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Solar Thermal Collector System with Parabolic Collector for Applications in Organic Rankine Cycle: Design, Manufacturing and Testing

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ABSTRACT

Generating power using an Organic Rankine Cycle (ORC) has the advantage of converting waste energy into useful power. This technology can utilize various low-level heat sources such as biomass, engine waste heat, geothermal and solar, and it significantly reduces thermal pollution as well as the reliance on fossil fuels. In this research, a parabolic collector with a tube length of 18.12 meters was designed and manufactured. The results showed that the parabolic trough can reach a temperature of 56.6℃ with a water flow rate of 0.042kg/s, from an initial temperature of 28.2℃ during a 2-hour test. The average turbine output power was 430.04 W in theoretical calculations and 248.57 W in reality for the ORC system. The highest thermal efficiency was achieved at a turbine inlet temperature of 63.5℃ and a turbine inlet pressure of 10.5 bar, with a value of 4.489%. Overall, using ORC technology can effectively utilize low-level heat sources and contribute to reducing reliance on fossil fuels and thermal pollution.

1. Introduction

The demand for energy worldwide is increasing gradually due to advances in technology, industrialization of developing nations, and population growth [1]. However, the predominant use of fossil fuels for energy generation has negative impacts on the environment, including air pollution, depletion of the ozone layer, global warming, and acid rain [1-5]. To overcome these issues, renewable energy sources such as wind, biomass, solar, geothermal, and waste heat are increasingly being used [4,6-8].

Solar energy is one of the most promising renewable energy sources, with inexhaustible, stable, and universal availability [9,22]. By using various technologies, solar energy can be harnessed to produce electricity or thermal energy [10,22]. Indonesia, for example, has over 500 GW of potential solar power sources based on average daily solar irradiation of 4.80 kWh/m^2, making it rich in solar energy resources [10].

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Solar collectors are specialized heat exchangers that convert solar radiation energy into internal energy, which is transported by a medium. The main component of a solar system is the solar collector, which absorbs incoming solar radiation, converts it into heat, and transfers it to a liquid flowing through the collector, with 60% of the heat being usable [11,12]. To maximize the amount of radiation intercepted and reduce reflection and cosine losses, solar collectors are usually installed at an angle rather than horizontally. System designers require measured or estimated radiation data to determine the amount of insolation on a terrestrial surface at a given location and time. However, most of this data is available only for horizontal surfaces or normal occurrences, so there is a need to convert it to radiation on an inclined surface [13].

The Organic Rankine Cycle (ORC) is a power generation system that uses an organic working fluid (refrigerant or hydrocarbon) instead of water in a modified Rankine cycle. Organic working fluids perform better than water at low temperature and pressure, making them ideal for harnessing low-level heat sources such as solar heat, biomass, engine waste heat, and geothermal energy [14-17]. By utilizing ORC, energy that would otherwise be waste can be converted into useful energy, significantly reducing thermal pollution and fossil fuel consumption [17].

Recent studies have shown that Organic Rankine Cycle (ORC) systems have the potential to improve energy efficiency in various applications. Anastasovski *et al.,* [18] investigated the use of waste heat sources in production processes, concluding that waste water integration in ORC adds a maximum of 2.3% efficiency to the system, increasing total power produced by 8.6%.

Loni *et al.,* [19] explored the use of solar collectors as a heat source and found that the system can achieve an efficiency of more than 20% with a PTC, which is an effective choice to achieve good efficiency at a reasonable price.

Bianci *et al.,* [20] experimented with using a water heater as a heat source and varying heat source temperature to produce 1.2 kW of electrical energy and 4.4% thermal efficiency with a turbine input pressure of 11-17 Bar.

Ismail *et al.,* [21] simulated various working fluids and found that toluene was the best choice for a simple ORC system, while dodecane and propylcyclohexane were better choices for an ORC system with an added Internal Heat Exchanger (IHE) or recuperator.

Sachit *et al.,* [22] conducted simulations on Serpentine and Serpin-direct PV/T Solar collectors, showing a thermal efficiency of 53% and an electrical efficiency of 14.3% at optimum conditions.

