Assessment of the Performance for a New Design of Storage Solar Collector

Dr Omer Khalil Ahmed *‡

*Department of Machines and Equipment, Technical Institute / Hawija, Northern Technical University

(omerkalil@yahoo.com)

‡ Iraq, Kirkuk, Hawija, Tel: +964 7708080836,

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Abstract- This research includes a numerical study for a new design of a storage solar collector to confirm its convenience for household use. This novel collector is called the wedge storage collector and can be utilized as storage water reservoirs to substitute the common cubical or cylindrical container commonly used for the domestic application. The study includes storage collector derived from cutting a cylinder at two planes, the first plane is vertical and the other is an inclined plane at 45º.

The fluent software was used to achieve the numerical study. The free convection process in the space of these storage collectors was investigated based on the finite volume method. From the results of CFD program (Fluent), the distributions of the temperature and velocity during the day were obtained. The ultimate value of mean storage temperature was 18 ºC and 41 ºC for this particular winter and summer day respectively. It is observed that the mean storage temperature of the water inside the collector decreased with increasing the volume of the collector, also the results show there is no obvious influence of the barrier on the mean storage temperature of the water inside the collector. This storage collector was better than the previous design of storage collectors because of the high sunlit ratio area to storage volume which is an important significant parameter affecting the performance of the storage solar collector

Keywords Storage solar collector, new design, collector performance, wedge storage collector.

1. Introduction

Solar water heater storage, integrating the reservoir and collector in a single unit is an appealing stand by to classical solar water collectors. The elimination of the storage tank reduces the cost of the solar water heating collector and should improve performance[1][2].

Experimental and theoretical investigations on such systems have been carried out by a number of investigators[3]. Joudi[4] suggested a new storage solar collector for domestic hot water supply. It is of low price and readily fabricated from prevalent materials without the requirement to advanced techniques. This novel design can be utilized as a reservoir for water to substitute the common cubical or cylindrical container usually used in houses. The fabrication includes four different fundamental engineering shapes inspired from cutting a cube or cylinder at diverse directions. Each shear generates a diverse storage volume and a diverse inclined face that can be oriented to face the sun as shown in Figs. 1 and 2.

Fig. 1. Triangular storage collector.

The sunlit surface is painted black to increase solar energy absorption. A transparent material such glass may be utilized as a cover to the inclined surface meeting the sun[5].

The other sides were insulated by thermal insulation. The activity of a rectangular storage collector as shown in the Fig.2 was analysed theoretically by Joudi.et.al.[6]. The finite element software (ANSYS) was utilized for this goal.

Rahman.et.al[7] presented a numerical study for the simulation of free convection in this design. Finite element method is utilized to solve the governing equations. Numerical data are presented for the influence of the design variables on local heat transfer rate. Some important data are found in this analysis.

Fig. 2. Rectangular storage collector.

Helal et.al[8] discussed the energetic efficiencies of the solar storage collector, This system includes a cylinder was located in the CPC reflector and was examined outdoors to calculate its thermal performance. The storage solar collector showed suitable performances and similar to other designs of solar collector existing despite its simplicity. The output water temperature is adequate for the customers.

Rakesh Kumar and Marc A. Rosen[9], analyzed analytically the new design of storage solar collector with an addition storage unit. In this suggested design, the collector and the water container are integrated into one unit with water flow caused by free convection fact. Two shapes of the design were analyzed. The first design is a classical design of storage solar collector, while the second design is an additional storage unit connected with the first shape. The results showed that the efficiency of such systems was larger than conventional systems. Also, the experimental results were in agreement with theoretical predictions.

Experimental analysis on the performance of a triangular storage collector was presented by Hamood and Khalifa[10], This article includes an experimental assessment on the thermal performance of storage collector. A comparison between the present experimental results and published theoretical data for the same design showed good agreement.

Souliotis et.al [11] studied experimentally three designs of storage solar collectors. The primary purpose is the design and manufacture of low-cost solar water collectors with improved thermal performance and lowers possible. Fraisse et.al.[12] developed a new design of integrated solar collector. Its design took into account various aspects: the amount of the fluid storage, the amount of absorbed solar irradiation, and technological limitations. The project made it possible to study on the one hand its stratification and on the other hand the free convective heat transfers inside the enclosure of the collector. The approach used both numerical and experimental analysis to achieve the aim of the study.

