American Journal of Interdisciplinary Research and Development
ISSN Online: 2771-8948
Website: www.ajird.journalspark.org
Volume 15, April, 2023

MODIFIED SOLAR WATER HEATER WITH CORRUGATED ABSORBER TUBE

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Abstract

A parabolic solar trough collector's working fluid's capacity for heat transmission was demonstrated to be greatly enhanced by turbulence (PTSC). This was accomplished by employing a novel approach that substituted a corrugated absorber tube for a plain one. The primary objective of the experiment was to boost the thermal efficiency of the PTSC system with the help of the corrugated absorber tube. Various tests were conducted, at different mass flow rates (m) ranging from 0.02 to 0.04 Kg/s. The Reynolds number (Re) was calculated to be between 2000 and 4000 for both plain and corrugated absorber tubes.

The modification of the inner geometry of the PTSC system yielded remarkable outcomes, with a noticeable improvement in its thermal efficiency and heat transfer coefficient, thanks to the generation of flow vortices. While using a corrugated absorber tube instead of a plain tube, collection efficiency increased by 5.1% to 5.5% under the same operating circumstances.

Keywords: Solar water heater, Parabolic solar trough collector , Thermal performance, Corrugated absorber..

Introduction

Dramatic increases in energy demand are being seen due to the improvement of living standards and industrial growth in various countries [1]. As a result, a notable discrepancy between energy supply and demand is anticipated, heightening the significance of sustainable development. The importance of renewable energy sources, which are both environmentally sustainable and renewable at their core, is beginning to be realized. Advanced and industrialized countries have made renewable energy a pivotal component of their energy generation [2].

Earth's existence hinges greatly on the Sun as it plays a key role in sustaining life on this planet. Without its warmth, Earth's oceans, atmosphere, and climate would be vastly different [3]. It is the Sun's influence that humanity needs in order to survive. Worldwide energy needs are easily exceeded by the ample power of the sun, which never runs out. Every year, the sun yields an immeasurable amount of energy[4].

Due to its ability to supply conventional energy while also being environmentally friendly, solar energy has gained widespread attention as one of the most significant sources of power in the world[5].

One essential technology for transforming the plentiful solar energy into useable energy is solar water heating systems (SWHS). These systems harness the power of the sun to turn solar energy into thermal energy, which is then used for various human needs. Unlike solar photovoltaic systems, which produce electricity, solar water heating systems generate thermal energy. The different types of solar thermal collectors used in SWHS include stationary collectors, also known as non-concentrating collectors, and sun tracking collectors, also known as concentrating collectors. Interestingly, there are two types of demand for SWHS - domestic use, which involves solar hot water for personal use, and solar space heating, which is used for heating spaces. Incorporating a working fluid, a solar water heating system is a straightforward method that takes the heat from a solar collector and stores it for future use in a tank [6]. It commonly follows the pattern of:

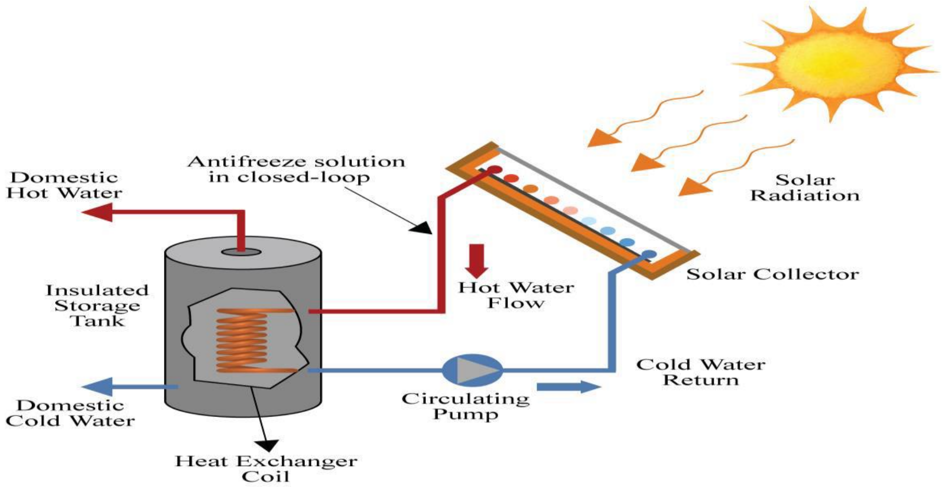

Figure 1: Solar water heating system [6].

