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Experimental Investigation of Thermal Performance for Novel Integrated Collector Storage

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ABSTRACT

To lower the expenses of manufacturing traditional solar collectors and perfect use of water tanks in developing countries, a new design of integrated water heaters has been presented in a rhombus shape. This new design consists of a cube whose upper surface was cut into two directions at a 45^{o} angle. This system's initial expenses can be kept to a minimum by using inexpensive commercial materials and little manufacturing skills. In cases of thermal instability, the MUE curve is typically employed to calculate the maximum efficiency that the system can attain. The MUE curve, which saves time and computer approaches in calculations of this kind, is the basis for this study. This experiment was studied during November and March to compare the system behavior under different climate conditions. The study included three cases per month. The first case was without any load, which reached a maximum useful efficiency of 59% for both November and March. In the case of continual loading, the system shows a maximum useful efficiency of 59% in March. When dealing with intermittent load, the maximum useful efficiency of 58% in March.

Nomenclature

A_c	The absorber's total area (m^2)
C_w	Specific heat for water (kJ/kg.^{o}C)
C_S	Specific heat of the storage (kJ/kg.^{o}C)
FPC	Flat Plate Collector
F_E	Enthalpy retrieval factor
F_R	Heat removable factor
ICS	Integrated collector storage
ICSSWH	Integrated collector storage solar water heater
I	Solar irradiance (W/m^2)
$\bar{I}$	Mean solar irradiance (W/m^2)
$\bar{k}$	The incidence angle modifier
m_w	Water mass (kg)
m_S	Storage mass (kg)
MC	The water within the reservoir effective heat capacity (W)
MUE	Maximum useful efficiency
MST	Mean storage temperature
SWH	Solar water heater
STC	Solar thermal collector
U_c	Overall heat loss coefficient (W/m^2.^{O}C)
U_L	Overall heat loss coefficient (W/m^2.^{O}C)
T_a	Ambient temperature (^{o}C)
UE	Useful energy (W)
T_{in}	Input temperature (^{o}C)
T_{max}	The maximum temperature at storage's tip (^{o}C)
$T_{f,in}$	Inlet fluid temperature (^{o}C)
$\bar{T}$	The mean temperature (^{o}C)
Δt	Period time of calculations (sec)
α_s	Absorptance of the absorber plate
θ	Incidence angle (degree)
$\grave{\mu}$	Maximum useful efficiency
τ_s	Transmittance of the glass cover
η_o	Optical efficiency of glass
η_C	Thermal efficiency

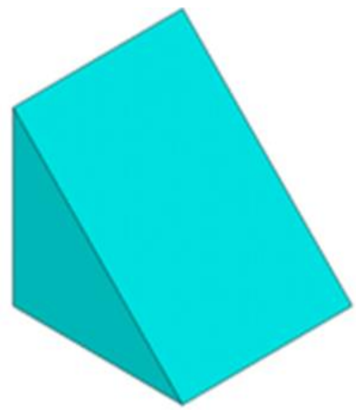
1- Introduction

Presently, conventional heaters employ electricity as the main energy source to heat water, which is the predominant energy form utilized in residential settings. [1]. Since the onset of the 21st century, there has been a rapid increase in both the global population and industrial activity, resulting in a greater need for fossil fuels, particularly oil and coal. As a result, this has led to a significant increase in costs and a significant rise in worldwide pollution levels [2]. Consequently, researchers have focused on creating alternative energy sources that are derived from renewable sources [3]. Solar energy takes up a significant amount of governments' plans for its utilization [4]. There are several different solar energy methods available, including solar collectors, photovoltaic cells [5], solar stills [6], solar air heaters [7], etc.. Solar thermal collectors (STCs) are one of the most popular and commonly utilized solar energy devices worldwide [8]. Traditional STCs mainly consist of absorber, tank, and pipes [8].