Al-Joubory[13] performed practically and theoretically study on a storage solar collector as suggested by Joudi. The study includes three different principal engineering forms. Rectangular and triangular collectors suggested by Joudi derived from cutting a cube at different cutting planes. Further, a cylindrical storage collector was suggested in this work derived from cutting a cylinder at an inclined cutting plane as shown in Fig.3. Performance results showed that the ratio of sunlit area to storage volume is a significant parameter affecting the performance of this type of storage solar water heaters. This ratio should be more than 12 to provide a suitable amount of warm water in the winter season. The triangular collector was better than the cylindrical and rectangular collectors because of the high ratio of sunlit area to the storage volume. The performance of these new storage solar collectors was, in general, similar to the performance of the conventional flat plate solar water heaters.

This research includes a numerical study for a new design of storage solar collectors to prove its convenience for household use. The study includes a storage collector derived from cutting a cylinder at two planes, the first plane is vertical and the other is an inclined plane at 45^{o} as shown in Fig.4. This new design is called the wedge storage solar collector.

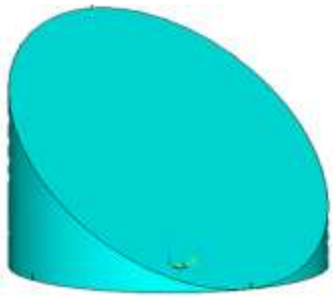


Fig. 3. Cylindrical storage collector.

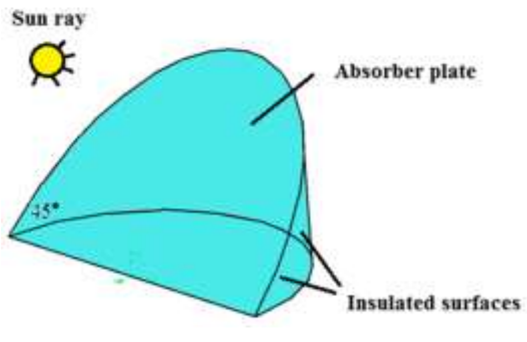


Fig. 4. Wedge storage collector.

2. Numerical Models

The complex shape of the wedge storage solar collector demands the numerical fluid dynamic (CFD) program. Standard heat transfer relations cannot sufficiently describe the free convection inside the system. It has been modelled using a numerical fluid dynamics program, based on the finite element method, Fluent and its accompanying mesh generation software, Gambit. Gambit was used to create the grid of the wedge collector as shown in Fig.5. the type of element used was tetrahedral. The pattern utilizes a segregated solver with implicit formulization. The momentum and energy equations are dissolved using the second order approach. The flow is buoyancy driven free convection and the Boussinesq criterion was used for the density expression. The body-force-weighted discretization is recommended for solving the high Rayleigh number flows. Therefore, body force weighted is used to discretize the pressure term[14].

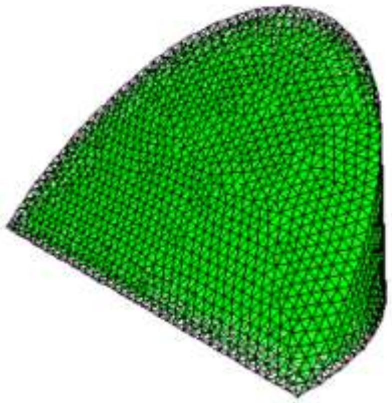


Fig.4. Mesh generated wedge collector by GAMBIT software.

Pressure-velocity coupling was accomplished using the PISO algorithm (Pressure-Implicit with Splitting of Operator scheme). PISO is recommended for transient flow calculation[15]. Under relaxation factors are applied in order to control the changes of variable values between successive iterations and to avoid divergence of the solutions. During the resolution of the equations, the typical values for the under relaxation parameters used are approximately 0.7 for momentum, 0.3 for pressure, and 0.8 for density and energy.