In terms of renewable energy sources, certain regions and nations are well-suited for utilizing solar power, and Iraq ranks among them. Featuring an impressive average of around 4000 hours of annual sunshine in locations conducive to solar energy, there are ample opportunities for leveraging this resource [7]. When it comes to harnessing solar radiation, Concentrated Solar Power (CSP) is the leading technology, providing a pathway for generating electricity. Power plants rely on various types of CSP to generate power effectively, with PTSC standing as the most prevalent and innovative technology available. While making use of the PTSC in solar energy, there are certain factors that tend to inhibit its full potential, namely heat losses during storage times and the overall efficiency of the PTSC [7]. Researchers have discovered that the utilization of a corrugated tube can greatly enhance the fluid's thermal conductivity and other thermophysical properties, thereby allowing for a more efficient transfer of heat. A longer characteristic length as a result of the surface changes promotes convective heat transfer from the absorber to the water. The corrugated tube also increases the surface area exposed to solar radiation, which improves the process [7].

In the pursuit of better efficiency and reliability of a PTSC system with an outward convex corrugated absorber tube, Fuqiang et al. conducted a distinctive numerical experimentation in 2016. With the utilization of D12 Oil as the primary heat transfer fluid, the specialists conducted a numerical analysis of the PTSC system while imposing various Reynold numbers, from 104 to 10^5. Results have shown that the PTSC system's heat transfer performance improved significantly after the implementation of an asymmetric outward convex corrugated absorber tube; however, it affected the pressure drop. In detail, the heat transfer rate rose by 148% when compared to the smooth absorber tube, marking a maximum performance factor. In a unique approach, Fuqianget et al. (2016) [9] came up with a design for parabolic trough receivers that utilizes the heat transfer properties of a symmetric outward convex corrugated tube. Through numerical analysis of varying Reynold numbers using water as a heat transfer fluid (ranging from 2×104 to 9×104), the design was found to significantly improve heat transfer performance while also reducing thermal strain on the metal tube of the trough receiver. Their findings were conclusive. Huang et al. (2017), on the other hand, discovered that a symmetric outward convex corrugated tube at Re = 81728 can lead to an increase in effective heat transfer coefficient (up to 8.4%) and a decrease in maximum thermal strain of the metal tube (down to 13.1%). Meanwhile, [10] carried out a numerical study to improve the fully-developed mixed turbulent convective heat transfer characteristics in dimpled tubes, in relation to the receiver of a PTSC system. The numerical analysis was performed of various values of Reynold number from 10000 to 20000 and thermal oil VP-1 as heat transfer fluid. The two cases of dimpled receivers were used, shallow dimple depth (d=1mm) and deep dimples depth (d=7mm). The numerical results showed that the heat transfer characteristics of a PTSC system with dimples absorber tube were considerably enhanced tube compared to the smooth absorber tube. Xiangtao et al. (2017) [11] executed a numerical study to investigate the heat transfer performance of a PTSC system with pin fin arrays inserting an absorber tube. Numerical analyzes were performed for different mass flow rates from 0.054 kg/s to 0.535 kg/s. Using D12 oil as the heat transfer fluid, the Reynolds numbers cover a range of 1979.5 to 11151.6. Results obtained reveal that inserting the absorber into the pin-fin array enhances the heat transfer performance of the PTSC system, although at the sacrifice of pressure drop. Notably, there was a 9.0% rise in the average Nusselt number, a 12.0% increase in overall heat transfer efficiency, and a 3% increase in heat transfer coefficient compared to smooth absorber tubes. Seeking to improve the heat transfer performance and thermal efficiency of PTSC systems with different internal longitudinally finned absorber tubes, Bellows et al. (2017) [12] performed a numerical study. Using Syltherm 800 as the heat transfer fluid, the heat transfer performance of the PTSC system was analyzed with internal longitudinally finned absorber tubes. This analysis was performed at varying inlet temperatures (ranging from 300 K to 600 K), flow rates (ranging from 50 L/min to 250 L/min), and Reynolds numbers (ranging from 10,000 to 140,000). It was discovered that, while the use of internal longitudinally finned absorber tubes improved heat transfer performance, it resulted in increased pressure drop. Notably, the Nusselt number was 1.652 times larger than for smooth absorber tubes with an increased performance of 65.8%. Meanwhile, the coefficient of friction was about twice that of smooth absorber tubes. In an experiment analysis conducted by Saad et al. (2018) [13], it was found that combining a helical tube receiver with a parabolic trough solar concentrator and a dual-axis solar tracking system resulted in a thermal efficiency increase of 0.82% to a total of 68.80, when compared to a smooth absorber. The study focused on testing different water flow rates and reporting the resulting thermal performance. Through an experimental study, we were able to determine the impact of varying water flows on temperature rise, thermal efficiency, and available heat gain. Interestingly, we discovered that as the mass flow of water increased, the average outlet water temperature steadily decreased to (63.82, 120.8, and 46.08 °C). Additionally, we found that the maximum outlet temperature reached (76, 160.5, 47) C˚. These findings led us to calculate an average available heat gain of (732, 1249.4, 732.5 W), showcasing a direct correlation between water flow and thermal performance. By numerical analysis, Kurs (2019)[14] assessed the Nusselt number, friction coefficient, thermal improvement factor, and ambient temperature difference to investigate the impact of internal longitudinal ribs on the parabolic trough receiver tube's thermal performance. The PTSC's average thermal efficiencies were reduced to 73.021%, 49.51%, and 44.31%, respectively. Interestingly, reducing water mass flow by 74.4% resulted in a 64.7% increase in the PTSC's thermal efficiency. With Reynolds numbers ranging between 2.104 and 8.104, the analysis involved manipulating the period length and amplitude of the sinusoidal shape. By doing so, it was shown that using the sinusoidal face geometry enhances heat transfer. In comparison to the flat fins, an improvement in Nu of 78% was achieved for the sinusoidal fins, while only 25% with the flat ones. In their study, Zou et al. (2019) [15] created a single-sided spiral-finned receiver tube that significantly enhances thermal efficiency in the PTSC system. They also conducted a detailed study on how the helical fin's structural parameters impacted the performance of the single-ended helical fin receiver tube. Between 0.5 kg/s and 3.5 kg/s lies the mass flow. The findings indicate that the general efficiency of the tube's helical fins can enhance by 12.5%, 9.8%, 10.8%, and 30.1% if alterations are made to the fins' structural parameters, such as corner radius, helix angle, fin height, and pitch. Chakraborty and colleagues (2020) [16] examined the impact of a spiral heat absorber on the thermal characteristics of a PTSC system both with and without turns. Using water as the working medium, a study was conducted on four absorber models to determine their thermal efficiency. The absorbers included three designs with differing number of turns, as well as one with a smooth absorption tube. The mass flow rate varied between 0.025 and 0.25 kg/s. Results showed that the most efficient absorber was the one with water as the working fluid, operating at 25 rpm and a mass flow rate of 0.25 kg/s, achieving a thermal efficiency of 67.7%. The smooth absorber's maximum total efficiency and exergy efficiency were found to be 75.23% and 6.93%, respectively, when operated at the same mass flow rate.