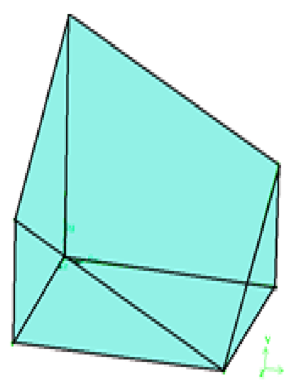
The primary deterrent to the adoption of solar collectors, particularly in low-income countries, is the high initial cost [9]. As a result, this resistance must be solved by inventing a new solar water heater (SWH) with less expense and a more efficient system [10]. As known the efficiency is highly connected and affected by the thermal losses that occur in these systems, the main part which is responsible of these losses is the connecting pipes between the absorber and the storage. Integrating the storage and the absorber to form a single unit will lead to a new system with higher efficiency and less initial costs, which is called an integrated storage collector (ICS) [11]. In developing nations such as Iraq, residential properties commonly feature water storage tanks, which are either in the shape of a cube or a cylinder, to store water when there is a limited supply. Some houses may have many tanks to store water for longer durations. Dr. K. A. Joudi presented the Iraqi patent for a new design for ICS [12].

This innovative design doubles as a SWH and storage in addition to replacing the common water tank seen in Iraqi homes. Three designs can be obtained by cutting a cubic tank in different directions, as shown in Figure 1. The primary objective of these systems is to enhance efficiency and decrease initial costs. Al-Joudi stated that this could be done by removing the pipelines that connect the storage with the absorber [12]. By removing the connecting tubes, which are responsible for the bulk of energy loss, the system can become more efficient than the normal flat plate collector (FPC), resulting in an increase in usable energy[13].

(a) Triangular collector



(b) Rectangular collector



(c) Rhombus collector

Fig. (1) The ICSs proposed by K. A. AL-Joudi [12].

Multiple iterations of ICS have been thoroughly examined. R. Kumar and Rosen [14] conducted an empirical evaluation, and the findings showed that 53.7% was the maximal thermal performance. Al-Hashimi & Al-Asadi [15] experimentally evaluated two unique ICS designs. The first design, which is known as design (A), measures (112×62×12) cm, whereas the other design, design (B), measures (112×27×12) cm. The results suggested that design (A) was more efficient than design (B). Ahmed et al. [16] introduced numerical and empirical investigations for an ICS, the findings indicated that the temperature differential was at its highest at 3:00 p.m., with a difference of 10.5 °C. Additionally, Jassim et al. [17] created an innovative design for an ICSSWH for household usage, At 4:00 p.m., the system attained its highest temperature of 47 °C.

To examine the performance and heat transfer processes associated with free convection. Fraissea et al. [18] developed a new system for ICS that combined computational and experimental methods. Thermal stratification may increase energy performance. Abed et al. [19] presented a numerical study double-glazed the conventional rectangular ICS for studying the effect of loading on the performance of the ICS, the results found that the system gave better performance at loading conditions. Çomakli et al. [20] studied the effect of storage volume on the performance of the ICS.

The study indicates that expanding the storage capacity in domestic heating systems may not enhance heating efficiency, but instead might lead to expensive, excessive utilization of space, and potentially unwieldy systems. Anderson et al. [21] presented empirical testing and creation of an inactive ICSSHW. The inspection of an ICSSWH for desert construction in Algeria was offered by Harmim et al. [22] This revealed that on a typical daily efficiency fell between 36.4% and 51.6%. Ahmed [23] recommended an innovative ICS design, calling it the triangle ICS. Under no-load conditions, the system's efficiency was found to be 48.7% overall with a maximal MST of 40.5 °C. Varghese et al. [24] compared the economic viability of two SWH system models. With an annual solar percentage of 0.55, the proposed approach has a reduced economic cost.

In this study, a new design of ICS was designed which is called the rhombus ICS. This new design is used for domestic purposes. This ICS is similar to the traditional tanks used in Iraqi homes which can be formed by cutting the upper part at a 45° as tilt angle in two directions as shown in Figure 2.

Previous studies have shown that the maximum tilt angle that can be used to obtain the highest system performance should be 10 to 15 degrees greater than the winter latitude angle [25]. In Iraq, the latitude angles of Basra, Baghdad, and Mosul are 31°, 33°, and 36°, respectively. So, 45° as a tilt angle is the best angle to facilitate simple production. The ICS base and sides are well insulated with good materials, which will be discussed in the following paragraphs. As for the inclined surface (absorbent plate), it is exposed to solar radiation and painted black to increase absorbency and covered with glass.