3. Estimation of Sun Radiation

The computing of the sun radiation on an open surface includes the calculation of the direct and indirect radiation, which is calculated after defining the solar time and location. As the sun radiation crosses during the layer of the air around the earth it is weaken depending on the length of its path according to a suppression coefficient B1, to make the normal radiation in the horizontal plane[16]:

$$I_D = A_1 * exp(-\frac{P_H}{P_o} * \frac{B_1}{sin(\alpha)}) \quad (1)$$

Where P_H/P_o is the ratio of the pressure at the location with respect to the standard atmospheric pressure at sea level and calculated as :

$$\frac{P_H}{P_o} = exp(-0.0001184 * H_{alt}) \quad (2)$$

Where, H_{alt} is the height in meters above the sea surface. The constant in the eq.(1) that represented the extra-terrestrial solar intensity A_1, the atmospheric suppression coefficient B_1, and sky-diffused factor, C_1, were calculated for any day of the year by the relations[13]:

$$A_1 = 1158 * [1 + 0.066 * \cos(360 * N_d / 370)] \quad (3)$$

$$B_1 = 0.175 * [1 - 0.2 * \cos(0.93 * N_d)] - 0.0045 * [1 - cos(1.86 * N_d)] \quad (4)$$

$$C_1 = 0.0965 * [1 - 0.42 * \cos((360/370) * N_d)] - 0.0075 * [1 - cos(1.95 * N_d)] \quad (5)$$

Where, N_d is the number of the day in the year.

The angle of the sun altitude (α) and the angle of declination (δ) are calculated by[17]:

$$\alpha = \sin^{-1}(cos\,\phi * cos\,\delta * cos\,\omega + sin\,\delta * sin\,\phi) \quad (6)$$

$$\delta = 23.45 * \sin\left[\frac{360}{370} * (N_d - 80)\right] \quad (7)$$

Where, ϕ represented the angle of latitude (equal to 35°21` for Kirkuk city).

ω is the hour angle and expressed in degree as:

$$\omega = 15 * [Ast - 12] \quad (8)$$

Where: *Ast* is the solar time and calculated by:

Solar time = Standard time + E /60 - 1/15(Lstandard - Llocal)* (9)

Where: *Lstandard* is the standard meridian of local time zone (for Iraq equal to 45°).

Llocal is the longitude location concerned (equal to 44° 28` for Kirkuk city).

Standard time is the local time in hours[5].

E is the time equation, which is estimated as[13]:

$$E = \sum_{K=0}^{K=5} \left[A_K\, cos(\frac{2 * \pi * K * N_n}{365.25}) + B_K\, sin(\frac{2 * \pi * K * N_n}{365.25}) \right] \quad (10)$$

Where,

N_n is the day number a 4-year cycle, with N_n =1 to N_n=1461 after four years.

A_K , B_K are constants are in table (1).

TABLE. 1 A_K AND B_K COEFFICIENT FOR EQUATION

K	A_K	B_K
0	$2.0870*10^{-4}$	0
1	$9.2869*10^{-3}$	$-1.2229 * 10^{-1}$
2	$-5.2258 * 10^{-2}$	$-1.2698*10^{-1}$
3	$-2.1867*10^{-3}$	$- 2.9823 * 10^{-3}$
4	$-2.1867 * 10^{-3}$	$- 2.9823 * 10^{-3}$
5	$- 1.51 * 10^{-3}$	$-2.3463 * 10^{-4}$

The beam solar radiation can be calculated as:

$$I_{beam} = I_D * cos(\theta_1) \qquad (11)$$

The incident angle θ_1 for any surface direction can be formulated as[18]:

$$\begin{aligned} cos\theta_1 &= cos\delta * sin\beta * sin\gamma * sin\omega - sin\delta * \\ &cos\phi * sin\beta * cos\gamma + cos\delta * cos\beta * cos\phi * \\ &cos\omega + cos\delta * sin\phi * sin\beta * cos\gamma * \\ &cos\omega + sin\delta * sin\phi * cos\beta \end{aligned} \qquad (12)$$

Where:

γ is the angle of the surface azimuth.

β is the slope of the collector.

The indirect or diffuse radiation on the inclined surface is given as[19]:

$$I_{diffuse} = I_{DN} * \begin{bmatrix} C_1 * \dfrac{(1+cos\beta)}{2} + s * \\ (C_1 + sin\alpha) * \dfrac{(1-cos\beta)}{2} \end{bmatrix} \qquad (13)$$

s represents the ordinary ground reflectivity (equal to 0.2).

Finally, the total solar radiation is the sum of the direct and indirect components:

$$I_{total} = I_{diffuse} + I_{beam} \qquad (14)$$

The hourly incident solar radiation on a titled surface for 365 days was obtained by a computer program developed in this work based on the ASHRAE clear sky model[20]. Fig. 6 showed the calculated solar radiation in the summer and winter seasons[21].

