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Experimental Study of the Performance of A Three-Dimensional Pyramid-Shaped Solar Water Heater In Different Conditions

Mojtaba Moravej[a,*], Farshad Ebrahimpour[b], Aydin Salimi asl[a]

[a]Department of Mechanical Engineering, Payame Noor University, Iran
[b]Department of Agriculture, Payame Noor University, Iran

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Abstract

One of the important and effective criteria in performance of solar collectors is the adsorption geometry. In this study, a three-dimensional and fixed solar collector with pyramid geometry and diagonal risers which is designed and built by the author, has been experimentally investigated in southern Iran. Studies included the effects of environmental factors such as changes in radiation, angles and temperatures over time. The thermal performance of the collector has been evaluated according to the ASHRAE standard. Experimental results showed that in addition to the proper stability of this geometry, the rate of return in the normal state and using water as the operating fluid is approximately 35.1% on average and the maximum return obtained was about 46.2%. In addition, in the experiment by using of CuO-Water nanofluid with a concentration of 0.1% in the collector, it was found that the collector efficiency increases about 6% compared to the use of ordinary water.

Keywords: Solar pyramid collector, CuO-water nanofluid, Experimental study, Efficiency

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1. Introduction

Solar energy is mainly used in the form of solar heat, photovoltaic and optical systems. In heating systems, solar collectors play a crucial role. Collectors are divided into fixed and movable. The solar flat plate collector is the most famous of these collectors. In these systems the installation angle with the ground is fixed therefore, they are called fixed collector [1,2].

Solar collectors are one of the most practical devices used in solar energy; the supply of hot water or heat transfer to other fluids is one of their main tasks. These collectors supply hot water, especially in domestic and residential applications, and their most important challenge is their low efficiency. So far, many methods have been used by researchers to increase the efficiency and performance of these collectors, which generally include changes in the geometry of the collector, the type of operating

*Corresponding Author Email Address: moravej60@pnu.ac.ir

fluid, the tubes containing the fluid and glass wall [3,4]. Moravej et al. [4] examined the three-dimensional and hemispherical collector without a riser. In their research, the collector was installed at an angle to the horizon and used water nanofluids and ordinary water. The results showed a good efficiency of this new and three-dimensional collector in values above 60%. Nogharabadi et al. [5] studied a three-dimensional collector with a conical geometry in which pipes containing the operating fluid installed from the bottom to the top of the collector. The coated glass wall was polygonal and tested in hot weather. Experiments performed for both ordinary water and SiO2-water nanofluids. Results showed an efficiency of about 60% for the collector and an output temperature above 77 ° C for the nanofluids.

Alawi et al. [6] used graphite nanofluid in a flat plate collector and tested it experimentally and theoretically in different conditions. The results showed that the efficiency increase is about 13% compared to ordinary water. They also presented a new relationship to determine the efficiency.

Alkalibi et al. [7] performed a comprehensive experimental analysis of flat and fixed solar panel collectors based on thermal efficiency and exergy of the collector and entropy generation and power consumption. They showed that all parameters are directly affected by solar radiation and with changes in function. It changes tangibly. Also, the maximum efficiency obtained in the case of nanofluid use mentioned to be approximately 70%. Kumar et al. [8] experimentally investigated the thermal performance of a flat plate collector. The fluid used was water and nanofluid (GGNP). Improvement of thermal performance in the collector reported by about 24% at 0.1 concentration and flow rate of 1.5 Lit/min compared to water. Aref et al. [9] designed and tested a new flat plate collector with a two-diameter arrangement of tubes containing the operating fluid. The results showed that their collector performance is better than conventional collectors and recorded efficiency of over 70%.

Akram et al. [10] conducted a detailed experimental study on a flat plate collector using carbon and metal nanofluids, including graphene, zinc oxide, and silicon oxide. In their studies, the energy and exergy performance of the collector was obtained according to the ASHRAE standard at different conditions. Variables such as thermal conductivity and heat transfer coefficient were studied separately theoretically and experimentally. The results showed that the increase in efficiency in the best condition was equal to 25.68% and also, the effect of increased flow on the rise in efficiency for graphene was more than 17%. Eidon et al. [12] conducted an interesting study for improving the efficiency of solar collectors using nanofluids of copper oxide and aluminum oxide acetone-based in the laboratory. The research was carried out in the HP-ETSC in the Middle East at different angles for the collector. Preliminary results showed that the suitable tip for the collector is 45 degrees. Using of this type of operating fluids and nanofluids increases the efficiency by about 15 to 38%.

