Experimental Study of a Rectangular Storage Solar Collector with a numerical analysis

Omer K. Ahmed¹, Raid W. Daoud², Omer T. Mahmood³
¹Technical college/Kirkuk, Northern Technical University, Kirkuk, Iraq
²Technical Institute/Hawija, Northern Technical University, Kirkuk, Iraq
³Technical Institute/Mosul, Northern Technical University, Mosul, Iraq
E-mail omerkalil@yahoo.com (Omer K. Ahmed)

Abstract. In this article, a practical and numerical assessment was accomplished on a rectangular storage collector to be used for household purposes. This design can be utilized as a water reservoir to substitute the classical reservoirs generally utilized in Iraq to achieve two goals are heating and storing water together. The experiment shows that the maximum temperature rise through this collector was about 10.5 oC at 3 p.m. An experiment with a continuous flow of working fluid was also conducted. Experiment results show that the outlet water temperature of 28 oC is reached about 1 p.m. and diminished after this time. Performance results showed that the ratio of sunlit area to storage volume is an important parameter affecting the performance of this design of integrated solar collector. This ratio should be more than 12 to provide a suitable amount of warm water in the winter season. The performance of the rectangular storage collector was, broadly, identical to the performance of the classical solar heaters. The free convection phenomenon in the enclosure of the rectangular collector was investigated by using the Fluent program. There is a good correlation between the Fluent data and the experimental results obtained from the experiments.

1. Introduction
The demand for hot water has increased recently for many applications and the solar energy can be utilized effectively, with efficiency and economy for this purpose[1]. Solar water heaters generally consist of a collector and a storage tank. The solar water heaters are the most widely used equipment in the world and there are several million in use around the world. The main components of solar systems used for water heating can be classified in two common models[2]: First; the thermosyphon system, where the storage tank was positioned above the collector, and working fluid flows by free convection due to density difference. The second type of solar heating system, which is a forced circulation system. Pumps are used to circulate the fluid inside the system. This pump which is controlled by a special sensors.

In the storage collector, the collector and the storage tank are integrated into a compact unit, is a likable choice to the ordinary solar water heating system[3][4]. The removal of the storage tank reduces the cost of the solar systems used for water heating and and increases their efficiency[5]. Experimental and theoretical investigations on such systems have been carried out by a number of investigators. The first design of the storage solar collector was designed by Tanishita[6]. Sodha et al.[7] gave an improved method of a storage solar collector. Chinnappa and Gnanalingam[8] studied the performance of a pressurized solar water heater of a combined collector and storage.

Garg[8] suggested a new design of solar water collector. This storage solar water heater of 90 liters capacity was made of a (112*80*10) cm rectangular tank. K. A. Joudi et al.[9] suggested a new idea of a integrated solar collector for domestic hot water supply. It is designed in such a way that works as a
solar heater and water storage tank at the same time. Joudi et al.[10] studied experimentally the performance of a triangular storage collector. This design can be used instead of the classical solar collector. An experimental and computational study was presented on a cylindrical storage collector by Ahmed[3]. This design was inspired by cutting the cylinder at an angle of 45°. Ahmed[11] presented a computational study for a novel system of an integrated storage solar system to confirm its convenience for domestic applications. This new design was named the wedge storage water collector[12].

The previous literature survey shows that numerous works have been carried out on solar water heaters. These systems are generally either natural or forced convection types with water circulation. In this paper, a novel system of storage solar collector for hot water application is investigated. This design idea was awarded an Iraqi patent[13]. The design is used for two purposes: water storage and heating at the same time. The advantages of this design are simplicity in design because all solar heater parts are integrated into one part and do not need a lot of space for the installation.

The new design also features a low manufacturing cost. This study deals with three-dimensional model filled with water as in Figure 1, which represent the models of this study. The inclined wall is subjected to the solar radiation. While the other walls were assumed insulated. The main objectives of this paper are developing and assessing a low cost, credible, and high efficiency solar heater for domestic uses and evaluating the system performance under variable load and no load conditions and comparing the performance of this new systems with the conventional solar water heating systems[14].

![Figure 1. Rectangular storage collector](image)

2. Methodology

The objective of this article is to assess the performance of rectangular solar storage collector under the Iraqi environment.