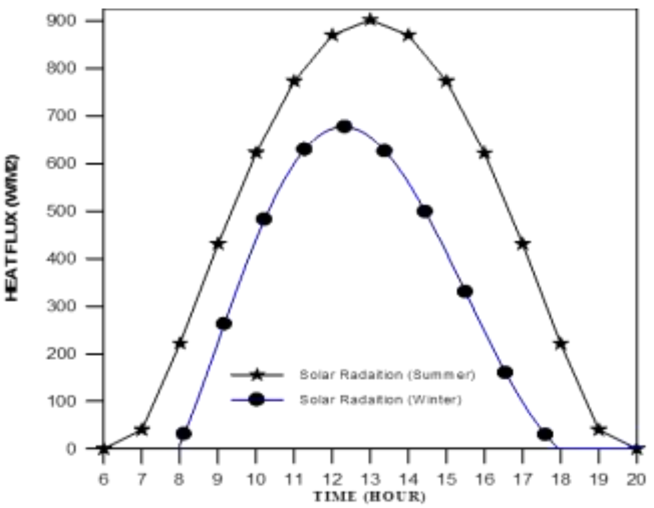


Fig. 4. Solar radiation in the summer and winter seasons.

4. Results and Discussions:

The incoming solar radiation was subjected the inclined face of wedge storage collector was modelled as parabolic heat flux. All conclusions were estimated for an ideal winter day (21th of December) and an ideal summer day (21th, of June). The parameters of the system performance were achieved methodically for all test conditions at each hour. These included the mean storage temperature, velocity distribution, and total stored energy. Typical results are presented.

4.1. Mean and Maximum Storage Temperatures:

The mean storage temperature is a key parameter for domestic hot water solar collection systems. It is determined as a mass weighted average temperature, which is evaluated as:

$$T_{mean} = \frac{\sum_{i=1}^{n} M_i * T_i}{M_{total}} \qquad (15)$$

Fig. 7 displays the variance of mean storage temperature during a typical clear winter and summer day. It is noticed that the mean storage temperature increased with time until the end of the operating period. The ultimate value of mean storage temperature was 18 ºC and 41 ºC for this particular winter and summer day respectively. This trend is typical of solar water heating systems[22].

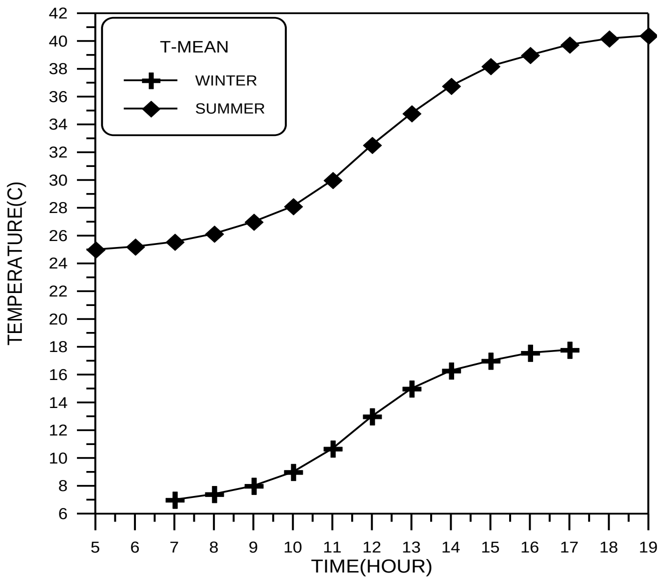


Fig. 7. Variation of mean storage temperature during a typical clear winter and summer.

Fig.8 displays the relation between the mean storage temperature and the volume of the collector. Varying height and base dimensions render varying storage volumes. It is observed that the mean storage temperature decreased with increasing volume. It is observed that the mean storage temperature reaches its maximum value (T mean = 29 ºC) at the collector volume equal to 83 litres. The minimum is obtained for a collector volume equal to 666 litres (T mean = 21 ºC). The maximum temperature of water occurs at the top of the storage tank as expected. It is noticed in Fig.9 that the numerical values of this temperature reach its maximum and decays during the end of the typical day. This trend is typical of solar water heating systems. Fig.(9) shows a slight difference of occurrence of maximum temperature in a typical winter day between the different volumes of wedge collectors.