Pandy and Caurasiya [13] evaluated the latest advances in flat panel solar collectors. In his research, criteria such as polymers, micro-mini-channels, nanofluids, adsorbents, phase change materials and other peripherals were investigated. They mentioned that the using of twisted tubes to produce turbulence flow for better heat transfer and propylene glycol as coolant were more effective. Ahmed [16] theoretically and experimentally studied a triangular collector of solar energy storage. In the research, he examined the collector tank temperature, velocity distribution, and stored energy. He found that the collector efficiency is about 48% and the maximum recorded temperature for the tank in winter is 65 degrees Celsius. That test was while its yield recorded at 62% in summer and the maximum temperature was around 70 degrees. Mishra et al. [17] conducted an interesting study on a solar integrated water heater. Three collectors of 10-liter built-in storage experimentally tested as a hybrid of electricity and solar. The experimental results showed that the use of plastic coatings reduces heat loss. Also, in the hybrid system, the solar energy reduces costs significantly compared to the electric system alone.

Zayed et al. [18] reviewed the factors affecting the increase in efficiency of solar flat panel collectors that work with nanofluids. The research included an extensive range of collectors that experimentally tested based on different nanofluids with different concentrations. Results showed that using copper oxide nanofluids have the highest efficiency of about 37% compared to others.

Sheikh et al. [19] conducted a comprehensive study on the applications of nanofluids in solar collectors. In this study, different types and models of solar collectors has been tested using of nanofluid as the base fluid. It was reported that the efficiency is increased depending on the type, concentration, operating fluid type, and other characteristics of nanofluid.

Shaykhelslami et al. [20] investigated the effect of turbulence flow simultaneously using a water-aluminum oxide nanofluid in a twisted strip in a flat plate collector. Results included a reduction in the production entropy and the Bejan's number by about 32 and 41%, respectively.

Sajadpour et al. [22] used ANSYS software to simulate the solar flat plate collector to estimate the exit temperature of the fluid before the test. They showed that the estimation can be used with proper approximation in radiation in different ways and can be extended to other collectors as well.

In a new research, Moravej et al. [23] tested a circular collector that was a flat plate type without riser with spiral tubes. In his research, using of water-silver nanofluid and ordinary water, he showed that due to the presence of secondary flow in this collector and the icrease in heat transfer, the maximum efficiency has reached close to 80%.

Due to the research on fixed and three-dimensional solar collectors, this study uses a particular geometry that is also a symbol of power in the pyramids of Egypt. The three-dimensional and fixed solar collector with pyramidal geometry that can be used in many buildings has been studied experimentally in different conditions.

2. Materials and Methods

2.1. Test set up

To study the desired geometry for the solar collector, a collector has been designed, built, and examined according to the dimensions listed in Table 1. A schematic of the experiment also shown in Figure 1. According to this figure, the tube containing the operating fluid is located at the side entrance of the pyramid and after entering it, distributed on all sides of the pyramid and exits through the risers and the top of the pyramid. To evaluate the parameters required in the research, ambient air temperature, inlet and outlet temperature of the operating fluid, solar radiation, and environmental parameters, as well as humidity, have been measured and recorded. Table 2 shows the ASHRAE standard for collector testing. In figure 2 the photo of pyramid collector is illustrated. The measurement devices are mentioned in Table 3.

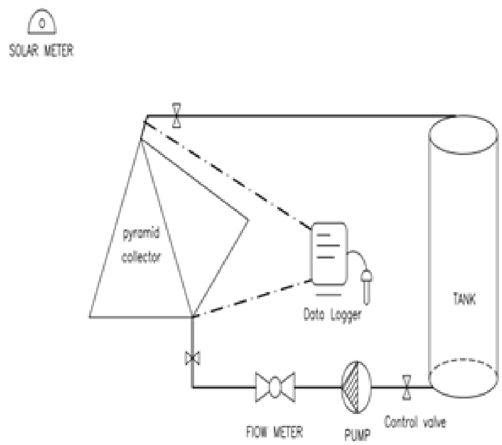

Figure 1 Schematic of equipment placement for experimental measurement of collector efficiency.