The system consists of an absorber and a storage combined into one. As a result, this design outperforms traditional solar collector systems because it eliminates the tubes, which cause noticeable less heat losses in the system, resulting in better efficiency. Additionally, it requires little room for installation, and the collector's size may be altered to suit the needs [14].

Nowadays, most researchers are making improvements to the previous shapes of the absorber plate such as rectangular, triangular, etc., and there are no recent studies to go beyond these improvements and come up with a completely new design by changing the structure. Therefore, this study presents an experimental study for the design of an ICS with a rhombus-shaped absorber plate to compare the behavior of this novel design at the beginning of using hot water in November and the end of using it in March.

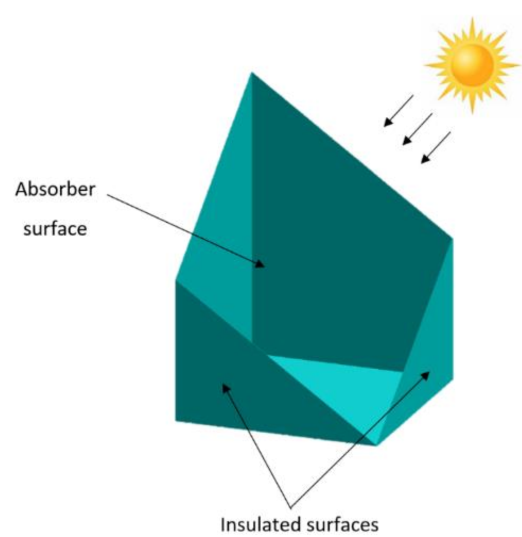


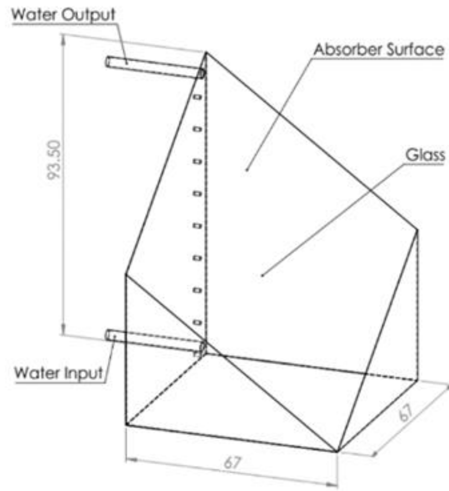
Fig.(2) The Rhombus ICS.

Any new SWH design must undergo a thorough analysis to ascertain if it is suitable for usage in a residential setting. This study aims to demonstrate the efficacy of the novel ICS design for residential usage by conducting an experimental evaluation of its performance. The experimental procedure will be described in section 2, the performance calculations will be shown in section 3, and the results will be shown and discussed in section 4, the conclusions will be reviewed in section 5. In the following sections.

2- Setup for experimentation

To prove the suitability of the recommended design for domestic usage, In Mosul, northern Iraq, an experimental site was established (36.35 °N, 43.15 °E). The rhombus storage was built from sheets of galvanized iron with 1.8 mm thickness. The height of the tank is 93.5 cm while the dimensions of the tank base are (67 × 67) cm. The sloped surface was 0.52 m^2 of absorbing area had and 210 L of overall volume. The inclined face was painted black. All other sides are insulated with a 5 cm Cork layer and a 2 cm wooden framework, as illustrated in Figure 4.

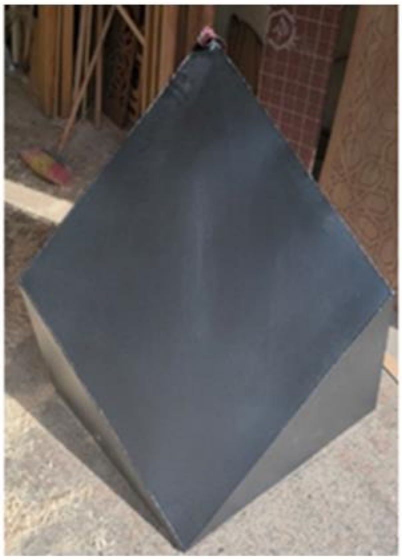
(a)