The effect of the shape of the solar storage collector on the performance was studied numerically by supplying the same solar heat flux to the front area of the wedge and triangular collectors. Fig.10 displays the change of the mean storage temperature for the wedge storage collector and the triangular storage collector that invented by Joudi (Fig.(1)). All the shapes were taken as having the same volume of 83 litres. The maximum temperature was recorded for the wedge storage collector comparable with the triangular collector.

The better performance for the wedge collector is benefited by the high value of the ratio of the front area to the storage volume for the new design that equal to 5.666 m^2/m^3. The minimum temperature recorded for the triangular cylindrical storage collector with the front area to storage volume ratio of 4.9 m^2/m^3. Thus, the area density is the main factor in the design of these solar storage systems that used water as storing media.

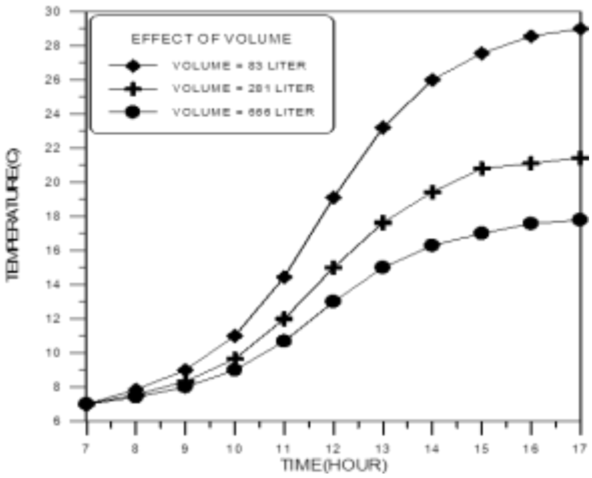


Fig. 8. Change of mean storage temperature for various volumes within the winter day.

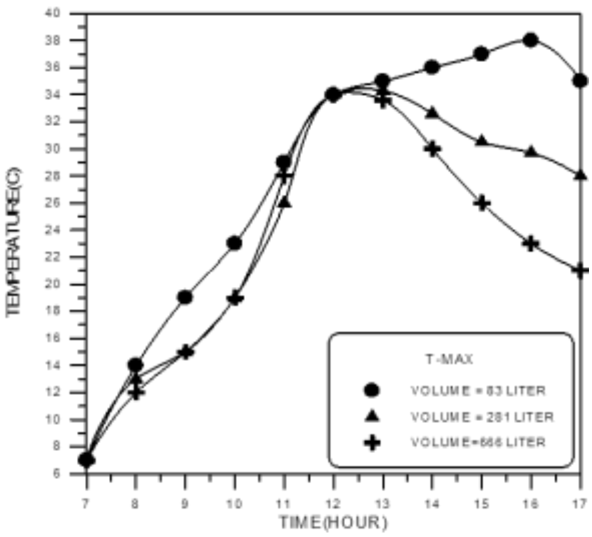


Fig. 9. Variation of maximum temperature of at the top of collector for different volumes.

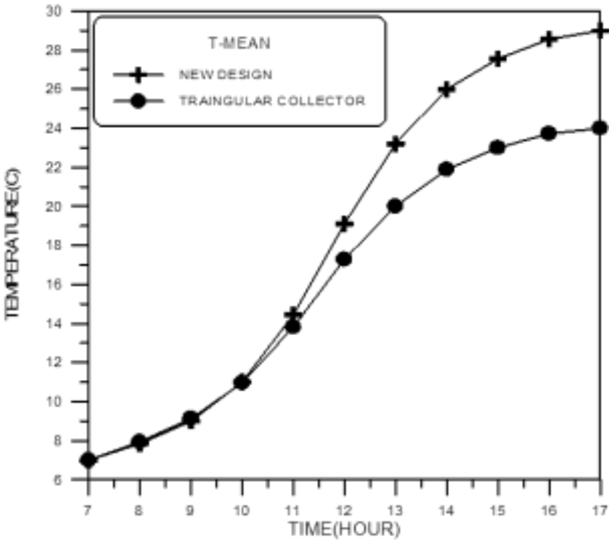
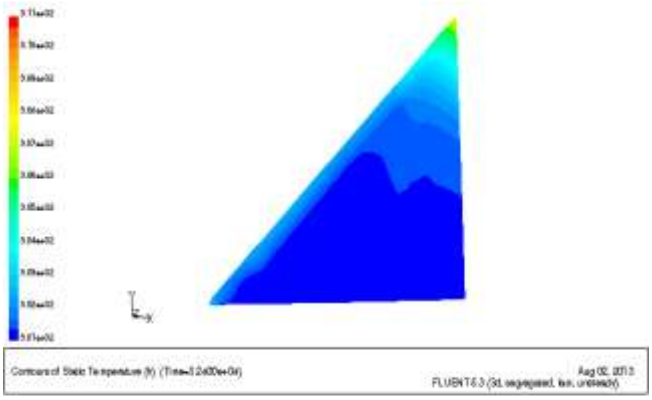