Table 1 Specifications of pyramid solar collector

Specification	Features	Units
Absorbent surfaces	A pyramid consisting of four triangles with a base of 800 and a height of triangle 500	mm
Absorbent type	The iron model with a thickness of 1.25	mm
Absorbent cross- section	0.64 Pyramid base section	m
Tubes	Copper with an outer diameter of 20	mm
Type of risers	Copper with an outer diameter of 13	mm
Glass cover	Flat and flat glass with a thickness of 6	mm
Insulation	Only on the floor with a thick wood, 15	mm
Storage tank	Insulated 10 -liter tank with a thickness of 20	mm

Figure 2 Picture of a pyramid collector during the experiment.

Table 2 ASHRAE standard for testing solar water heater [21].

Parameters	ASHRAE Standard	Unit
Inlet temperature variation	±1	°C
Outlet temperature variation	±0.5	°C
Ambient temperature	120 cm height	°C
Ambient temperature variation	±0.5	°C
Flow rate variation	±1	%
Incident sun radiation variation	±50	W/m^2

Table 3 Measurment devices.

Parameter	Model	Accuracy	Unit
Sun radiation	VoltCraft-slx 300	1	W/m^2
Wind speed	Lutron	0.1	m/s
Humidity	DC103	1	%
Temperature	Kimo	0.1	^{0}C
Flow rate	Rotameter Km450	0.1	Lpm

2.2. Governing equations

For more comprehensively evaluating the performance and efficiency of the solar thermal collector, its thermal efficiency is considered. Generally, efficiency calculated and applied to the amount of work obtained to the given assignment.

$$\eta = \frac{W_{out}}{W_{in}} \tag{1}$$

If in the above equation the concepts of energy are used instead of the concept of work done and employed, then the following equation is reached as eqation (2):

$$\eta = \frac{\sum E_{out}}{\sum E_{in}} \tag{2}$$

Now in a fixed solar collector, given energy is equal to the solar radiation received to the collector and the energy taken is equivalent to the heat given to the operating fluid. So, the collector efficiency will be obtained based on Equation (3).

$$\eta = \frac{Q}{AG_T} \tag{3}$$

Where A is the cross-sectional area of the collector and G_T is irradiated. To calculate the useful heat obtained from the collector we can use equations (4 & 5). The Equation (4) and Equation (5) are used respectively for water and nanofluid operating fluids [1].

$$Q = \dot{m}c_p(T_{out} - T_{in}) \tag{4}$$

Where $\dot{m}$ is mass flow rate, T_{in} and T_{out} are the inlet and outlet temperatures of the working fluid, and C_p is the specific heat of the working fluid, respectively.

$$C_{p,nf} = (\varphi)C_{p,np} + (1-\varphi)C_{p,bf} \tag{5}$$

In equation (5), φ is the nanofluid concentration, $C_{p,np}$, is the specific heat of the nanoparticles, $C_{p,bf}$, is the specific heat of the base fluid, and $C_{p,nf}$ is the specific heat of the nanofluid. By combining equations (4 and 3), the collector efficiency can be written as equation (6) [1,3]:

$$\eta = \frac{\dot{m}C_p(T_{out} - T_{in})}{AG_T} \tag{6}$$

By defining the heat loss coefficient, the efficiency can be introduced as Equation (7) [1, 3].

$$\eta = F_R(\tau\alpha) - F_R U_L\left(\frac{(T_a - T_{in})}{G_T}\right) \quad (7)$$

By considering the $(T_a-T_{in})/G_T$ as an independent variable and the efficiency as a dependent variable, it can be found that ther is a linear relationship between $(T_a-T_{in})/G_T$ and η.Therefore, the maximum efficiency occurs when the temperature reduction parameter becomes zero, and this happens when the inlet temperature and the ambient temperature are equal. At this time, the maximum efficiency is the same as $F_R(\tau\alpha)$.