Liang *et al.,* [23] developed a solar-tracking robot that increased the efficiency of solar energy conversion by 10.47% compared to fixed solar photovoltaic panels.

Martin *et al.,* [24,25] found that the ORC system generated 0.279 kW of electrical energy with a thermal efficiency of 3.33% using R-134a as the working fluid and a water heater as the heat source.

Naibaho *et al.,* [26] designed a helical type evaporator and condenser and a flat plate collector as a solar heat absorber, and found that the ORC system produced 0.305 kW of electrical energy and 4.3% thermal efficiency.

Overall, ORC systems show promise for small-scale generators with low temperatures, and this research aims to design, manufacture, and test an ORC system using a parabolic solar collector as the source of energy.

2. Methodology

2.1 Design of Parabolic Collector

The initial parameters used for the design of the parabolic collector can be found in Table 1.

Table 1
Design Variables

Variable	Value
To	95°C
Ti	27°C
$\dot{m}$	0,042 kg/s
$C_{P\ Water}$	4,185 kJ/kg°C
$D_{o,tube}$	0,009525 m
$D_{i,tube}$	0,0084074 m
T_∞	33°C
$R_{f,i}$	0,0002 m^2.°C /W
k_{Copper}	385 W/m.°C
τ_g	0,97
α_p	0,95
ρ_p	0,87
Gsc = *solar constant*	1366,1 w/m^2
Latitude angle (L)	0.48°
Water Volume	40,7 liters

The formula used for designing the parabolic collector is as shown in Table 2 [27,28]

Table 2
Parameters and formula to design of the parabolic collector

No.	Parameters	Formula
1	Solar radiation received by the collector	$s = \tau_g . \rho_p . \alpha_p . I_t$
2	Useful energy generated by the collector	$Q_u = A_c . [S - UL . (T_i - T_\infty)]$
3	Tentative tube leght	$Q_u = \frac{\dot{m} . Cp . (T_o - T_i)}{\pi . D. L}$
4	The total amount of energy to the water	$Q = \dot{m} . \Delta h$
5	Surface area	$A_s = \frac{Q}{U . \Delta T}$
6	Fluid flow	$V = \frac{\dot{m}}{\rho . A}$
7	Reynold Number	$Re = \frac{\rho . V . D}{\mu}$
8	Nusselt Number	$Nu = 0,023 . Re^{0,8} . Pr^{1/3}$
9	H_i and h_o	$h = \frac{k}{D} . Nu$
10	The overall heat transfer coefficient	$R = \frac{1}{h_i . A_i} + \frac{R_{f,i}}{A_i} + \frac{ln\left(^{D_o}/_{D_i}\right)}{2 . \pi . k . L}$ $U = \frac{1}{R}$
11	Total collector tube leght	$A_{total} = \frac{Q}{U . \Delta T_{lm}}$ $L_{total} = \frac{A}{\pi . D}$
12	Sun azimuth angle	$z = sin^{-1}\left(\frac{\cos(\delta) . \sin(h)}{\cos(\alpha)}\right)$

Figure 1 shows the calculated solar azimuth angle for the parabolic collector based on the given parameters.