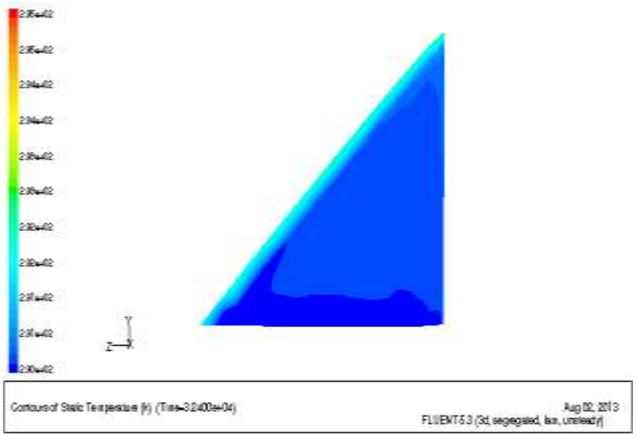
Fig. 10. Comparison of mean storage temperature for the wedge and triangular collectors (83 litres).

4.2. Temperature Distribution

Fig. 11 shows the temperature distribution in the wedge storage collector at 4 p.m. for different volumes. There are significant thermal gradients inside the volume of water.



(A) Volume = 83 Litres



(B) Volume = 666 Litres

Fig. 11. Temperature distribution (K) through the wedge collector.

The water is stratified and this behaviour is useful for finding the best locations for the inlet and outlet flow connections. The best location for the water inlet in the bottom of collector and the best location of the outlet of the warm water in the top of the collector. The Fluent predictions show that the stratified behaviour diminishes with increasing volume as shown in Fig.11-B-. A larger volume means the water capacity increases, and hence the storage water temperatures at the end of day decreases and vice versa.

4.3. Velocity Distribution

The three-dimensional simulation renders more information about the convection motion of water inside the collector and allows visualization of particle tracks. The tracks are coloured by the magnitude of the speed as shown in Figs.12 and 13. Absorbed solar irradiation generates natural heat transfer over the body of the water with a producing variation in the water density. The buoyancy influence causes natural flow of the water relative to the inside collector walls. The phenomenon is uninterrupted so long as there is a solar radiation influx. Particles in contact with the hot inclined front surface rise under the effect of buoyancy forces follow the path A (Fig.12) towards the top and then turn down to the back side of the collector as indicted by path B (Fig.13). The fluid was moving to the right near the back of the collector. This figure shows the particles circulating helically inside the collector to make two closed tornado motions that diminish the stratification in the collector.