2.3.Uncertainty analysis

The errors in the tests are inevitable. However, minimizing the errors is essential to ensure more confidence in the test results. To achive it, the maximum effort has been made to reduce the error rate in this study by calculating the uncertainty to increase the change quality. The following method was used to calculate the uncertainty of function U [3].

$$S_U = \left(\sum_{i=1}^{n}\left[S_{x_i}\frac{\partial U}{\partial x_i}\right]\right)^{\frac{1}{2}} \quad (8)$$

By applying the $U = Cx_1^a x_2^b \dots x_n^N$ in Eq.(8), where x_1 to x_n are variable parameters and C, a, b,…N are conctant numbers, it is written as [3]:

$$S_U = \sqrt[2]{(a\frac{S_1}{x_1})^2 + (b\frac{S_2}{x_2})^2 + \dots + (N\frac{S_n}{x_n})^2} \quad (9)$$

Where $S_1, S_2, \dots S_n$ are uncertainty of x_1 to x_n. Therefore, for the present study, according to Eq. (6), C_P is constant, and a, b,…N are ±1, so we can write [3,22]:

$$S_\eta = \sqrt[2]{\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta DA}{DAc}\right)^2 + \left(\frac{\Delta DT}{DT}\right)^2 + \left(\frac{\Delta G_T}{G_T}\right)^2} \quad (10)$$

Table 4 Uncertainty of measuring parameters

Parameter	Uncertainty (%)
Area	0.01
Flow rate	5
Solar irradiance	۳,۱
Temperature	0.5

According to the data obtained from Table 4 and Equation 10, the uncertainty related to the collector efficiency in these tests are determined, which is equal to 5.9%.

3. Results

All expriments were repeated on in different conditions in 2022 in the location that is mentioned in Table 5. Figure 3 shows a graph of the radiation received by the collector during the experiment. As can be seen from this figure, the radiation ascends in the morning until it reaches the time of sunrise, which has its maximum value. Then the radiation decreases and reaches zero at sunset. According to the data recording and testing on sunny days and changes in radiation, it follows a particular model, and its ascending and descending trend is a function of time.

Table 5 Test site specifications.

Country	Iran
Location	Payame Noor University of Aghajari
Altitude	122 m above the sea
Latitude	$30^{0}\ 69^{/}\ 08^{//}$ N
Longitude	$49^{0}\ 82^{/}\ 40^{//}$ E
Selected day	19 April 2022

In Figure 4, the parameters of the environment and air around the collector test site, including temperature and humidity, are measured. According to the figure, the air temperature has an upward trend, which indicates that the conditions are sunny and have a stable atmosphere during data collection. Also, in this figure, the relative humidity of the air is shown, which according to the range of 26-25%, does not change much and it can be said to be almost constant. This humidity also indicates that the test site is hot and relatively dry. Due to the lack of changes, it is not possible to comment on the effect of humidity on the collector's efficiency.

In Figure 5, the efficiency of the collector evaluated during the tests. As can be seen in this figure, the efficiency increases with the increase of solar radiation, and at noon the sun reaches its maximum value and then goes through a relatively downward trend. In Figure 6, the inlet, outlet, and ambient temperature measured while measuring efficiency. It should be noted that according to Equation (7), the closer the inlet temperature to the ambient temperature, the higher the efficiency, which is because of heat loss reduction. Also, according to the chart, the inlet temperature and the outlet temperature increase with increasing ambient temperature, however their difference is higher at higher temperatures. In other words, the difference between the inlet and outlet temperatures, which indicates the efficiency of the collector, starts to increase from the beginning and reaches its maximum value around noon and then decreases. But the difference between the inlet temperature and the ambient temperature is always ascending because at higher temperatures, it is a little harder to adjust the inlet temperature to the ambient temperature. Based on Equation (7), the collector efficiency is considered as a linear equation, a function of the parameter (T_a-T_{in}/G_T), and the efficiency function plotted based on this variable. The values of efficiency, inlet temperature, ambient temperature, and solar radiation have all calculated and measured in experiments, so the diagram of this function presented as a linear equation in Figure 7.