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In this study, a parabolic solar collector with a zigzag tube was selected and its thermal performance was compared with a smooth tube under the same conditions.

Theoretical Methods

The design of a typical solar system in Figure shows a PTSC and a storage tank (2). The working medium experiences heat gain and loss at the top, bottom, and edges as a result of the solar energy that the solar collector has gathered. The methods below can be used to compute these energies.

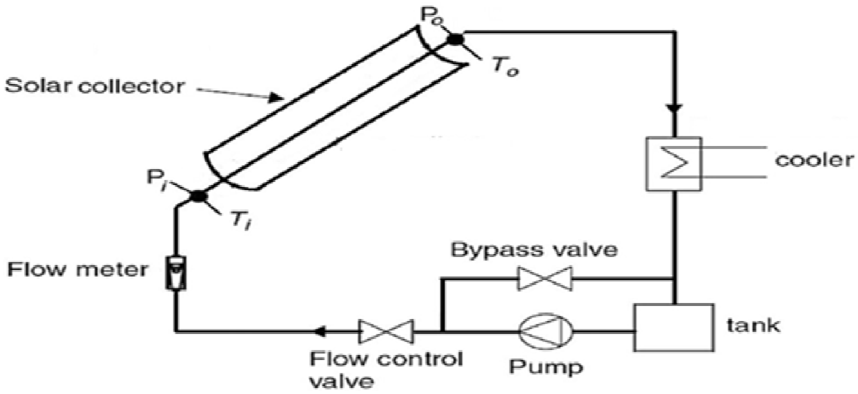

Figure 2: A PTSC system's schematic design [2].

Heat loss from the collector occurs from various locations: the top of the glass cover, edges, and bottom. The total collector heat loss can be represented by equation [18].

$$Qloss = Ul\ A\ (Tr - Ta)$$

Where Q_{loss} =The heat rate of loss, W; U_l = Overall heat loss coefficient, W/m².K ; A= Gross Collector area, m²; T_r = The collector temperature, ° ;T_a = The ambient temperature, °C.

The solar energy Q_s at the collector opening is calculated as the product of the collector area A_a and the direct solar radiation I, as shown in the following formula [18,19]:

$$Qs = A_a\ I$$

Where

$A_a = (W - d_{ro})L$ is the collecting area (m²); W is aperture width (m); d_{ro} is outer diameter of absorber (m); L is length of the receiver (m); I is the direct beam solar irradiation (W/m²). Water in the absorber tube obtained useful energy rate Q_u from the solar radiation mainly through the process of convective heat transfer. Thereby, Q_u was assumed to be equal to the heat flow convective inside the test tube and could be expressed as [20,21]:

$$Q_u = m^{\circ}\ Cp\ (T_{out} - T_{in})$$

Where

$m^{\circ} = \rho\ V$ is mass flow rate (kg/s); ρ is fluid density (kg/m³); v is the volumetric flow rate (m³/s); C_p is Specific heat capacity of fluid (J/Kg. K); T_{out}, T_{in} is Outlet and inlet temperature of water (C°).

