the study of increasing the performance of the SET collector by studying the effect of the angle of inclination, the flow rate and the intensity of solar radiation, which have a clear effect on the gain of useful solar thermal energy through SET collector, where the researchers found that the best performance can be obtained at lowest flow rate and highest radiation intensity and when using the reflector.

Other studies focused on studying the factors affecting the increase in heat transfer to the absorber tubes carrying fluid in the evacuated tube solar collector, and thus increasing the performance of the system in several ways, including choosing the appropriate tube shape that contains a circular fin of aluminum and the efficiency increases when using more than one tube U- type and choose the appropriate metal type copper.

In several studies, researchers found that decreasing the conductive resistance between the inner wall of the glass and the absorbent tube, such as using a filler from graphite, wax, antifreeze fluid or oil, leads to a good increase in performance.

The collector geometry of the solar water heating to be studied here in this work is a variant of the standard U-tube solar evacuated tube collector, such that it contains copper U-shaped tube inside an oil-filled Dewar evacuated glass tube. The copper U-shaped tube has no any fin attached to it. The oil actually acts as a sensible heat storage and mediator to transfer the collected heat energy to the U-tube. The performance of this SET was simulated by Ansys Fluent software.

II. NUMERICAL MODELING

A three-dimensional simulation of the solar collector that contains a U-shaped tube was carried out according the main steps shown in figure1 below. The computational fluid dynamics CFD of temperature distribution in water and oil, which uses the Finite Volume Method (FVM).

The input parameters were taken according to experimental readings done in separate previous research, in which several experiments were done in two forms, the first is exposing the device to the solar radiation to charge the oil with heat energy then circulating the water through the U-tube to take the heat from the oil, the second form were continuous solar heating of the oil and circulating the water through the U-tube.

Design Geometry Model

The geometry of SET in this work the three-dimensional model was created as in Figure 2 by design-modular program to create the geometry according to the design dimensions given in Table 1 below where the following measurements were adopted for the SET collector.

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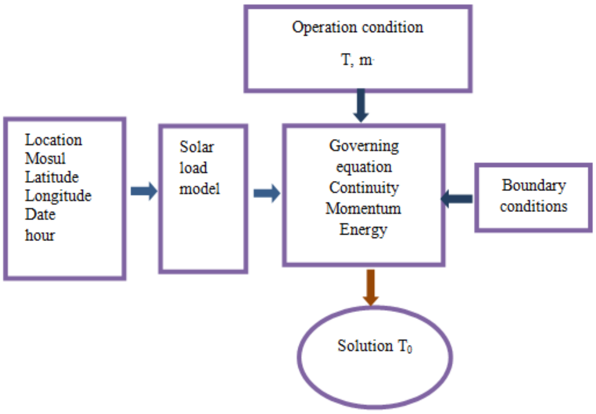

Figure 1: Main steps of simulation process

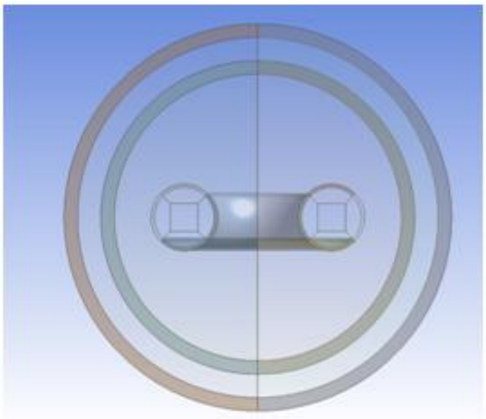

Figure 2: Cross section of the SET

Mesh generation

Meshing is one of the most important aspects of getting accurate results from FEM and CFD simulations. Usually, the results become more accurate as the network becomes smaller and denser. However, the trade-off between this is that simulations get larger and solution times get longer.

The parts were named and the network worked as in Figure 3 according to the points mentioned below

- The type of the element is hexahedral mesh

Table 1: Dimensions and parameters of the SET

Parameter of the Solar evacuated tube SET	Value
Diameter of the outer glass tube	0.058 m
Outer glass tube transmittance	0.8%
Thickness of the outer glass tube	0.002 m
Inner glass tube diameter	0.047 m
Inner glass tube thickness	0.002
Inner tube absorbency	0.92%
The inner surface of the inner glass tube, emissivity	0.8%
U-shaped tube outer diameter	0.01 m
U-shaped tube inner diameter	0.009 m
Collector SET length	1.8 m

Table 2: Number of mesh elements in each domain

Nodes	Elements	domain
16006	7977	Air
53800	38400	copper
17462	7977	Inner glass
181141	125603	Oil
16006	7977	Outer glass
167241	160000	Water
451656	347934	Total

- The type of methods used multi-zone edge sizing body sizing.
- Results data for the networking process in a table.

Assumptions

- The flow of water is continuous and non-compressible, and all the physical properties of water are constant.
- The flow is laminar, transient, 3D.
- Adiabatic region at the end of the glass tube and near the water inlet hole.
- The longitude 43.1 and latitude 36.34 were chosen for the city of Mosul and the time zone +3.
- Application of fair weather model option to track solar rays.