By using the obtained regression and graph, the values of $F_R(\tau\alpha)$ or the place of collision with the vertical axis and F_RU_L or the slope are found in which the $F_R(\tau\alpha)$ and F_RU_L show the maximum efficiency and amount of loss respectively.

According to Figure 7, based on regression in the given conditions, the number of $F_R(\tau\alpha)$ and F_RU_L is equal to 0.361 and 8.31, respectively, at a flow rate of 1 Lpm.

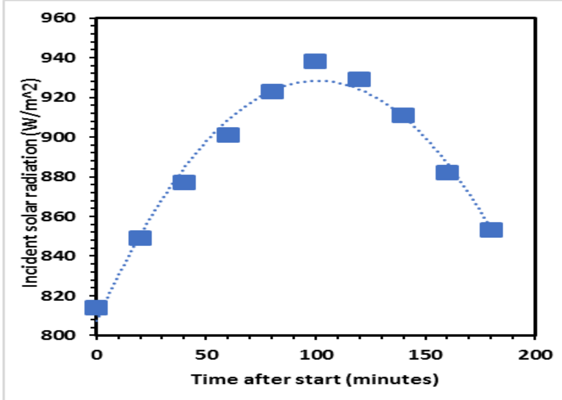

Figure 3 Solar radiation reaching the collector during the experiment

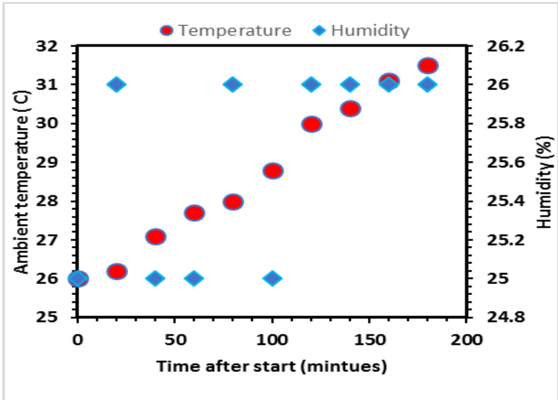

Figure 4 Investigation of temperature and relative humidity of the collector test environment.

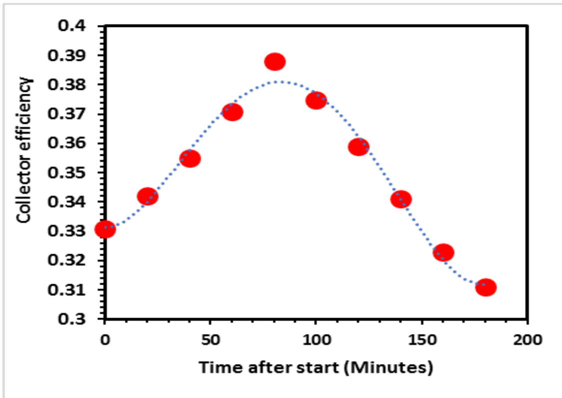

Figure 5 Collector's efficiency changes during the test.

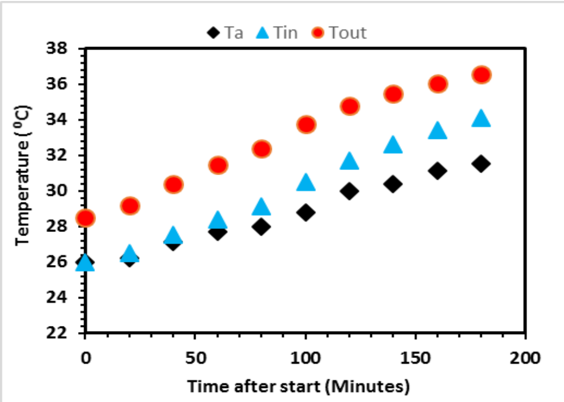

Figure 6 Changes an inlet, outlet, and ambient temperature during the collector efficiency test.