The thermal efficiency (ηth) of the solar water collectors served as the most crucial metric for assessment. As shown below [22,23], this parameter was derived as the ratio of the available solar energy to the useable energy:

$$\eta_{th} = \frac{Q_u}{Qs}$$

To show the heat transfer performance, the average heat transfer coefficient h was utilized. For convective heat transfer from the inner wall of the absorber tube to the heat transfer fluid, the following equation give the heat transfer coefficient [22,24]:

$$h = \frac{Q_u}{A_{ri}(T_r - T_m)}$$

where

h is Heat transfer coefficient (w/m².k); $A_{ri} = \pi\, d_{ri}\, L$ is absorber area (m²); d_{ri} is inner diameter of absorber (m); L is the length of receiver (m);T_r is the receiver temperature (C°); $T_m = \frac{(T_{out}+T_{in})}{2}$ is the mean fluid temperature (C°).

The heat transfer performance of the PTSC system was determined using the Nusselt number (Nu). The following equation was applied to calculate the Nusselt number [25,26]:

$$N_u = \frac{h\, d_{ri}}{K}$$

where

P is the wetted perimeter of the flow (m); k is the thermal conductivity of fluid (W/m K).

Reynolds number Re for circular tube for the PTSC system was expressed as [22,27]:

$$Re = \frac{\rho\, U d_h}{\mu} = \frac{4\, m^{\circ}}{\pi\, d_{ri}\, \mu}$$

Where

$dh = \frac{4\, Ac}{P}$ is the hydraulic diameter (m); $Ac = \frac{\pi\, {d_{ri}}^2}{4}$ is the cross-sectional are of the flow (m²);μ is viscosity of working fluid (N s/m²); U is velocity of fluid (m/s).

The friction factor f could be calculated using the pressure drop ΔP along the tube [28,29]:

$$f = \frac{\Delta P}{\frac{1}{2}\rho\, u^2}\frac{d_h}{L}$$

where

ΔP represents the pressure losses along the absorber tube (Pa).

Experimental work

The operating process and experimental setup used to complete the task are provided. As a result, this part opens with a description of the experimental apparatus, its design, and the method used to conduct the experiment.

1. An experimentation setup

In the current experimental design, the following were utilized:

Parameters	Value
Collector aperture	0.30 m
Collector length	0.98 m
Aperture area	1.25 m^2
Rim angle	90°
Focus length	34 cm
Concentration ratio	39.06
Mod of tracking	One axes tracking (N-S)
Tracking mechanism type	Electro-optical
Reflector material	Acrylic sheet
Insulation material	glass Wool
Receiver material	Cupper
Receiver length	0.80 m
Smooth receiver inner diameter	12.7 mm
Smooth receiver outer diameter	15.2 mm
Corrugated receiver inner diameter	12.68 mm
Corrugated receiver outer diameter	15.17 mm
Thermal conductivity of Cupper	400 W/mk
Glass length	0.80 m
Glass inner diameter	24 mm
Glass outer diameter	28 mm
Thermal conductivity of glass	1.1 W/mk
Heat transfer fluid	Water
Tank material	Galvanize
Storage tank capacity	31.5 L
Water pump	120 W
Support Structure material	Cast iron

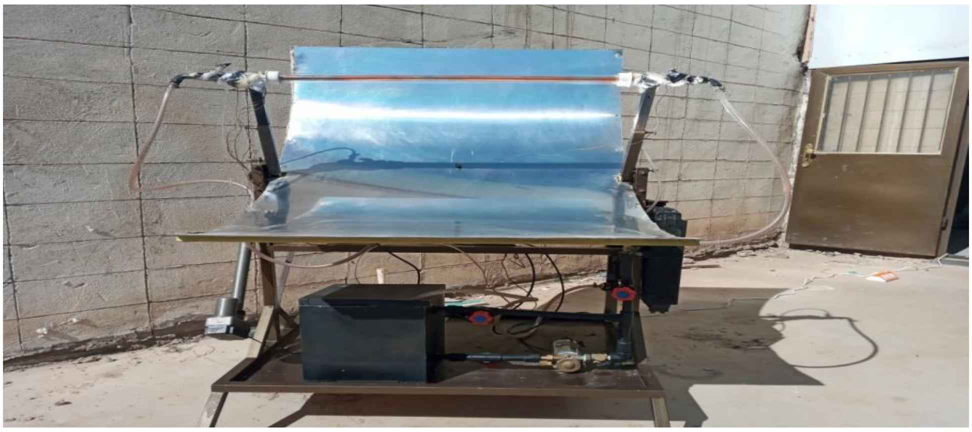

Figure 3: Fabricated PTSC system with various components.