3. Experimental set-up

An experimental set-up was manufactured to study the performance of this design. The volume of this collector is 285.893 litres and the front inclined area is 0.974 m² as shown in Figure (2a). The height of the rectangular collector is 0.83 m. 1.5 mm metal plates were used for the manufacture of this design. The front inclined surface was painted with a black paint to increase its absorption of solar radiation. The tank was connected with an inlet cold water pipe at the bottom, whereas the hot water was taken from the top of the tank. Ordinary window glass of 4 mm thickness was utilized as the top transparent cover for the tilted surface facing the sun. The distance between the absorber plate and the bottom surface...
of the glass was kept at 45 mm[11]. According to this study, such a distance was supposed to provide a good insulating gap for the conduction-convection heat transfer from the hot absorber plate to the cooler glass cover. The glass cover edges were sealed to prevent the leakage of the hot air from the gap between the inclined absorbing surface and the glass cover. The refractive index and extinction coefficient of window glass were taken as 1.526 m$^{-1}$ and 0.02 mm$^{-1}$ [15]. The sides and bottoms of the design were insulated with corkboard of 50 mm thickness, which rendered a total coefficient of the heat transfer was 0.8 W/m$^2$.oC[16].

(a) A photographic view of experimental set-up  (b) The position of thermistors

Figure 2. Rectangular storage collector.

The rectangular tank and insulation were placed in a wooden container that rises 30 cm from the ground. The system was oriented southward to gain the largest amount of solar radiation. The irradiated face was inclined at 45o. This inclination is nearly 10o above, the local latitude of 35.33 oN for Kirkuk, where the experimental tests were carried out, to provide a mean maximum collection of solar energy incident on the collector during the winter months[17]. Temperature is an important criterion of the heat gain obtained from the integrated solar storage collector, which determines the efficiency of the system. Therefore, arrays of thermistors were used to determine the temperature distribution within the body of the storage water in these systems. The system interior was also instrumented with 10 thermistors
incorporated into five vertical probes distributed along the centerline of the rectangular collector as can be seen in section C-C of Fig. 2-b. The location of each thermistor is given in table 1. Two thermal sensors were used to measure the temperature of the inlet and outlet water from the storage tank. Two additional sensors were utilized to measure the temperature of the inclined black surface and one thermistor to enable glass temperature determination. All the thermistors that used in the experimental set-up were connected to a typical selector switch to sense the temperature of the different points in the collector and the output of the selector switch was connected to a multimeter type FUKE DT 9205.

| Number | X (m) | Y (m) | Z (m) | Number | X (m) | Y (m) | Z (m) |
|--------|-------|-------|-------|--------|-------|-------|-------|
| 1      | 0.78  | 0     | 0     | 6      | 0.27  | 0.40  | 0     |
| 2      | 0.62  | 0.13  | 0     | 7      | 0.14  | 0.33  | 0     |
| 3      | 0.47  | 0.14  | 0     | 8      | 0.14  | 0.63  | 0     |
| 4      | 0.47  | 0.3   | 0     | 9      | 0.04  | 0.48  | 0     |
| 5      | 0.27  | 0.22  | 0     | 10     | 0.04  | 0.8   | 0     |

Calibration of the thermistor was carried out by gradual changing the temperature and recording the corresponding resistance change. Calibration of thermistor was carried out against a ordinary mercury thermometer and the variation in thermistor resistance was recorded by a digital multi-meter. The accuracy of the digital multi-meter was stated by the manufactured to be ± 0.8 %. Data obtained regarding the temperature variation and the corresponding resistance is shown in Figure 3. the maximum error of the temperature measurements was ± 1 oC. The equation of the calibration curve was:

\[
T = 84.521 e^{-0.24068 R}
\]  

The solar radiation incident on the collector surface was estimated analytically because a solar meter for this purpose was unavailable at the test site in the present time. A computer program was modified to calculate the hourly incident solar radiation.

The heat loss from the front area of the rectangular collector is of obvious importance in the calculation of the performance for solar systems. Some of the absorbed energy is lost to the ambient atmosphere by radiation and convection upward through the glass cover. The heat transfer from the inclined absorber surface to the glass cover is[2]:

![Figure 3. The calibration curve of the thermistors](image-url)
\[ Q_{p-g} = h_{p-g} \cdot A_f \cdot (T_p - T_g) + \sigma \cdot A_f \cdot \frac{T_p^4 - T_g^4}{\varepsilon_g + 1 - 1} \]  
where \( h_{p-g} \) is the convection heat transfer coefficient between two inclined parallel surfaces which calculated from the Nusselt number, the relationship that used for the Nusselt number between two rectangular plates\[18\]:

\[ Nu = 1 + 1.44 \left( 1 - \frac{1708}{Ra \cos \beta} \right)^{\frac{1}{4}} \left( 1 - \frac{\sin(1.8 \beta)}{Ra \cos \beta} \right)^{\frac{1}{4}} + \left( \frac{Ra \cos \beta}{5830} \right)^{1/3} - 1 \]  

Where, the symbol (+) refers to that only positive value of the terms are used (if the term is negative, it is equal to zero in this case).