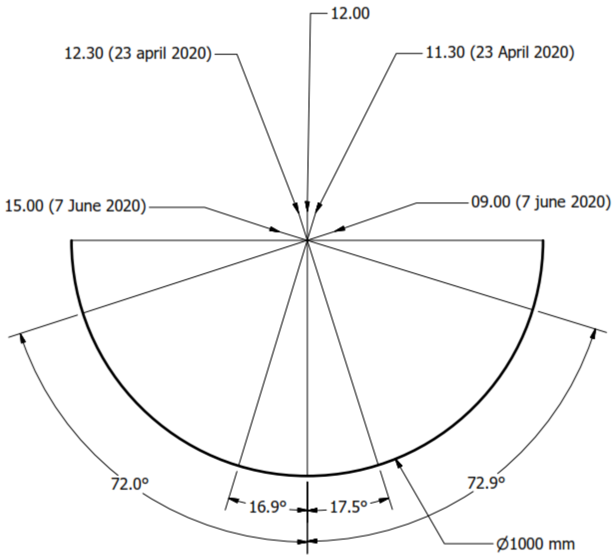

Fig. 1. Azimuth angle calculation result

One important aspect in designing the parabolic collector for the ORC system is determining the dimensions of the serpentine tube. Based on previous research, the angle on the lower center side of the concave is 34.40°, which is used to find the arc length and calculate the length of the connecting tube between the left and right sides. The width of the area for the serpentine tube is determined by the angle on the left and right sides, which is 55.1°. Additionally, the number of bends of the serpentine tube is also an important factor in determining the overall efficiency of the ORC system. The calculation of these dimensions and angles are crucial in designing a high-efficiency parabolic collector for the ORC system. The results of these calculations can be seen in Figure 2.

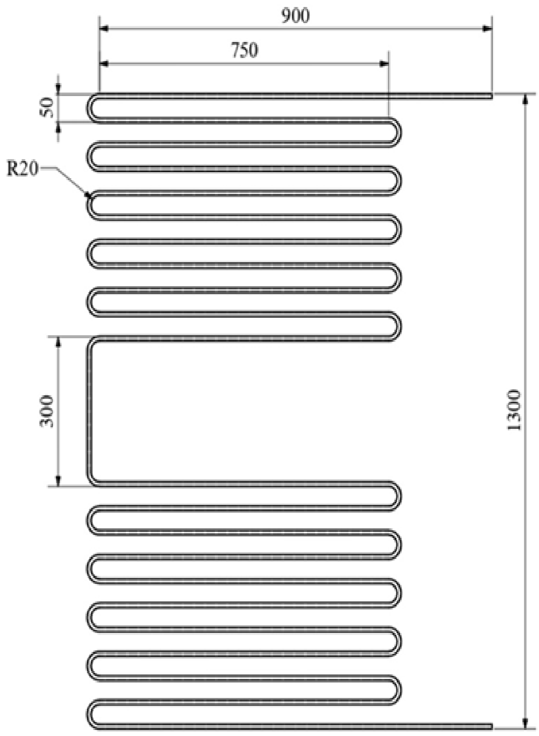

Fig. 2. Serpentine tube design

From the results of the parabolic collector design, the following recapitulation results are obtained as shown in Table 3.

Table 3
Result of Design Recapitulation

Parameter	Value
Total Tube Length	18.12 m
Radius u bending	20 mm
Connecting Tube Length	300 mm
Absorber Side Width Left-Right	480 mm
Final Water Temperature (°C)	56.6°C
Parabolic Supply Energy	43.5%
Parabolic Glass Diameter	1000 mm
Parabolic Glass Length	1000 mm
Parabolic Glass Thickness	8 mm

2.2 Manufacturing of Parabolic Collector
2.2.1 Assembly of all components of the parabolic collector

Once all the components were completed, they were assembled into the frame. The box was made up of five layers, starting with a 3 mm wooden plywood layer at the bottom, followed by a 2 cm layer of Styrofoam, a 1.2 cm layer of Armaflex, and a 1 mm thick layer of aluminum plates. The Serpentine Tube was placed on top of the plate, leaving a 2 cm space before the top layer of 8 mm thick glass was added. Figure 3 shows the completed parabolic collector.

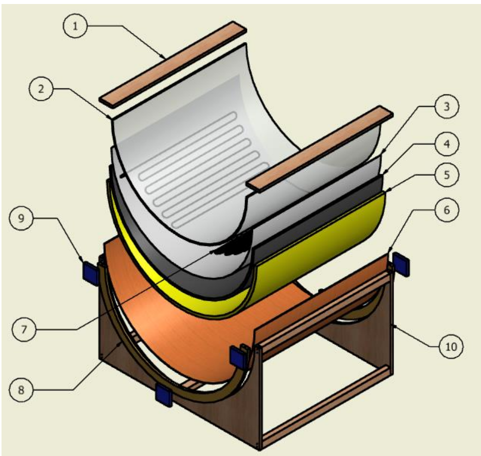

Fig. 3. Parabolic collector assembly

where the parabolic collector consists of (1, 8, 9, 10) frames, (2) curved glass, (7) serpentine tube, (3) aluminum plate, (4) Armaflex, (5) Styrofoam and (6) plywood/bottom cover.