2- Experimental Procedure

It is suggested in experimental work that the thermal performance of the PTSC system be improved. Water is used as the working medium for the tests, which are carried out in two different scenarios: (1) smooth receiving pipe and (2) corrugated receiving pipe. The three scenarios are then compared for heat transfer characteristics and thermal efficiency.

A few examples of experimental equipment include pipes, valves, accumulators, water pumps, heat exchangers, mechanical tracking systems, mirrors, receiving tubes, heat transfer fluids, and accumulators. In the trials, mass flow rates of 0.02 kg/s, 0.025 kg/s, 0.03 kg/s, 0.035 kg/s, and 0.04 kg/s were employed. Calculations for the Reynolds number range from 2000 to 4000. The project was finished after the experimental work, which took place at the Ramadi Campus of the School of Mechanical Engineering at Anbar University, from December 2019 to February 2020. The whole working day, from 11:00 am to 2:00 pm, will be used to complete tasks.

Then, direct the reflected light toward a receiver tube with a flat surface. The test facility's storage tank capacity was 31.5 liters. There is water in the water tank. The water is circulated to the absorption pipe by a pump after the storage tank. To start the system and let water flow into the absorber tube, turn on the pump.

In order to turn the entire structure of the system in the direction of the sun's rays, the tracking system is activated. A turbine flow meter is connected to the inlet side of the receiver pipe to regulate the water mass flow. Pressure sensors at the inlet and outlet of the absorber tube are used to calculate the pressure drop for each flow rate. The intensity of solar radiation is measured with a pyranometer.

Thermocouples linked to the receiver tubes at T_{in}, T_{out}, and T_r continually measure the water temperature. To maintain stability, turn on the PTSC system for 20 minutes before to reading. Keep a note of the T_{in}, Tout, T_r, I, and P values after the liquid flow has reached steady state.

Results and Discussion

Experimentally, a PTSC system was used to generate hot water. Use measuring devices to determine the actual results of inlet and outlet water temperature, water receiving pipe temperature, pressure loss and solar radiation intensity. Based on actual results, values for available heat gain, thermal efficiency, heat transfer coefficient, Nusselt number, and friction coefficient were calculated. The results are then displayed graphically in Excel.

Case 1: Smooth Copper Absorber Tube

The receiver tube for the initial thermal performance assessment of the PTSC system was a smooth copper absorber tube. The receiving tube of the PTSC system was employed in the first instance of experimental work on a PTSC system. This receiving tube was made of a smooth copper absorber tube and coated with glass. The findings of the experimental study demonstrate that when the Reynolds number rises, the thermal performance of the PTSC system does as well.

According to the test data obtained in practice, the thermal efficiency of Case 1 changes with time as shown in Figure 4. Experimental results show that the highest thermal efficiency of the PTSC system occurs at the highest mass flow rate (m^o = 0.04 kg/s) at 12:40

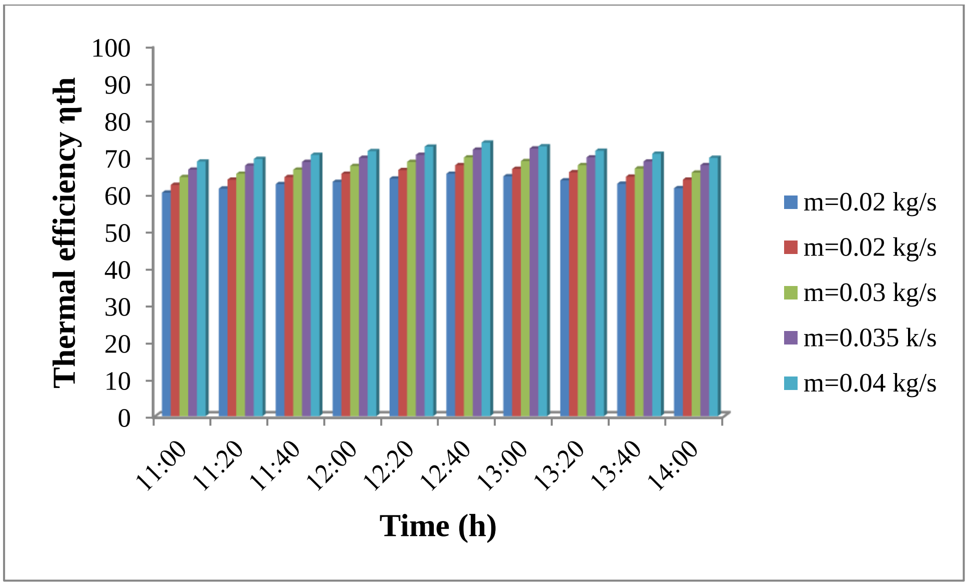

Figure 4: Variation of time with thermal efficiency of case 1.