The useful energy output of a rectangular collector for no-load condition can be evaluated from the relation\[19\]:

\[ q_u = m \cdot c_w \cdot (T_{mf} - T_{in}) \]  
The heat gain by the storage collector with load conditions was evaluated from the relation\[20\]:

\[ q_u = m \cdot c_w \cdot (T_{mf} - T_{in}) + m \cdot c_w \cdot (\bar{T}_{out} - \bar{T}_{in}) \]  

At the beginning of each experiments the tank was filled with clear water, remove the dirt and dust from the glass cover and temperature sensors were examined and the collector faced south. The measuring devices were switched on. Each experiment begins at sunrise and ends in the evening for the day of testing. The experiment readings were recorded at the end of each hour included the different temperatures inside collector, glass cover, inclined surface and the collector inlet and outlet as well as the flow rate of the withdrawn hot water during the experiments. The experiment run was repeated with and without for each load pattern. The load was connected to the storage tank in such a way that the cold inlet water entered at the bottom of the tank and the hot water outlet was taken from the top of the tank. The amount of water flowing can be controlled by a valve at the inlet of the tank. The amount of water flowing was measured by calculating the amount of water collected in a graduated cylinder of 1 liters capacity over a period of time.

4. Numerical analysis

Heat transfer in three-dimensional closed spaces is a difficult type of analysis because the flow is three-dimensional. Therefore, the two-dimensional analysis frequently invoked for numerical studies cannot release all the important facts of these phenomena. Three-dimensional analysis is a complex task because the non-linear momentum equations must be solved in addition to the mass and energy equations. FLUENT is a famous computer program for modeling thermal science in complex geometries. GAMBIT program was used for building the grid as shown in Figure 4.

The body-force-weighted scheme is preferred to be used for solving the high Rayleigh number phenomena. Therefore, it is used to discretize the term of the pressure. Pressure-velocity coupling was implemented using the (PISO) scheme (Pressure-Implicit with Splitting of Operator scheme). PISO is proposed for unsteady flow problems[21]. Under-relaxation factors are used in order to avoid the disturbing changes of variable values between sequential iterations and avoiding divergence of the solutions. During the solving of the equations, the optimum values for the under-relaxation factors selected are approximately 0.7 for momentum, 0.8 for energy, 0.3 for pressure, and 0.8 for enstity[22].
5. Results and discussions
The main purpose of a storage solar collector is to take advantage of solar radiation and convert it into heat gain, which is stored in the water. The experiments were carried out at the technical college at Kirkuk (35.33 N latitude) on selected typical sunny days in March, July, November, and December. At the beginning of each experiment the experimental model is filled with water and the glass cover was thoroughly cleaned from the dust and dirt. The required measurements (temperature and flow rate of water) are recorded at the end of each hour of the test period. In this section, the results are presented for this design for different cases.

5.1. Parametric storage temperatures
The mean storage temperature is an important factor to evaluate the system performance. It was calculated as[23]:

$$T_{mean} = \frac{\sum_{i=1}^{n} M_i \cdot T_i}{M_{total}}$$

The water temperature change during the winter day was illustrated in Figure 5. As it is evident from this figure, the collector can heat the water up to 23 oC, when the inlet water temperature was 12 oC. The experiment shows that the maximum temperature rise through this collector was about 10.5 oC at 3 p.m. The same temperature difference (which was 11 oC) was shown in the study of Alawi[24] for a winter day in February. The principle difference between this study and that of Alawi is the behaviour of temperature variation through the day. In this study, the mean water temperature reaches its maximum value and then decreases after 3 p.m. whereas it increased continuously with time until the end of the day in the study of [24][9]. The confidence between numerical predictions and experimental result is good before 3 p.m. Also, it noted that the mean storage temperature reaches its ultimate value and then decreases after 3 p.m. This is because the absorbed solar energy becomes just lower than the heat losses.
Figure 5. Variation of mean water temperature of a rectangular collector in a winter day

Figure 6 shows a three-dimensional distribution of water temperature at 2 p.m. on a winter day. The water is stratified. The same result was obtained by [9] using ANSYS software as in Figure 7. In order to check the validity of these results, a FORTRAN program was built according to the vorticity-stream function method for this purpose. The results showed the water is stratified as shown in Figure 8.