2.2.2 Installation of measuring instruments

In the final stage, measuring instruments are installed on the input and output channels of the Parabolic Collector. To measure the temperature, a Thermocouple is used, while a flowmeter is installed at the input of the collector to measure the flow rate of the working fluid. Once the parabolic collector is completed, it is integrated with the ORC system as a heat sink system, as illustrated in Figure 4.

Fig. 4. Parabolic collector application to ORC

2.3 Testing of Parabolic Collector

In this research there are several measuring instruments as follows.

2.3.1 Data logger

In order to collect and record temperature data at several predetermined points automatically, a data logger was utilized. This includes the input and output temperatures of the ORC pump, turbine input and output, and input and output of the parabolic collectors. The data logger has the following specifications.

Type of data logger : OMEGA USB TC-08
Accuracy : ± 0.2 % or ± 0.5 C
Measurement range : Type K, -270 C to 1370 C

2.3.2 Temperature controller

The temperature controller is a device that is employed to regulate the water temperature in the evaporator and condenser by switching the water heater on or off. It includes a port for connecting the thermocouple as a water temperature sensor, which can be displayed on the panel, and a relay that functions to switch on or off the heater once the desired temperature has not been attained or has been reached. The temperature controller utilized in this study has the following specifications.

Manufacturer : Autonics
Model : TC4S
Measurement range : K type thermocouple, -50^{o}C - 1200^{o}C
Accuracy : ± 0.5 % or ± 1 C
Power supply : 100 – 240 VAC 50/60 Hz

2.3.3 Solid state relay

The solid state relay (SSR) is an additional relay that is connected to the temperature control device. Its main function is to ensure safety in the event of an electrical disturbance, preventing any direct damage to the temperature controller. The SSR has similar functions to the relay in the temperature controller, acting as a backup system in case of any malfunction. The specifications of the SSR used are as follows.

Manufacturer : Fortek
Model : SSR-25 DA
Current : Maximum 25 A

2.3.4 Heater

The heater is an essential component used to heat the water in the evaporator with a specified power of 3.5 kW. It is immersed in water and the temperature is set according to the desired variation using a temperature controller. The temperature can be easily adjusted and maintained at the desired level, making it an efficient heating source for the evaporator.

2.3.5 Flowmeter

Flowmeter is used to measure the flow of fluid that flows. The flowmeter specifications used are as follows.

Manufacturer : Wiebrock
Fluid : Water
Measurement range : 0.2 – 2 GPM

2.3.6 Working fluid R-134a

This study utilizes refrigerant R134a as the working fluid in an ORC system with a parabolic collector, as illustrated in Figure 5. The ORC system comprises three cycles: the organic Rankine cycle (indicated by a green line), the air conditioning cycle (indicated by a blue line), and the parabolic collector cycle (indicated by a red line). The ORC cycle involves four primary components: the pump, evaporator, turbine, and condenser, with pressure gauges and thermocouples installed at each stage to monitor the system's operating pressure and temperature. The turbine is connected to a generator, and voltage readings are taken using a voltmeter.

The evaporator uses a water heater and the parabolic collector as a heat source, and the parabolic collector cycle includes a thermocouple and flowmeter to regulate the working fluid's mass flow rate. The yellow line in the figure represents an electrical circuit, which includes two kWh meters to measure the electrical energy consumption. Additionally, a series of thermocouple cables are connected to a data logger, and the temperature data at predetermined points, including the input and output temperatures of the ORC pump, turbine, and parabolic collectors, are automatically recorded and transmitted to a PC for analysis.