The copper corrugated absorber tube covered in glass was employed as the PTSC system's reception tube in the second instance of the experimental operation. The findings of the experimental investigation demonstrate that an increase in Reynolds number improves a PTSC system's thermal performance.

The variation of the thermal efficiency with a time of case 3 was shown in Figure 5 using the experimental data that was obtained in practice. According to the testing results, the PTSC system's best thermal efficiency occurred at its peak mass flow rate (m^o=0.04 kg/s) around 12:40 PM.

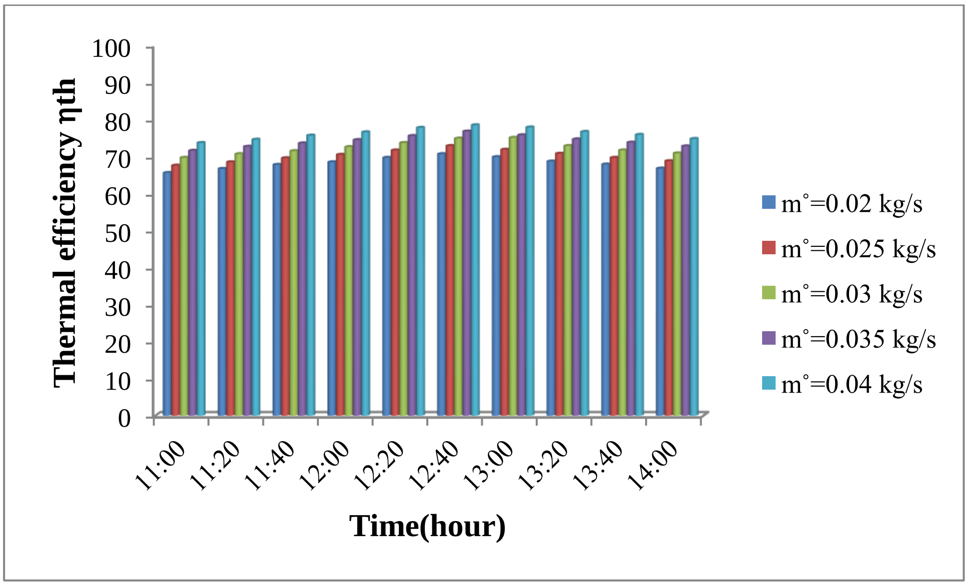

Figure 5: Validation the thermal efficiency with time Reynolds number of case 2.

The Effect of Copper Corrugated Absorber Tubes on PTSC System Performance

Most heat transfer enhancement technologies envision pressure drop to improve heat transfer performance. The thermal performance of the PTSC system at various Reynolds numbers was evaluated through experimental work using smooth and corrugated copper absorber tubes.

Using data collected in the field, Figures 6, 7 and 8 illustrate how the copper absorber bellows affect the performance of the PTSC system. The thermal performance of corrugated copper heat sinks was found to be superior to that of smooth copper heat sinks. Therefore, the thermal efficiency of the PTSC system and the heat transfer coefficient of the corrugated heat absorbing tube are higher than those of the smooth tube. The reason for this increase is the newly designed geometry with increased inner tube surface, which increases liquid flow in turbulent regions.

The internal geometry of the pipes causes indentations in the interior which in turn cause eddies to form in the flow area. In addition, corrugations in the pipe cause the thermal boundary layer to rupture and cause flow turbulence, which increases the temperature difference between the inlet and outlet.

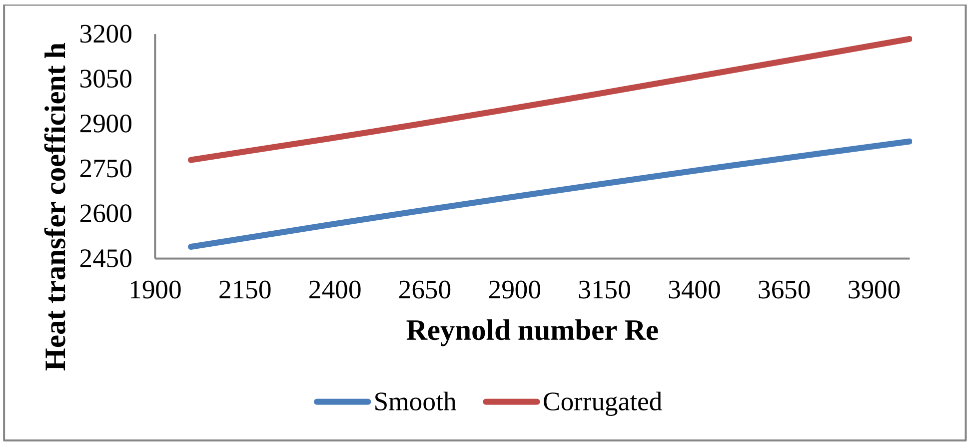

Figure 6: Variation the heat transfer coefficient with Reynold number of case 1 and case 2.