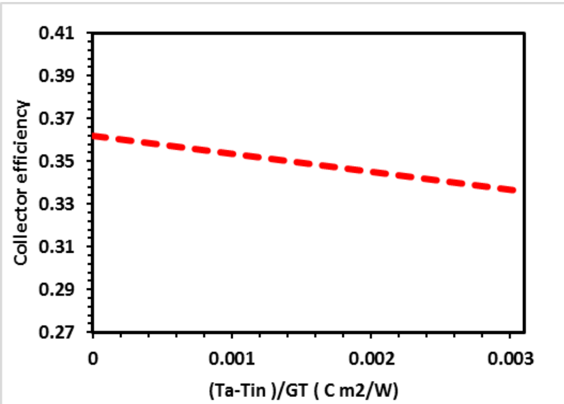

Figure 7 Evaluation of collector efficiency based on temperature reduction criteria.

3.1.The effect of using nanofluid on pyramidal collector

To study the pyramid collector more completely, in addition to using ordinary water as the operating fluid, copper-water oxide nanofluid with a concentration of 1000 ppm has been used. Due to the repetitive use of metal nanofluids in the discussion of heat transfer in solar systems, water-copper nanofluid is one of the most common ones, and it has been mentioned in previous researches and it is also used here. The nanofluid is prepared by Nanosadra Company, and its specifications shown in Table 6. Figure 8 shows the nanofluid used in this experiment, and Figure 9 shows the effect of using nanofluid on the collector efficiency and comparing it with an ordinary water.

By using of nanofluids, there would be an improvement in the efficiency and performance of the collector. Also, according to this study, when using nanofluids, similar to ordinary water working fluid, the maximum efficiency occurs at noon. Another critical point is that with increasing temperature, the difference between water use and nanofluids is more evident.

In other words, at higher temperatures, the nanofluid shows better performance compared to ordinary water.

Table 6 Specifications of nanofluids by: Nanosadra Company.

Specification	Value	Unit
Purity of nanoparticles	۹۹,۹%	%
Average particle size	۴۰	nm
Specific surface area	۱۰-۱۴	m^2/gr
Morphology	Spherical	-
Bulk density of CuO-nano suspension	۱,۰۵	gr/cm^3
The actual density of nanoparticles	۸,۹	gr/cm^3

Figure 8 Nanofluid used in the experiment.

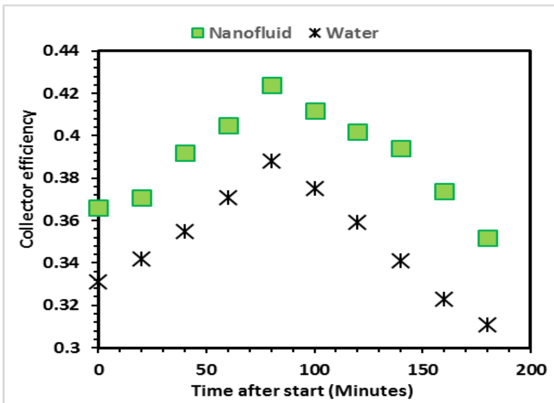

Figure 9 Effect of copper-water oxide nanofluid and ordinary water on collector efficiency.

3.2. Investigating the effect of flow rates

To more comprehensively evaluate the performance of the pyramid collector, the collector's efficiency in different discharges has also analyzed. Figure 10 shows the efficiency of a pyramid collector based on changes in volume flow.

Based on this figure, in the pyramid collector, with increasing the flow rate of the operating fluid, the efficiency increases. The reason for this behavior is the effect of discharge on Reynolds number and consequently the effect of Reynolds number on the amount of heat transfer. With increasing Reynolds number, the amount of transfer also increases as a result of collector efficiency.

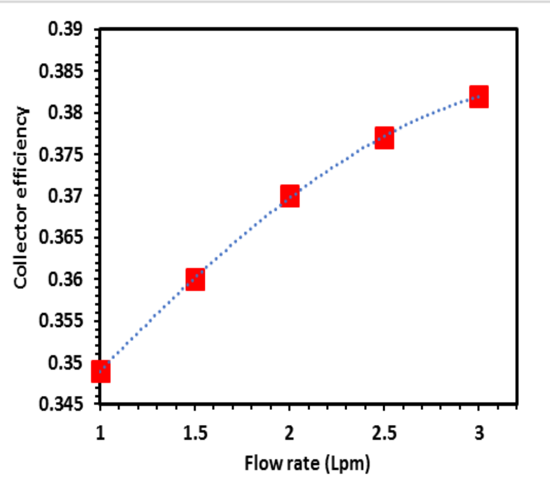

Figure 10 Investigation of the effect of volume flow on collector efficiency.