Figure 6. The temperature distribution in the rectangular collector at 2 p.m. in a winter
**Figure 7.** The water temperature (K) of the rectangular collector at 2 p.m. in winter according to [9].

**Figure 8.** The temperature distribution of a rectangular collector at 2 p.m. according to the two-dimensional computational programme.

### 5.2. Description of fluid movement

Figure 9 shows the visualization of liquid particles movement inside the collector. The figure shows the full three-dimensionality of liquid flow especially in the top of the new design because of the high value of Ralyeigh number in this shape. In comparison with Figure 10, which represents the result of [9], dissimilarity in the behavior of particle motion is observed. The particle motion is laminar in the results of [9]; while in this study it is turbulent as shown in Figures 9 and 11. The condition that determines the type of the flow (laminar or turbulent) is the Ralyeigh number. Most of the researches consider a Ralyeigh number less than 108 to indicate a laminar flow. The Ralyeigh number in this study was more than 108.
Figure 9. Movement of liquid particles (m/s) show full three-dimensionality of the flow at 2 p.m.

Figure 10. Fluid velocity (m/s) of the rectangular model at 2 p.m. according to [9].

Figure 12 shows a streamlines of particles when the height of the collector was taken as 10 cm, which means the Raleigh number is about 104. This behavior is similar to that found in study of [24] [9].
5.3. Effect of the rate of withdrawn water:
An experiment with a continuous flow of fluid (water) from the rectangular collector was achieved. Practical results for this case with the volume flow rate of 12 litres/h performed in January is shown in Figure 13, this figure shows that the outlet water temperature of 28 oC was reached at 1 p.m. and decreased after this time.
5.4. Comparison between various shapes:
The influence of the design of solar storage collector on its performance was studied numerically by supplying the same solar heat flux to the front area of three shapes of storage solar collector (rectangular, triangular, and cylindrical collector)[10][3]. Figure 14 clarifies the behavior of the mean temperature for various designs of the present new designs. The size of the three designs is equal to the size of 41 litres. The maximum temperature was shared for the triangular collector with a front area to storage volume ratio of 8.48 m²/m³. The lowest temperature was for the cylindrical collector with the front area to the storage volume ratio of 5.67 m²/m³. Therefore, the area density is the main factor in the design of these solar storage systems. Figure 15 shows a comparison in the performance between the triangular collector and a thermosyphon system by [25] for the same area density of $A_f/V = 12$ m²/m³. This figure shows that the present design is efficient and slightly better than the classical system for the same area density.

Figure 13. Variation of system temperatures of the rectangular collector in a winter day with a continuous load.

Figure 14. Change of mean water temperature for three designs of integrated storage collectors.
6. Conclusions and recommendations:
The results presented in the preceding paragraphs have shown the following conclusions:
1. There is a good agreement between the results of the fluent program and the experimental data obtained from the experiments.
2. The ratio of sunlight area to storage volume is the important factor for the performance of storage solar collector and this ratio must be more than 12 for domestic uses.
3. Stratification exists in the new solar collectors investigated at all conditions.
4. The results indicated that the water withdrawal should be from the top of the collector (hot region). Also, these results verify the inlet flow to the system must be at the coldest region, in the bottom of the tank.

Nomenclatures

| Symbol | Description                                      | Units     |
|--------|--------------------------------------------------|-----------|
| $A$    | The collector height                             | m         |
| $A_f$  | An irradiated inclined surface                   | m$^2$     |
| $c_w$  | Water specific heat                              | J/kg.K    |
| $m$    | Water mass in the tank                           | kg        |
| $\dot{m}$ | Water mass flow rate                           | kg/s     |
| $M_{total}$ | Mass of water in the collector                   | kg        |
| $M_i$  | Mass of specified layer                          | kg        |
| $Nu$   | Nusselt number                                    | -         |
| $q_u$  | Useful Heat                                      | W/m$^2$   |
| $R$    | Resistance                                       | Ω         |
| $Ra$   | Rayleigh number (Gr.Pr)                          | -         |
| $t$    | Time                                             | s         |
| $T$    | Temperature                                      | °C        |
| $T_i$  | Temperature of specified layer                   | °C        |
| $T_p$  | Temperature of the absorber plate                | °C        |
| $T_g$  | Temperature of the glass cover                   | °C        |
| $T_{mean}$ | A mean water temperature inside tank         | °C        |
| Symbol | Description                                      | Unit |
|--------|-------------------------------------------------|------|
| $T_{in}$ | A mean water temperature inside tank at end hour (without load) | °C   |
| $T_{wo}$ | A mean water temperature inside tank at beginning of hour (without load) | °C   |
| $\bar{T}_{outL}$ | Outlet water temperature from the system | °C   |
| $\bar{T}_{inL}$ | Inlet water temperature from the system | °C   |
| $\varepsilon_p$ | An emissivity of the absorber plate | -    |
| $\varepsilon_g$ | An emissivity of the glass cover | -    |
| $\beta$ | The angle of the absorber plate | 45°   |
| $\sigma$ | Stefan – Boltzmann constant | -    |