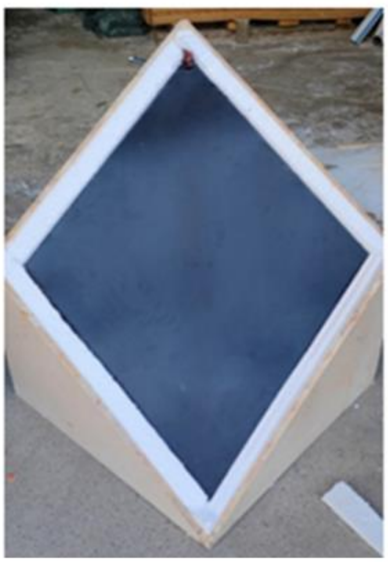
(b)

Fig.(3). (a) A photographic for the ICS and (b) A schematic of ICS.

A 1.5 cm diameter tube upper the bottom of the storage delivers cold water to the intended system; warm water is extracted from the top using the same way as for cold water. Two valves are used to control the water entering and leaving volume. The new ICS provided with a second tank of cold water. 4 mm thickness of glass sheet used as cover and positioned above the absorber by 4.6 cm. Transparent silicone material was used to seal the gaps during the installation of the glass to prevent air leakage that leads to noticeable losses affecting the performance of the system [25]. The ICS was also directed towards the south to increase the absorption of solar radiation in addition to increasing the time of exposure to solar radiation [27]. To test the practicality of the present design for multiple applications, the temperatures of the design suggested need to be monitored. The thermocouple positions are presented in Figure 5, Table 1, and Table 2. Every hour of the day saw the collection of the data.



(a)



(b)

Fig. (4) An image of the storage
(a) The black painting of storage, and
(b) The insulation with cork and wood.

Table 1. Thermocouple installation locations .

No.1	Location	Description
1	Inside the storage	Measuring storage temperature of water. The distance between each tow thermocouples is 9 cm.
2		
3		
4		
5		
6		
7		
8		
9		
10	Top of absorbent plate	To measure the temperature of the absorbent plate .
11	Middle of absorbent plate	
12	Bottom of absorbent plate	
13	The outside of the glass	To measure the temperature of the glass cover
14	Water inlet pipe	To measure the temperature of water inlet and outlet
15	Outlet water pipe	
16	Ambient	To measure temperature of ambient

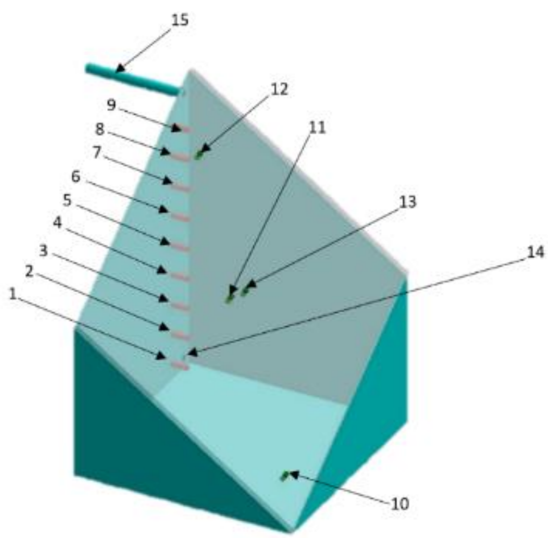


Fig.(5) The locations of thermocouples.

3- Performance Calculations

The Hottel-Whillier-Bliss equation has been used to characterize the performance of flat solar collectors. It states:

$$\eta_c = F_R \alpha_s \tau_s - \frac{[F_R U_c (T_{f,in} - T_a)]}{I_c} \quad (1)$$

As seen in Figure 6, this equation is linear. The revised design is integrated, with parts limited to absorber and storage in one structure. The techniques utilized in FPTs are not relevant to this research because of the large mass of thermal. This large mass cannot enable this system to establish steady-state conditions [28]. Therefore, the investigation will identify the maximum useful efficiency (MUE) reported by Faiman [29], which states:

$$\acute{\mu} = F_E \bar{K} \eta_o - F_E U_L \left(\frac{\bar{T} - T_a}{I}\right) \quad (2)$$