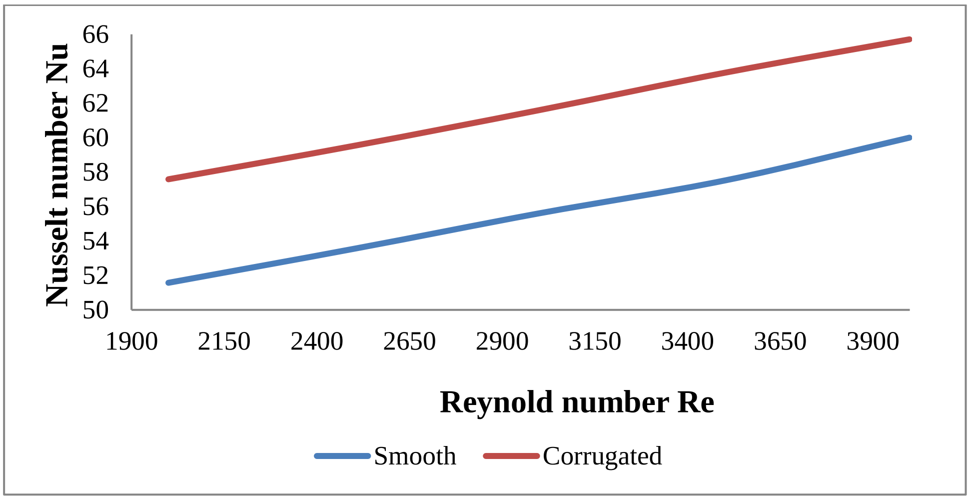

Figure 7: Nusselt number variation for cases 1 and 2 using the Reynolds number.

Figure 8 illustrates the relationship between the friction coefficient and the Reynolds number when using a corrugated absorber. The internal flow of bellows is very difficult. The resistance to fluid flow imposed by the bellows, the swirling flow created by the bellows, the increase in frictional resistance, and the flow restriction associated with the reduction in the cross-sectional area of the tube are the causes of the pressure drop across the bellows.

Each of these factors would have an influence on the pressure drop and friction factor values concurrently. Nevertheless, since the corrugated surface constituted a barrier to the flow direction, the major problem with this type of tube was the pressure drop caused by drag. The friction factor trend for corrugated tubes was generally different from that of smooth tubes. The effects of friction drag and pressure drag that were present in the corrugated tube are the cause of this. The friction factor value in the smooth tube was influenced only by the friction drag. The friction factor trend in corrugated tubes therefore displayed a range of characteristics.

Because the copper corrugated absorber tube had a bigger contact surface area than the copper smooth absorber tube, the friction factor was as expected much higher. As a result, a specialized design was created to minimize these losses. In addition, a fast rate of pressure drag growth and high rotating velocities were blamed for the increase in friction factor.

Moreover, the main vortex, which causes a significant fluctuation in the flow layers and a high intensity of turbulence, is generated by the corrugated depth. These factors cause the friction factor to rise as the corrugated depth increases.