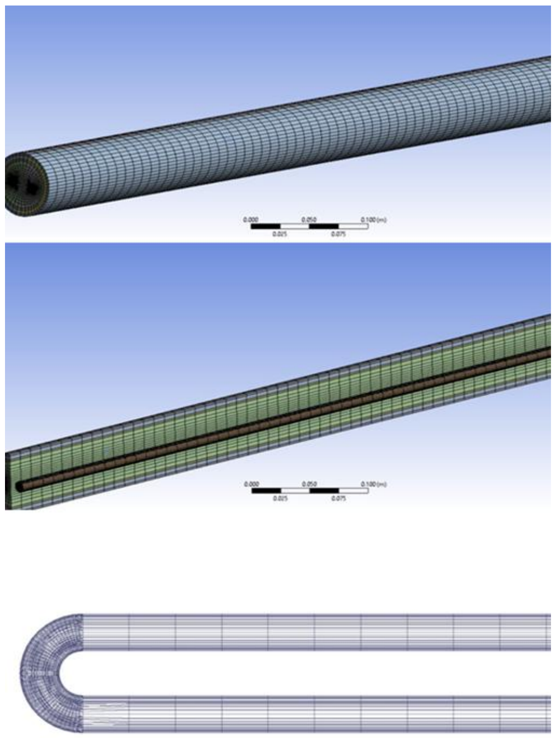

Figure 3: The generated mesh for each domain

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Governing Equations

The condition of heating oil and water together.

The water flow is very slow, its speed is 0.08 m/s, and the type of flow is laminar, and in the, the

- Equation of continuity

$$\frac{\partial(\rho u_x)}{\partial x}+\frac{\partial(\rho u_y)}{\partial y}+\frac{\partial(\rho u_z)}{\partial z}=0$$

- Momentum equation in the direction of the x axis

$$u_x\frac{\partial(\rho u_x)}{\partial x}+u_y\frac{\partial(\rho u_y)}{\partial y}+u_z\frac{\partial(\rho u_z)}{\partial z}=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left\{\mu\left[2\frac{\partial u_x}{\partial x}-\frac{2}{3}\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)\right]\right\}+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_x}{\partial z}+\frac{\partial u_z}{\partial x}\right)\right]$$

- Momentum equation in the direction of the y axis

$$u_x\frac{\partial(\rho u_y)}{\partial x}+u_y\frac{\partial(\rho u_y)}{\partial y}+u_z\frac{\partial(\rho u_y)}{\partial z}=-\frac{\partial P}{\partial y}+\rho g_y+\frac{\partial}{\partial y}\left\{\mu\left[2\frac{\partial u_y}{\partial y}-\frac{2}{3}\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)\right]\right\}+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u_y}{\partial x}+\frac{\partial u_x}{\partial y}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_y}{\partial z}+\frac{\partial u_z}{\partial y}\right)\right]$$

- Momentum equation in the direction of the z axis

$$u_x\frac{\partial(\rho u_z)}{\partial x}+u_y\frac{\partial(\rho u_z)}{\partial y}+u_z\frac{\partial(\rho u_z)}{\partial z}=-\frac{\partial P}{\partial z}+\frac{\partial}{\partial z}\left\{\mu\left[2\frac{\partial u_z}{\partial z}-\frac{2}{3}\left(\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}\right)\right]\right\}+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u_z}{\partial x}+\frac{\partial u_x}{\partial z}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u_z}{\partial y}+\frac{\partial u_y}{\partial z}\right)\right]$$

- Energy Equation

$$u_x\frac{\partial(\rho c_p T)}{\partial x}+u_y\frac{\partial(\rho c_p T)}{\partial y}+u_z\frac{\partial(\rho c_p T)}{\partial z}=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Sh$$

III. DISCUSSION OF THE RESULTS

The results obtained using Ansys Fluent R21 software, for simulating the SET with the U-tube under the circumstances under which the experimental readings of the experiment conducted on 30th May 2021 outside the laboratory. These circumstances are described in table 3 below. The results of the simulation are summarized in the form of results for calculating the maximum oil temperature and the water exit temperature from the U-tube under continuous exposing the SET to solar radiation with water circulating continuously for about 3 hours, starting from 10:00AM local time.

The program settings were adjusted so that the water passes at a very low flow speed of 0.08 m/sec when the SET is exposed to radiation, as the oil and water are heated together by solar radiation.

The average oil temperature initially was 30°C as well as the water inlet temperature to the U-tube. After continuous running for 3 hours the average oil temperature reached 50°C which means they gained solar energy was able to continue heating up the oil under continuous heat removal by the water entering the U-tube at 30°C.