Where $\bar{K}$ is the average incidence angle modifier, F_E is the enthalpy retrieval factor, $\bar{T}$ is the average temperature η_o is the optical efficiency. These parameters can be calculated from the following equations:

$$F_E = \frac{m_w C_w}{MC} \quad (3)$$

Where MC is the water's and storage's effective heat capacity, can be found from

$$MC = m_w C_w + m_s C_s \quad (4)$$

$$\bar{K} = \cos\theta \,(1 + \sin\theta^3) \quad (5)$$

Where θ is the incidence angle.

$$\bar{T} = \frac{T_{max} + T_{in}}{2} \quad (6)$$

To find useful energy for these types of collectors:

$$q_{useful} = MC(T_{max} - T_{in}) \quad (7)$$

4- Results and Discussions

The ICS was studied and tested in Mosul, Iraq (36.35°N, 43.15°E). Three days were chosen during November and March for the study, as each day of the month represented a specific case. The first case was the case of pure load, where no water entered or exited during the entire experiment period. The second case was the case of partial load, where the owners of the house were considered employees who returned home at 2:00 p.m. and drew 50 liters of hot water. The third and final case was the case of continuous load, where 0.5 liters of water was applied per minute throughout the experiment.

The study days were carefully selected so that the wind speed was very low, so as not to affect the system's performance, as the wind speed on these days ranged between 2 to 5 m/sec. At seven o'clock in the morning, the device, especially the glass cover, is cleaned of dirt. Then the experiment begins at eight o'clock in the morning and continues until five o'clock in the evening. The readings are recorded at the beginning of each hour. The system faced to the south direction [27].

Solar radiation is the main parameter to understand and analyze to understand the behavior of the ICS and to calculate all parameters in the ICSs. As shown in Figure 7. There is a difference behavior of solar radiation between March and November. This can be referred to several parameters that affect solar radiation, mainly the day long, in November the sun starts to rise at about 6:45 a.m. while it is 6:00 a.m. in March also the sunset is different. The solar radiation in March will give more hot water at a more time than in November. The maximum solar radiation recorded in November and March was 1007 W/m^2 and 1100 W/m^2, respectively.

Due to the storage's significant thermal mass, achieving thermal dynamic stability [28] is not achievable. The conventional equations used to determine the thermal efficiency of FPC are not applicable. Equation 2 was used to calculate the efficiency for the three cases.

The efficiency of the storage collector is graphically represented as a function of the parameter $\left(\frac{\bar{T} - T_a}{I}\right)$.

The Y-intercept corresponds to the value of MUE, while the slope of the line indicates the correlation coefficient. U_L. These curves are unlike the other curves which put each day in a single line, the MUE gives the MUE that the system can achieve during the whole experiment for each case.

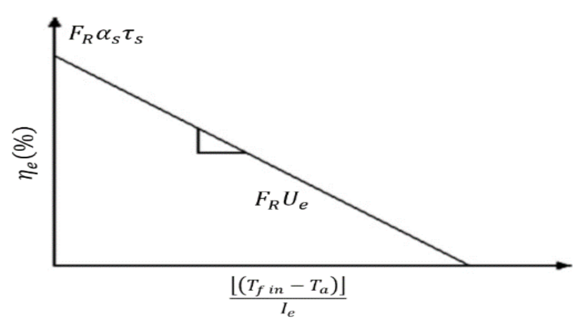


Fig.(6) Hottel-Whillier-Bliss equation.

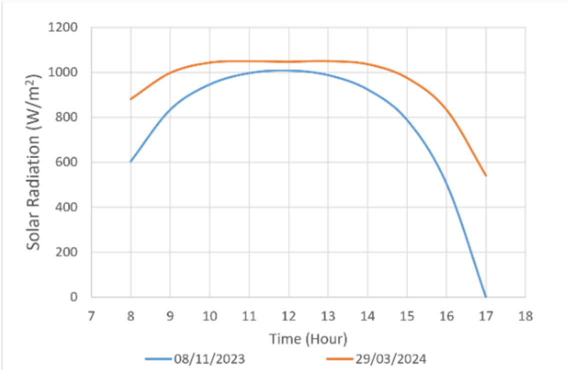


Fig. (7) Global solar radiation through time.

4.1. No-load case:

The usable energy (UE) of ICSSWH refers to the quantity of energy collected during sunrise that is effectively converted into heat for the purpose of water heating [25]. Equation 7 was used to determine the useful energy transferred.