3.3.The effect of changing the collector installation angle

The effect of the absorber plate angle with the horizon in flat plate collectors investigated by various researchers so far [1]. Of course, we know from physics that the maximum vertical radiation is when the absorber plane makes an angle equal to the region's latitude with the horizon. But the vital point of the present study is that the collector is a three-dimensional type. Usually, the pyramid plates have an angle with the horizon and solar radiation, while their angles are different. In this section, the whole set of three-dimensional pyramidal collector tested at three angles, including 0 and 45 degrees and also 42 degrees, means the latitude of the region. Figure 11 shows this review. According to this figure, it is clear that the effect of radiation causes an increase of about 5% compared to the horizontal mode. Table 7 also provides a comparison based on the performance and efficiency of different collectors from previous research.

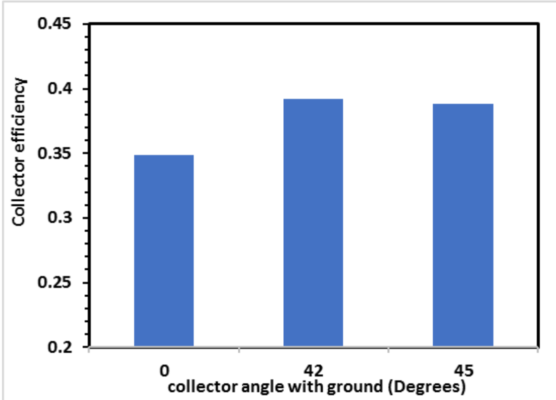

Figure 11 Investigating the effect of collector installation angle on efficiency.

Table 7 Comparison of the results of the present study with some previous research.

Researcher	Collector geometry	fluid	Maximum efficiency
Noghrehabadi et al. [22]	Rhombic	Water	56.2%
Moravej et al. [23]	Hemispherical	Ag-water	61.1%
Moravej et al.	Triangular	Water	58.9%
Ahmed [16]	Triangular storage	Water	48.7%
Poongavanam et al. [25]	flat plate	Water	54.24%
Present study	Pyramid	Water	46.2%

4.Conclusion

The most important results obtained from the experimental study of the solar pyramid collector include the following:

- Despite having a three-dimensional geometry in pyramid collector, it is suitable for the gable roof of many houses and also for solar water heaters.
- The average efficiency obtained from a solar pyramid collector with ordinary water-operating fluid is 35.1%.
- When using copper-water nanofluid with a concentration of 0.1%, more than 6%

obtained in increasing the collector efficiency.

- The solar pyramid collector can be used both angularly and horizontally and can have different functions depending on the location and position of the sun.
- With increasing radiation and fluid flow, the efficiency has changed, and the maximum value obtained is reported to be 46.2%.
- The type of design is such that, it can be used as a gable roof in houses or other places. In snowy areas, with this type of collector, snow removal can be done with hot water in winter and it can be heated in summer.

Nomenclature

Parameter	Specification	Unit
A	Collector area	(m^2)
C_p	Specific heat for fluid	(J/Kg k)
$C_{p,nf}$	Specific heat for nsnofluid	(J/Kg k)
$C_{p,np}$	Specific heat for nanoparticles	(J/Kg k)
$C_{p,bf}$	Specific heat for basefluid	(J/Kg k)
E_{in}	Inlet energy	(J)
E_{out}	Outlet energy	(J)
F_R	Coefficient of energy in collector	-
G_T	Incident sun radiation	(W/m^2)
$\dot{m}$	Mass flow rate	(Kg/s)
Q	Useful energy gained from collector	(W)
S_η	Uncertainty	%
T_a	Ambient temperature	(^{0}C)
T_{in}	Inlet temperature to the collector	(^{0}C)
T_{out}	outlet temperature of the collector	(^{0}C)
U_L	Total loss energy coefficient	(W/m^2 K)
W_{in}	Inlet work	(J)
W_{out}	Outlet work	(J)
$\tau\alpha$	Absorption-transmittance product	-
φ	Nanofluid concentration	%
η	Instantaneous collector efficiency	%

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