Table 3: Data and results of the 30-5-2021

Sun exposure time	3 hours starting from 10:00 AM
Water inlet temperature	30°C
ambient temperature	30°C
Water outlet temperature	33.5°C
Initial temperature of oil	30°C
Oil temperature after 3 hours	50°C

The temperature of the water during a period of 3 hours is shown in the Figure4. The maximum temperature of the oil during a period of 3 hours is shown in the Figure 5. The longitudinal and transverse temperature distribution in the glass, oil, copper U-tube and water are demonstrated in Figure 6. Three transverse sections at depths measured from the opened upper end of the SET they are 0 m, 0.9 m and 1.77 m were demonstrated in Figure 6.

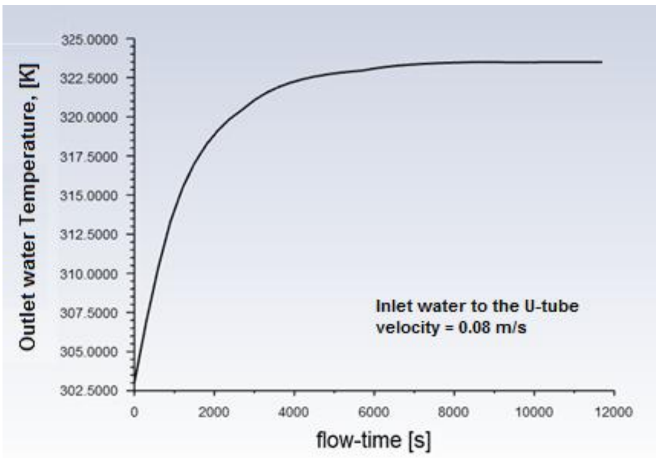

Figure 4: Outlet temperature of water from the U-tube

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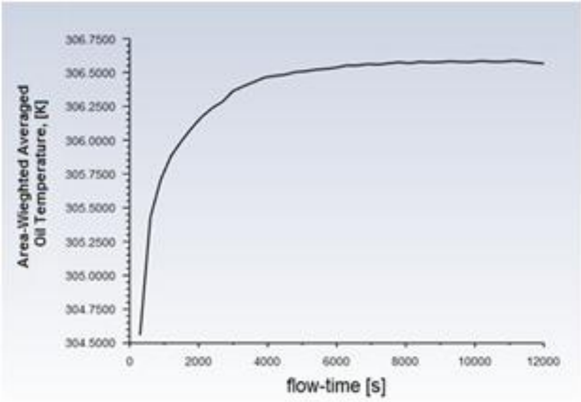

Figure 5: Oil temperature inside the SET

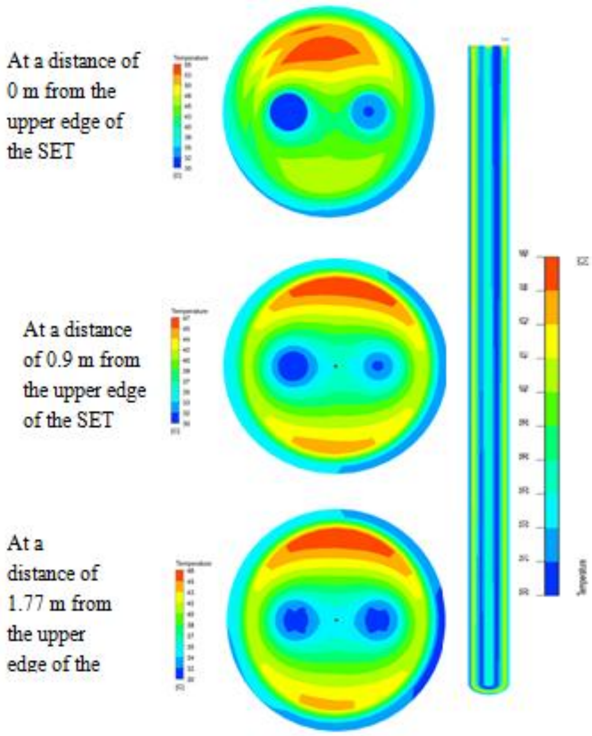

Figure 6: Contours of temperature at 0 m, 0.9 m, 1.77 m

IV. CONCLUSIONS

Contour shapes were obtained for the distribution of temperatures through the longitudinal and transverse sections of the double-walled solar tube, which is vacuumed from the outer glass tube to the water that flows inside the copper tube, which forms a U-shaped heat exchanger that is immersed in oil inside the inner solar collector cavity.

1) The simulation results showed agreement with the experimental data for the exit water temperature, which increases by 6-9°C when passed for 28 seconds.
2) A clear effect of solar radiation in the form of temperature charts and water circulation inside the solar collector, where the highest oil temperatures are from the side of the water entry the top end of the SET and the lowest at the bottom of the SET collector.
3) Replacing the vacuumed space between the two glass tubes SET collector with Aerogel, being the most appropriate solution instead of the vacuum part because it is difficult to represent it in the program, and it gave close results for the work of the vacuum inside the collector.

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Citation of this Article:

Amina Salal Zayyan Alnajmawy, Mahmoud Usamah Jasim, "Simulation of U Tube Heat Exchanger Immersed in Oil inside Solar Evacuated Tube", Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 6, Issue 8, pp 53-60, August 2022. Article DOI https://doi.org/10.47001/IRJIET/2022.608008

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