Figure 8 displays the UE for the no-load case. November at 12:00 p.m. saw a maximum UE of 447.44 W. This is a result of the little heat loss with surrounding water caused by a good temperature differential between the input temperature at sunrise and the highest temperature of the water within storage. The maximum UE for March was 410.57 W.

As shown in Figure 9, the ICS achieved a MUE of 59% for both November and March, which prove the system. The MUE for both months was almost the same, this due to, as mention above, the instability of the system which gives the maximum efficiency for the whole day not like the traditional SWHs which give the efficacy for each hour through the day.

4.2. Load case:

To evaluate the functionality of any solar heating system, it is imperative to subject it to overload conditions. Two loading conditions were implemented in the present investigation: intermittent and Continuous loading.

The UE for the case of intermittent load is displayed in Figure 10. Before extracting water in November, 640.12 W of UE was recorded at 1:00 p.m. and 245.29 W after extracting; this decrease represents the mean temperature drop following the cold water feeding of the storage. Just before taking out water for March, around 1:00 p.m., the maximum UE of 628.68 W was recorded.

Figure 11 displays the UE for the continuous load condition. In this case, March was better where 477.44 W was recorded and 350.15 W was recorded in November. This refers to the ambient temperature which was less than in November so the inlet cold water was low; as known in Iraq March is colder than November; as a result, a higher temperature difference appeared between the inlet and outlet temperature.

In the case of intermittent load, as shown in Figure 12 the system achieved MUE of 58%. And finally for the case of continuous load, the system achieved A MUE of 59% as shown in Figure 13. The values above show that the device is highly efficient and almost stable in various weather conditions, as well as in load cases.

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Table 2 shows a comparison between the current study and previous studies. This comparison showed that this new design has higher efficiency and performance than its previous counterparts, as the new design recorded a maximum efficiency of 59%. This superiority over previous studies has several reasons, including the large surface area of the absorbent plate, which improves the area density, which is the ratio of the absorbent plate area to the tank volume is [30].

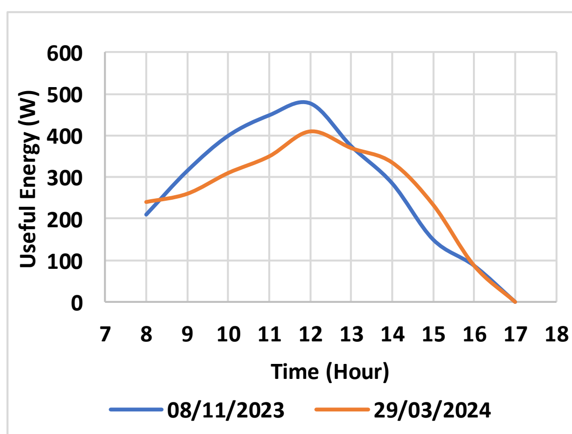

Fig.(8). The UE variation over the period of time in a no-load case.

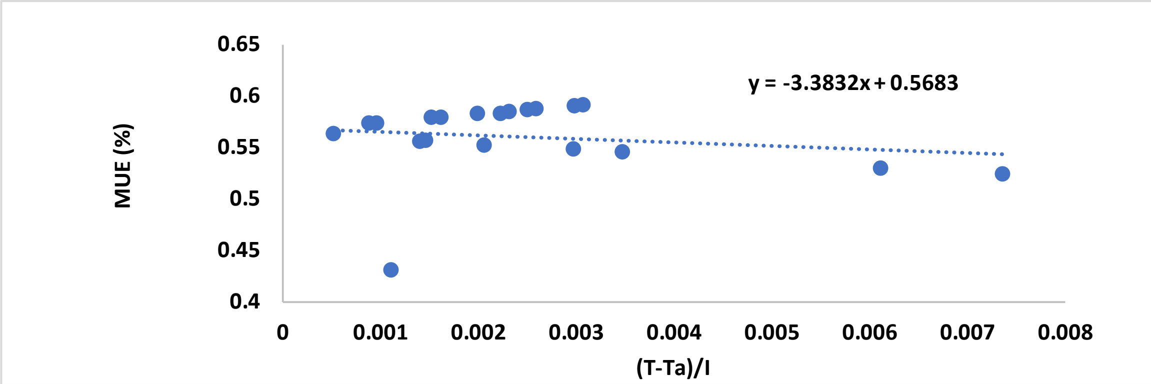

Fig.(9) The MUE variation in the case of no-load.