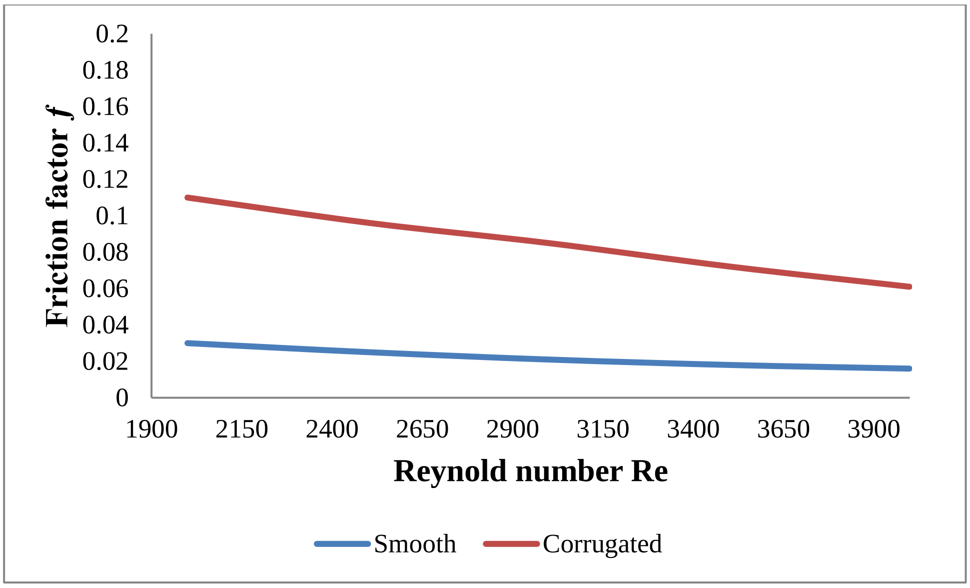

Figure 8: Change of the friction factor for cases 1 and 2 using the Reynolds number.

Finally, the results show that the convective heat transfer coefficient of the corrugated heat absorber is significantly higher than that of the smooth heat absorber under the same flow conditions. At the same time heat transfer increases faster than hydraulic resistance and exceeds it. Accordingly, the corrugations of the present invention can significantly improve heat transfer while significantly increasing the coefficient of friction.

American Journal of Interdisciplinary Research and Development
ISSN Online: 2771-8948
Website: www.ajird.journalspark.org
Volume 15, April, 2023

Thermal efficiency has grown in significance as heat transport technology has advanced. Hence, increasing thermal efficiency is a goal in addition to improving heat transfer. According to experimental findings, corrugated copper heat sinks are more thermally efficient than smooth copper heat sinks. Comparing smooth absorber tubes to internal geometry, the efficiency is increased by 5% to 5.5%.

Conclusions

PTSC technology may be very effective and useful in heating water applications if the cost of the system is reduced to a certain limit.

We're aiming to increase the PTSC system's thermal performance with some experimental work detailed in this thesis. The two approaches we used are perforate twisted tape in the absorber tube and a corrugated absorber tube to improve heat transfer. We'll contrast this modified PTSC system with the standard one as well. To predict the thermal efficiency and Nusselt number of the PTSC system, we will use a fuzzy model system. The experimental study was done in the mechanical engineering department of the University of Anbar in Al-Anbar city, and it measured five different mass flow rates: 0.02 kg/s, 0.025 kg/s, 0.03 kg/s, 0.035 kg/s, and 0.04 kg/s. The appropriate Reynolds numbers from 2000 to 4000 were found. The experiment, which lasted from December 2019 to February 2020, was conducted every day from 11:00 AM to 14:00 PM.

The usable heat gains, thermal efficiency, heat transfer coefficients, Nusselt number, and friction factor were estimated for each case of the receiver tubes and mass flow rate based on the experimentally collected data. According to the experimental findings, the thermal efficiency and Nusselt number increased as the Reynolds number did. While in all situations, the friction factor dropped as the Reynolds number rose.

When compared to the smooth variant, the ribbed absorber tube in the collector had a roughly 5% higher thermal efficiency. This is partly because of the increased surface area exposed to solar radiation and the lengthened typical length for convective heat transfer from the redesigned surface to the water. Corrugated surfaces have been found to hold greater water temperatures for longer periods of time than smooth ones. More solar energy conversion into useful heat is achieved while the water heater is running, which suggests a reduction in something.

List of Symbols

Abbreviation	Description	
SWH	Solar water heating.	
PTSC	Parabolic trough solar collector.	
CR	Concentration ratio.	
English Symbols	**Description**	**Units**
A_a	Collector aperture area.	m^2
A_c	Cross-sectional are of the flow.	m^2

A_r	Surface area of the receiver.	m^2
A_s	Surface area of the concentrator.	m^2
C_p	Specific heat capacity of water.	J/Kg.C°
d	Diameter of absorber tube.	m
d_h	Hydraulic diameter.	m
f	Friction factor.	-
H_p	height of the parabola.	m
h	The average heat transfer coefficient.	$W/m^2.K$
I	The direct beam solar irradiation .	W/m^2
K	Thermal conductivity of fluid.	W/mK
L	Length of absorber tube.	m
m°	Mass flow rate.	Kg/s
Nu	Nusselt number.	-
P	Wetted perimeter of the flow.	m
Q_s	Solar energy.	W
Q_u	Useful heat gain.	W
R	Ratio of arc-plug radius to the receiver radius.	-
Re	Reynolds number.	-
T	Temperature.	C°
TR	Twist ratios of twist tape insert	-
U	Velocity of fluid.	m/s
V	Volumetric flow rate.	m^3/s
W_a	Aperture width.	m
W	width of the perforate twist tape insert.	m
μ	Viscosity of working fluid.	$N.s/m^2$
η_{th}	Thermal efficiency.	-
ρ	Fluid density.	Kg/m^3
ΔP	Pressure drop.	Pa

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