The study to investigate the thermal performance of solar cooker using a spot Fresnel lens for concentrators of solar thermal energy is conducted.

The main objectives of the present work are:

a) to develop a new design of the cooking pot of solar cooker as an absorber of solar thermal from a spot Fresnel lens;

b) to analyze the relationship of several temperature parameters in the cooking pot with the thermal efficiency of the Fresnel solar cooker (FSC);

c) to conduct field test by heating test and cooling test to obtain a performance characteristic of FSC.

The experimental test was conducted at Brawijaya University (7.9553°S, 112.6145°E), East Java, Indonesia during August – September 2019. The Fresnel lens operation method uses the azimuth manual tracker to concentrate direct normal irradiance (DNI). The measurement of Direct Normal Irradiance (DNI) was made by the SM 206 Solar Power Meter and placed on the FSC frame. A new design of solar cooking pot has been developed. That is a cylindrical shape for boiling water and food cooking with a cone cavity as a solar collector. While on the cooking pot, the temperature sensor is placed:

1) ambient temperature;

2) cooking pot temperature;

3) focal point temperature on the receiver surface;

4) water temperature in the solar cooking pot.

It is connected to the Digi-Sense 12 CH-Scanning Benchtop Thermometer for temperature data acquisition system. The measurement of wind speed was made by Cup Anemometer ABH-4224. The procedure for testing the FSC was developed based on existing international testing standards. The receiver/cooking pot was tested for thermal performance characteristics of cooking by conducting the following tests:

1) no-load test;

2) water heating and cooling tests.

The experimental results show that the average stagnation temperature in a cooking pot with a conical cavity receiver was 267.35 °C. The receiver shape with a conical cavity has better heat transfer capability and low heat losses, hence, making it suitable for applications on FSC. DNI ±850 W/m² produces a focal point temperature of 1064 °C, a heat removal factor of 7.39 W/m²·°C, and an optical efficiency factor of 0.312. Therefore, the thermal efficiency of the FSC is 27.72 %. The thermal efficiency tends to decrease until the end of the process due to the influence of the optical efficiency factor

Keywords: Fresnel lens, solar cooker, solar energy, solar cooking pot, receiver, conical cavity, temperature, heat removal factor, optical efficiency factor

AN EXPERIMENTAL STUDY OF SOLAR COOKER PERFORMANCE WITH THERMAL CONCENTRATOR SYSTEM BY SPOT FRESNEL LENS

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1. Introduction

Solar thermal energy is one of the potential energy to be managed and developed further as a source of energy reserves, especially for countries located on the equator, including Indonesia, where the sun shines throughout the year. The potential of solar power in this region can reach 5.1 kWh/m²/day (Eastern Indonesia) and 4.5 kWh/m²/day (Western Indonesia). However, the majority of energy use in Indonesia comes from fossil energy sources. Until 2019, power plants in the country are still dominant from conventional energy sources, including coal (50 %), followed by natural gas (29 %), fuel (7 %). While the use of renewable energy is only about 14 %, and for solar energy, utilization is less than 1 % [1].

Currently, the largest energy user in Indonesia is the industrial sector by 36 %, the transportation sector by 40 %, the household sector by 16 %, and the commercial sector by 6 %.

The use of energy in the household sector is still significant because it comes from LPG fuel, crude oil, or electricity. From this fact, alternative use of solar thermal energy as an alternative energy source is needed. The advantages of using solar thermal energy include:

1) solar thermal energy is the energy that is available in almost all parts of the earth's surface and is not used up (renewable energy);

2) the use of solar thermal energy does not produce pollutants and emissions that are harmful to both humans and the environment;

3) the use of solar thermal energy for cooking stoves, water heaters, drying of crops will be able to reduce the need for fossil energy;

4) solar energy technology for household applications is quite simple and has economic value.

One alternative to the reduction of energy demand in the household sector is the development of solar cooker equipment. Currently, the solar cooker that is developed for more households uses a box-cooker type. This solar cooker model besides has advantages of being simple and inexpensive, but also has disadvantages. The disadvantages of this type of stove include the cooking process takes a long time and cannot be used for frying because the temperature of the stove is too low. The primary device in solar cooker technology is sun collector equipment. The working principle of a collector is a process of heat transfer, which includes radiation, conduction, and convection. The collector converts solar energy into thermal energy through the absorber/receiver, so that this thermal energy can be used for cooking purposes.

Presently, many solar collectors use conventional technology, both in terms of design and material. Glass material is still the dominant use for both the flat collector and the concentrating collector. Because it is needed for the development of solar collector technology that is lightweight, easy to operate, inexpensive to produce, heat generation is fast and produces a high energy density. The use of appropriate and efficient solar collectors can be one of the solutions to the problems of solar cookers so far.