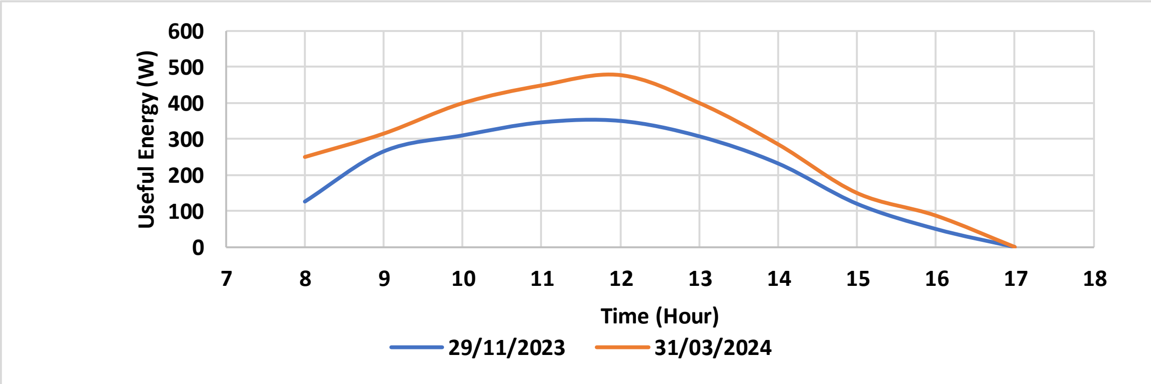

Fig.(10). The UE variation over the period of time in a continuous load.

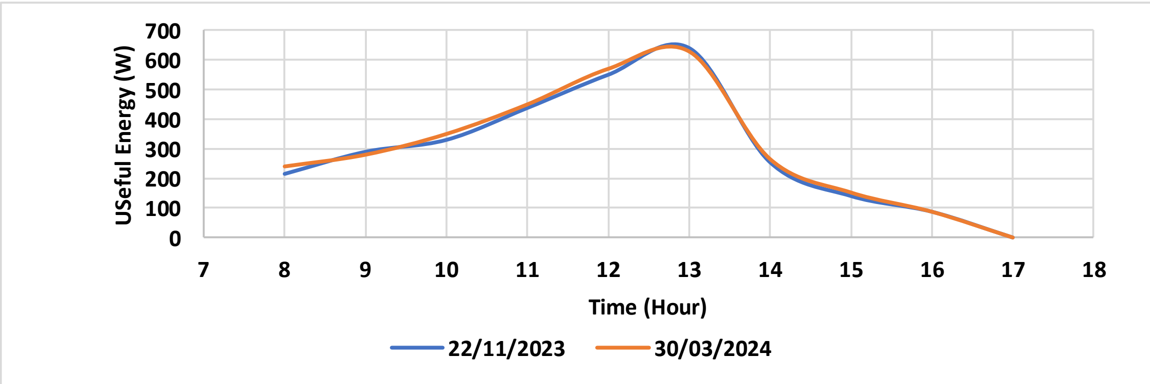

Fig.(11). The UE variation over the period of time in intermittent case

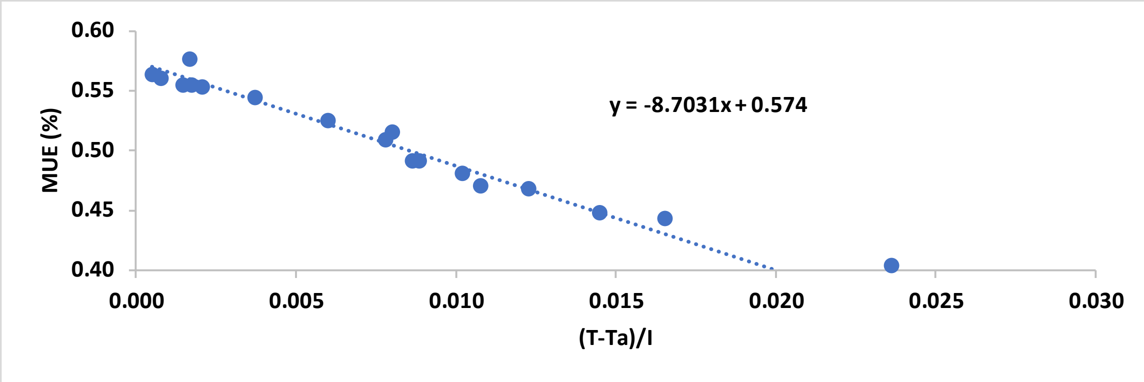

Fig.(12) The MUE variation in the case of intermittent load.