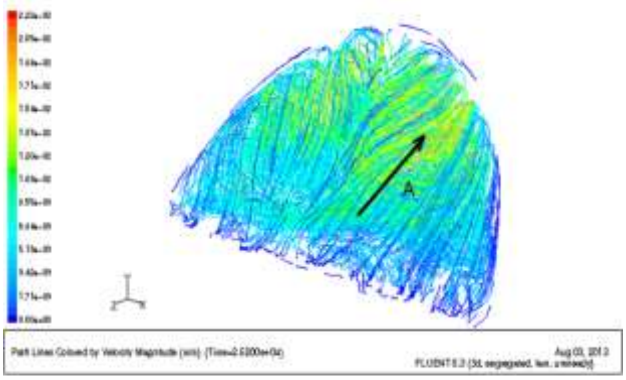


Fig. 12. Particle path lines in the front of the wedge collector

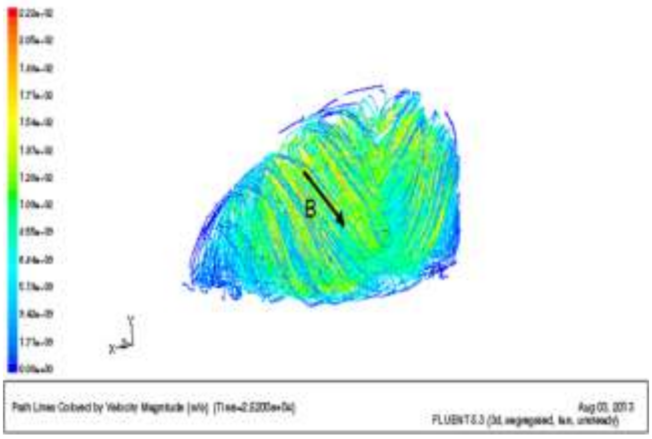
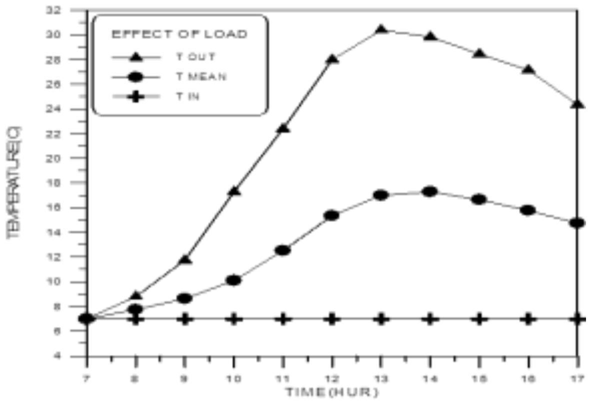


Fig. 13. Particle path lines in the back of the wedge collector.

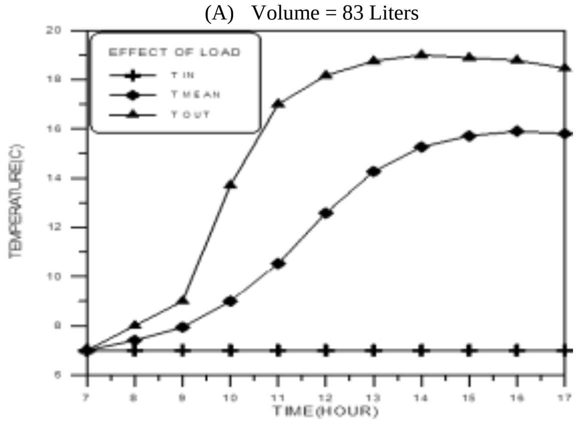
4.4. Effect of Loading

In order to show the effect of loading conditions on the system performance, some cases were carried out using Fluent software with hot water withdrawal from the collector during the operating period. The hot water withdrawn was taken continuously. This was done by permitting cold mains water to enter the collector at its bottom, and the hot water was withdrawn from the top of the collector. Fig. 14-A- shows the variation of system temperatures for a clear winter day with continuous load condition and the volume of the collector was 83 litres. The mass flow rate was 0.2 litre/ min. The outlet temperature reaches the maximum value of 30 ºC at 2 p.m. The temperature difference between the outlet and inlet temperature is 14 ºC at 2 p.m. and 10 ºC at the end of the day. This is because the net energy absorbed becomes just lower than the heat losses, which means that the useful energy transferred to the water is insufficient to cause any further increase in the mean storage temperature.

Fig. 14 -B- depicts the hourly variation of the system temperatures of the collectors that its volume equal to 666 litres. It is noted that the outlet temperature from the collector starts to increase from the beginning until nearly the end of the operating period. Towards the end of the operating period the outlet temperature of the collector reaches its maximum value of 19 ºC and then slightly decreases. Also, it is noted, that the temperature difference between the inlet and outlet water temperatures of the collector was about 3 ºC at the end of the day.



(A) Volume = 83 Liters



(B) Volume = 666 Liters

Fig. 14. Variation of system temperatures of wedge collector with continuous load at 0.2 litres/min.

4.5. Effect of the Internal Partition

It was suggested to investigate the effect of presence an interior barrier inside the collector to prevention water circulation and study its influence on the distribution of temperature and collector performance. This was done by using an internal partition as shown in Fig. 15. The volume of the collector was 666 litres which sufficient for Iraqi family utilization and the distance between the partition and the base of the collector was 50 cm. Results show there is no obvious influence of the barrier on the mean storage temperature.