The analytical method was employed in this study. Initially, the water temperature and flow rate were tested to ensure that the expected temperature could be achieved and maintained. In cases where the temperature could not be maintained or achieved, a water heater was used to stabilize the water temperature in the evaporator. Once the evaporator and condenser temperatures had been achieved, the ORC was activated. The temperature and pressure of the refrigerant at the input and output of the pump and turbine were recorded, as well as the temperature of the water in the ORC evaporator and condenser, the refrigerant flow rate, and the voltage generated by the generator. With this data, it was possible to calculate the ORC Pump Power ($w_{in,p}$), Evaporator Heat Intake Rate ($Q_{in,evap}$), Turbine Power ($\dot{W}_{out,T}$), Condenser Heat Out Rate (Q_{out}), so that the ORC System efficiency (η_{th}) and the ORC system clean power ($W_{net,ORC}$).

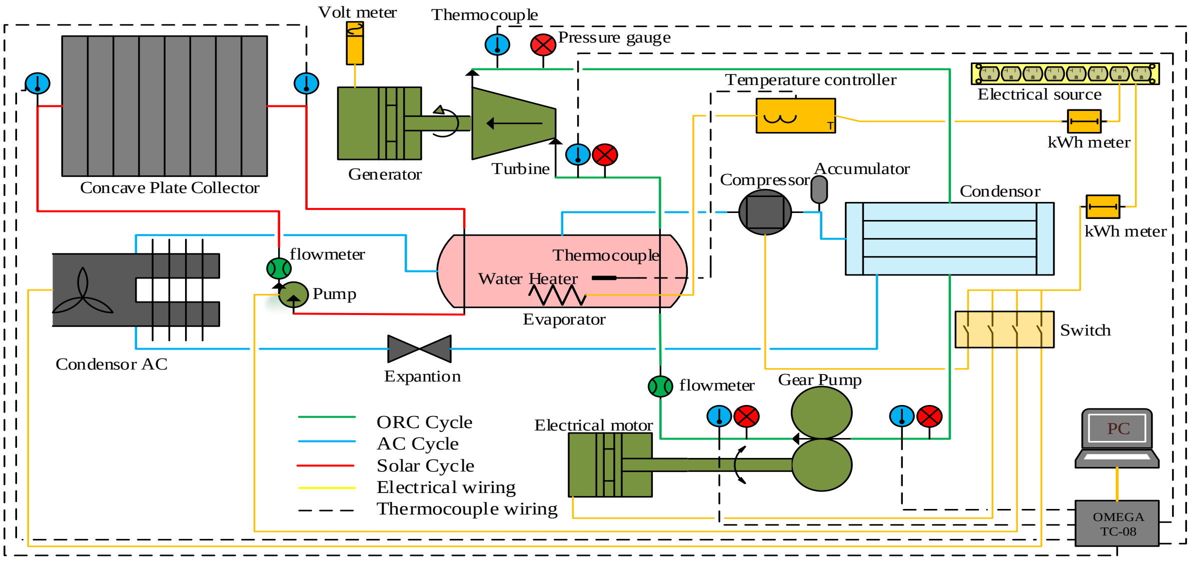

Fig. 5. Schematic ORC system with parabolic collector

3. Result and Discussion

The test results revealed various temperature variations on the parabolic collector as well as pressure and temperature variations on the ORC. Figure 6 shows the results obtained from the parabolic collector. Initially, the water in the evaporator had a temperature of 27Ꞓ and the water pump was turned on. The parabolic collector test was conducted from 10:00 to 12:00 and based on the test data, the water temperature increased and reached a peak of 56.6Ꞓ. However, this temperature was still below the desired temperature of 95°C, so a heater was used to assist in reaching the desired temperature. The heater was later connected to the temperature control to maintain the desired temperature, which was achieved between 12:00-13:00. After the desired temperature was reached, the ORC system was tested from 13:00–14:00.