References

[1] Rahman M M, Billah M M, Rahim N, Amin N, Saidur R and Hasanuzzaman M 2011 A numerical model for the simulation of double-diffusive natural convection in a triangular solar collector Int J Renew Energy Res 1 50–54.
[2] Duffie J A and Beckman W A 2013 Solar Engineering of Thermal Processes, Fourth ed. John Wiley & Sons, Inc.
[3] Khalil A O 2017 Experimental and numerical investigation of cylindrical storage collector (case study) Case Stud Therm Eng 10 362–369.
[4] Ahmed O K 2018 A numerical and experimental investigation for a triangular storage collector Sol Energy 171 884–892.
[5] Nakoa K M A, Karim M R, Mahmood S L and Akhanda M A R Effect of Colored Absorbers on the Performance of a Built-In-Storage Type Solar Water Heater Int J Renew Energy Res 1 232–239.
[6] Tanishita I 1970 Present Situation of Commercial Solar Water Heaters in Japan in Melbourne International Solar Energy Society Conference.
[7] Sodha M S, Nayak J K, Kaushik S C, Sabberwal S P and Malik M A S 1979 Performance of a collector/storage solar water heater J energy Convers 19 41–47.
[8] Chinnappa J C and Gnanalingam K 1973 Performance at Colombo, Ceylon, of a pressurised solar water heater of the combined collector and storage type 15 195–204.
[9] Joudi K A, Hussein I A and Farhan A A 2004 Computational model for a prism shaped storage solar collector with a right triangular cross section Energy Convers Manag 45 391–409.
[10] Ahmed J K, Hussein I A and Ahmed O K 2014 An experimental study for a new design of a storage solar collector Al-Taqani 27 76–88.
[11] Ahmed O K 2018 Assessment of the Performance for a New Design of Storage Solar Collector Int J Renew energy Res 8 250–257.
[12] Ahmed O K and Daoud R W 2018 Determining the Coefficients of the Wedge Storage Solar Collector Based on Fuzzy Logic 7–12.
[13] Ahmed Joudi K 1990 Storage solar collector 2255.
[14] Kumar R and Rosen M A 2011 Integrated collector-storage solar water heater with extended storage unit Appl Therm Eng 31 348–354.
[15] Ahmed O K and Mohammed Z A 2017 Dust effect on the performance of the hybrid PV/Thermal collector Therm Sci Eng Prog.
[16] Ahmed O K, Hamada K I and Salih A M 2019 Enhancement of the performance of Photovoltaic / Trombe wall system using the porous medium: Experimental and theoretical study Energy 171 14–26.
[17] Shukla R, Sumathy K, Erickson P and Gong J 2013 Recent advances in the solar water heating systems: A review Renew Sustain Energy Rev 19 173–190.
[18] Ahmed O K and Bawa S W 2018 Reflective mirrors effect on the performance of the hybrid PV/thermal water collector Energy Sustain Dev 43 235–246.
[19] Ahmed O K 2016 Effect of Dust on the Performance of Solar Water Collectors in Iraq Int J Renew Energy Dev 5 65–72.
[20] Souliotis M, Chemisana D, Caouris Y G and Tripanagnostopoulos Y 2013 Experimental study of integrated collector storage solar water heaters *Renew Energy* 50 1083–1094.

[21] Teo H G, Lee P S and Hawlader M N A 2012 An active cooling system for photovoltaic modules *Appl Energy* 90 309–315.

[22] Mohammed F, Khalil O and Emad A 2018 Effect of climate and design parameters on the temperature distribution of a room *J Build Eng* 17 115–124.

[23] Gowda N, Gowda B P B and Chandrashekar R 2014 Investigation of Mathematical Modelling to Assess the Performance of Solar Flat Plate Collector *Int J Renew ENERGY Res* 4.

[24] Alawi W 2004 Numerical and experimental study of the solar collector storage pyramidal with right angle University of Technology.

[25] Hayan A and Ioudi K A 1984 An experimental investigation into the performance of a domestic thermosyphon *Energy Convers Manag* 24 205–214.