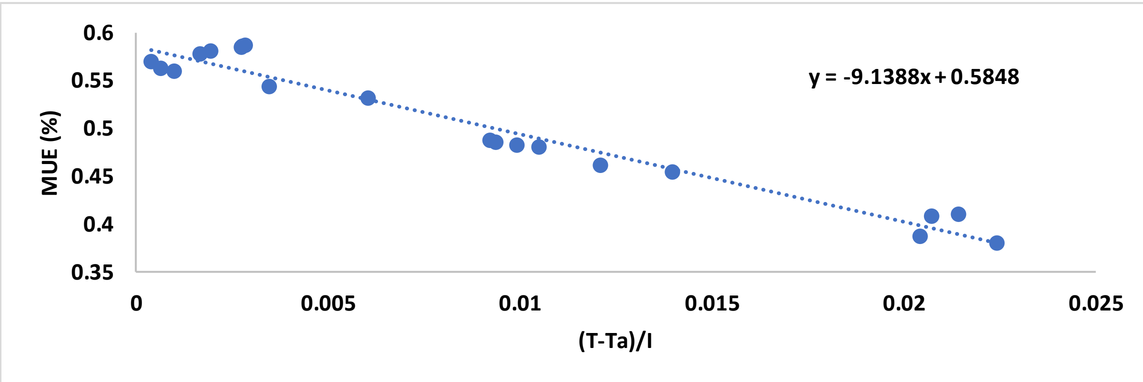

Fig. (13) The MUE fluctuation in case of continuous load

Table 2. Comparison between previous studies and the current study

Author	Effectiveness	Reference
R. Kumar & Rosen (2011)	53.7%	[14]
Varghese et al. (2017)	38%	[31]
Harmim et al. (2018)	51.6	[22]
Muhumuza et al. (2019)	52.2%	[32]
Kumar & Prakash (2022)	42.56	[33]
Current study (2024)	59%	

5- Uncertainty Analysis

The uncertainty of the instruments used is displayed in Table 3, and the degree of uncertainty in the outcomes is determined using the following equation. [34]:

$$\omega_R = \sqrt{\left(\frac{\partial \Phi}{\partial x_1} \times \Omega_1\right)^2 + \left(\frac{\partial \Phi}{\partial x_2} \times \Omega_2\right)^2 + \cdots\cdots + \left(\frac{\partial \Phi}{\partial x_n} \times \Omega_n\right)^2} \qquad 8$$

Table 3. Specification of instruments.

Instrument	Quantification	Error
Thermocouples	Temperature	±1 ^{o}C
Rotameter	Water flow rate	±2.5%
Seaward Solar	Solar radiation	±0.8 W/m^2

6- Conclusion

A novel ICSSWH design in a rhombus form is presented in this work. The system's performance was also explained in light of Iraq's climate conditions for the months of November and March. The system has shown excellent performance and has proven that it can replace traditional water tanks in Iraqi homes. This new system can be used as a solar heater in winter to provide hot water, in addition to being used as a cold water tank after covering the absorbent plate with a piece of white cloth in summer, which is very hot in Iraq. Thus, this design has solved two major problems in Iraq. Using the given results, one may draw the following conclusions:

- During the winter, a variety of factors, including weather, heat losses, intake temperature, and solar radiation intensity, can affect the performance of the ICS.
- The MUE curve achieves its maximum value when the MST becomes closer to the ambient temperature.
- A significant temperature differential between the highest temperature of the water in storage and the input temperature at sunrise can reduce heat loss and increase useful energy.
- The system achieved 59% of MUE during the whole experiment.
- The system proved to be very efficient during November and March.

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