Before the test is carried out, all temperature and pressure data are recorded as follows

T_h : 95Ꞓ is the water temperature in the evaporator
T_c : 5Ꞓ is the water temperature in the condenser
P_1 : 2.1 bar is the refrigerant pressure at pressure gauge 1 (into the pump)
P_2 : 2.1 bar is the refrigerant pressure at pressure gauge 2 (out of the pump)
P_3 : 2.1 bar is the refrigerant pressure at pressure gauge 3 (inlet turbine)
P_4 : 2.1 bar is the refrigerant pressure at pressure gauge 4 (out of the turbine)

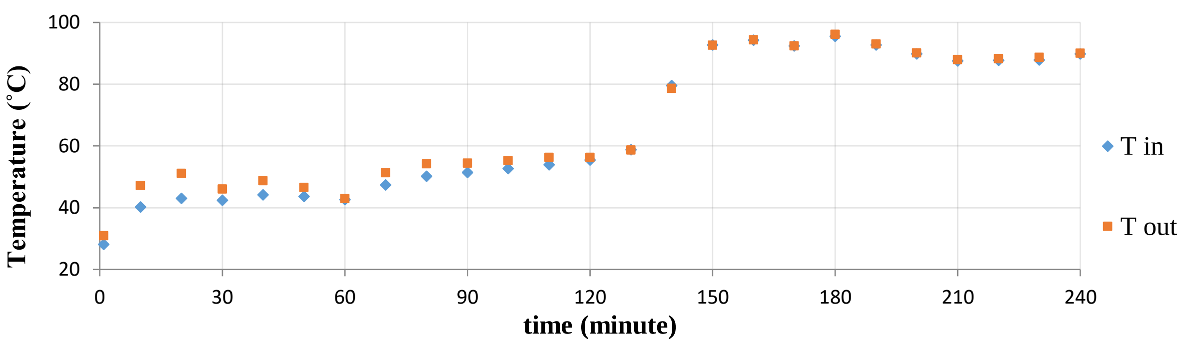

Fig. 6. Parabolic collector testing result

Two different testing methods were employed to evaluate the performance of the ORC system: one using a water heater as the heat source and the other using a combination of water heater and parabolic collector. The data collected from the tests were then used to calculate various performance parameters of the ORC system using the equations described earlier.

After collecting the test data, the next step was to determine the enthalpy values at each test point. This was done using mini REFPROP software by inputting the temperature and pressure values. It was essential to ensure that the data entered met the theoretical conditions for analysis. The following conditions were taken into consideration for the analysis

i. The fluid quality for test point 1 (pump input) is subcooled.
ii. The fluid quality for test point 2 (pump output) is subcooled.
iii. The fluid quality for test point 3 (turbine input) is superheated.
iv. The fluid quality for test point 4 (turbine output) is superheated.

After checking the quality of the fluid, it can be calculated.

The testing and data collection process in this study was conducted for one hour, with measurements taken every five minutes. The final temperature conditions in the evaporator and condenser were Th = 89 °C and Tc = 27 °C, respectively. Analysis of the collected data revealed that the ORC system exhibited maximum efficiency at the 20th minute of testing. Table 4 summarizes the results obtained at this time point.

Table 4
Experimental Data at Minute 20

Position	T (℃)	P (bar)	h (kJ/kg)
1	25.1	6.8	234.69
2	29.7	10	241.28
3	63.5	10.2	444.87
4	46.6	9.1	429.14

Then the calculation results are obtained as Table 5.

Table 5
Calculation Results

$\dot{m}_{act,reff}$	0.0325 kg/s
$P_{p,act}$	213.87 Watt
$P_{t,act}$	510.49 Watt
Q_{in}	203.59 kJ/kg
W_{net}	9.14 kJ/kg
η_{th}	4.489 %

For the ability of the parabolic collector to absorb solar energy, based on the data on the highest water temperature test, which is 56.6°C, it can be seen in Table 6.

The test results showed that the water from the parabolic collector, at a temperature of 56.6°C, can provide 45.22% of the total energy needed, indicating a significant potential for renewable energy sources. Meanwhile, the highest efficiency of the ORC system was 4.48%, achieved in the test with a heat source temperature variation of 95°C and an average evaporator temperature of 91°C. The differences in efficiency values were influenced by the temperature variations at each observation time, which affected the enthalpy values.