Fig.16 shows the effect of the barrier on the maximum temperature at the upper part of the collector. As before, the ultimate temperature occurs at 2 p.m. and tapers off at the end of the operation period. The ultimate temperature is 38 °C comparable with the no partition case which reached 34 °C. The barrier prevents the direct contact between warm and cold water, this conclusion is beneficial for locating the inlet cold water inlet and the warm water outlet. As well the stratification in the collector was not disturbed by the existence of the adiabatic partition as shown in Fig.17.

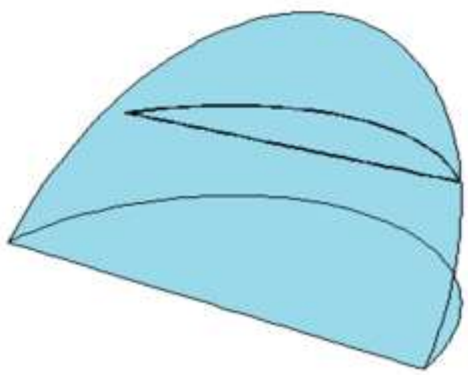


Fig. 15. Location of the partition on the collector

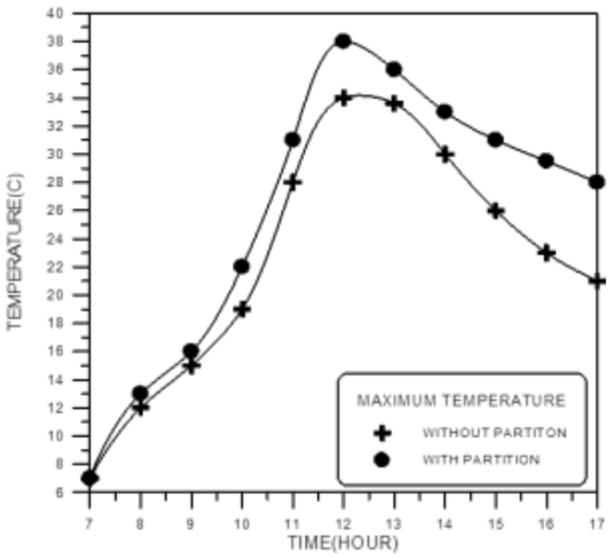


Fig.16. Influence of the barrier on the maximum temperature of the storage collector.

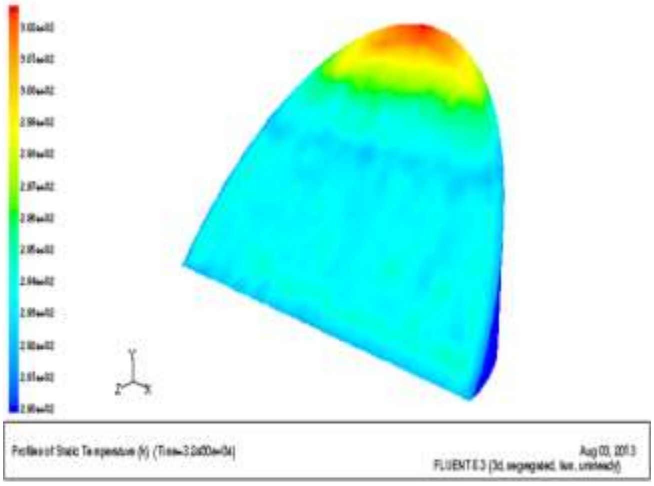


Fig. 17. Temperature distribution inside collector with the presence of a partition.

5. Conclusions and Recommendations

A new design of storage solar collector has been presented to prove its convenience for household use. The design has been validated by using Fluent Program. From the results offered, the essential consequences can be observed.

The behaviour of performance parameters in the wedge solar collector is similar to conventional solar water heaters with and without load conditions. The ratio of sunlit area to storage volume is the important factor for the performance of storage solar collector.

The position of a horizontal barrier within the wedge storage collector doesn't enhance the performance of the new design. Also, the stratification occurs in the wedge storage collector and this stratification behaviour diminishes with increasing volume. For the same ratio of sunlit area to the storage volume, the wedge collector is more efficient than other design.

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