Table 6
Parabolic Collector Data

Heat Source Temperature	91°C
Initial Temperature	28.2°C
CPC temperature	56.6°C
CPC Heat	4836.94 kJ
Heat *Heater*	5857.711 kJ
Total heat	10693.730 kJ
CPC Contribution	45.22%

During the test, the heat source temperature was set at 95°C, but the temperature couldn't be maintained due to the low temperature output from the pump, affecting the hot water in the evaporator. Therefore, the average temperature data for hot water were used, resulting in an average temperature of 91.08°C for the heat source from the water heater and 91°C for the heat source from the combination of a water heater with a parabolic collector. Figure 7 presents the test results for the average thermal efficiency.

Figure 7 shows that the ORC system achieves its highest efficiency at an average evaporator temperature of 91°C when using a parabolic collector, with an efficiency of 2.97%, compared to 2.65% when using only a heater. In terms of power generation, Figure 8 provides a comparison between using a heat source from heating water and a combination of heating water with a parabolic collector. The average turbine power obtained using a water heater is 420.69 Watts and 246.13 Watts from the generator output or actual data. On the other hand, using a combination of a water heater with a parabolic collector, the average turbine power obtained is 430.04 Watts through theoretical calculations and 248.57 Watts through generator power output or actual data.

It is worth noting that the theoretical average turbine power is always higher than the actual average turbine power due to factors such as the absorption of heat by the turbine body and the transfer of the input heat temperature to the turbine's cover. Consequently, the work produced by utilizing differences in temperature and pressure between the turbine input and output is reduced.

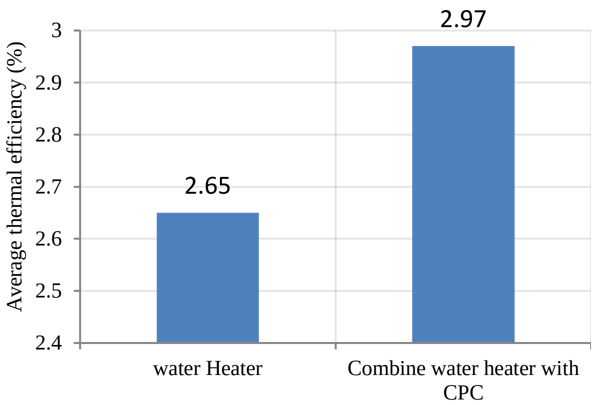

Fig. 7. Average thermal efficiency

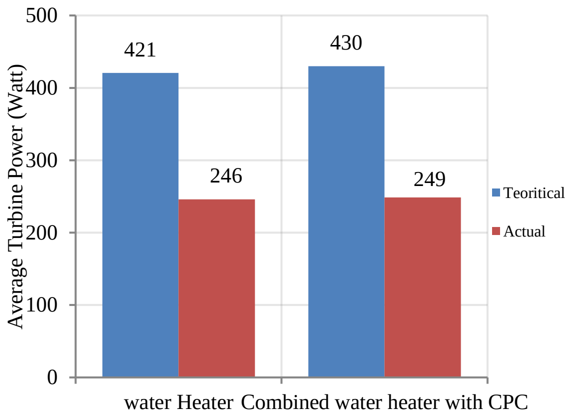

Fig. 8. Average turbine power

4. Conclusion

This study presents the design, manufacture, and testing of an Organic Rankine Cycle (ORC) system powered by a Parabolic Collector as its energy source. The Parabolic Collector has a tube length of 18.12m, a diameter of glass curvature of 1000mm, a width of 1000mm, and a glass thickness of 8mm. During a two-hour test, the Parabolic Collector was able to heat water to a maximum temperature of 56.6℃ with a flow rate of 0.042 kg/s from an initial temperature of 28.2℃.

The ORC system achieved an average turbine output power of 430.04Watt in theoretical calculations and 248.57 Watts in actual measurements. The highest thermal efficiency of the ORC system was 4.489%, achieved at the turbine input temperature of 63.5℃ and the turbine input pressure of 10.5 bar. These results demonstrate the potential of using a Parabolic Collector as a renewable energy source for ORC systems, with the ability to generate significant power outputs with high thermal efficiencies.

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