One alternative to developing a solar cooker is to design a solar thermal energy collector using a large lens. The Fresnel PMMA lens used can focus sunlight into a focal point on a cooking pot or receiver. The heat transfer to an absorber/receiver as a cooking pot can be used for cooking purposes. Testing the performance of Fresnel Solar Cooker (FSC) based on standards also needs to be considered by researchers. So that the performance of a solar cooker that is designed can be compared with others. Therefore, the research topics to develop solar cooking pot design and an investigation of the potential of Fresnel lenses as thermal concentrators for solar cooker applications are relevant.

2. Literature review and problem statement

Over the past few years, solar power is an alternative energy source for cooking. This is a simple, safe, and convenient way to cook food without consuming fuel, heating the kitchen, and polluting the environment. Solar stoves have many advantages, on the health, time, and income of users and the environment. In tropical countries such as Indonesia, solar energy is very large and therefore a reliable and sustainable source of energy. The principle of a solar cooker consists of three heat transfers. First, direct solar rays, i. e., sunrays, are directed to food objects. Second, by convection, food is heated with hot air in an isolated chamber. Third, conduction is the heat transfer due to sunlight absorbed by metal plate collectors (steel or aluminum). This heat will be delivered to the food through a pan placed above the metal plate collector. Combining these three heat transfer combinations will increase the cooking process efficiency with a solar cooker [2–7]. Geometry types and designs of solar cookers are, in principle, classified into three types, namely (1) concentrator type, (2) box-type designs, and (3) indirect types. Also, the classification of solar stoves into four types is (1) box-type solar cookers, (2) concentrating-type or reflector cookers, (3) heat-accumulating solar cookers, and (4) solar steam cookers [8–11].

So far, solar stoves are developing more types of direct solar cookers. This solar cooker model, besides, has the advantage of being inexpensive and straightforward. However, the cooking process takes a long time, cannot be used for frying because the stove temperature is too low [12, 13]. Until now, the solar cooker design modifications continue to be studied by experts to obtain optimal performance by correcting the type of direct solar cookers. Various studies and development of methods of heat energy transfer in solar cookers have been carried out. The heat transfer media used can be in the form of oil, pressurized steam, or solar energy storage systems that use Phase Changing Materials [14, 15].

In recent years, the application of solar thermal concentrating technology based on the author review [16] has become an interesting study to be applied to the household and industrial sectors. This solar concentrating system can produce a temperature range of 80–250 °C. This method has the advantage of delivering uniform focusing characteristics of sunlight, optimal thermal performance, and high optical efficiency.

However, according to the author [17], nowadays the application of solar thermal energy concentrators is still dominated by the reflective method of mirrors in the form of a parabolic trough collector, linear Fresnel reflector (LFR), parabolic dish, and central receiver. One of the weaknesses of this model is that the material is heavy, so it needs a sturdy framework, so it is not economical. Besides this, it requires much power to move the solar tracking mechanism.

Therefore, the use of Fresnel lenses made of plastic can be a solution to the problem above. The Fresnel lens is a unique optical lens. Now it can be made from plastics such as acrylic Fresnel lenses, PolyMethylMethAcrylate (PMMA), PolyVinylChloride (PVC), PolyCarbonate (PC), and HDPE. Nowadays, the PMMA Fresnel lens is one of the best choices in the field of concentrated solar thermal energy applications. PMMA Fresnel lenses also have many advantages, namely light weight, low cost for mass scale, can increase energy density effectively and have higher efficiency compared to glass reflectors [18, 19]. Fresnel lenses replace the curved surfaces of conventional lenses with a series of concentric grooves, printed on a thin and light plastic sheet. Slots act as individual refracting surfaces, like small prisms when viewed in a cross-section, bending parallel rays in estimates that are very close to the typical focal length [20–22].

In the last ten years, studies and experiments of Fresnel lens application have been carried out by many authors. In [23], the authors developed the design and manufacture of prototypes of solar cooker using a large Fresnel lens as a solar concentrator, with a manual tracker system in zenith and azimuth directions. The result of the focused temperature

of the Fresnel lens on the stovetop surface can reach 300 °C. This prototype is also designed to allow the process of heating/cooking indoors by flowing heat transfer fluid into the furnace in the room.

In [24], the author investigates and designs solar water heater using Fresnel lens collectors. The purpose of this research is to study the thermal performance of solar thermal energy collector storage by using paraffin wax, which functions as a storage of heat energy or called Phase Change Material (PCM). Where the PCM thermal mass is obtained by direct heating using a Fresnel lens, then through the thermal mass fins are conducted into a phase change material (PCM). The experimental results obtained that the water temperature for the water heating system is around 60 °C.

The author of [25] presented an experimental and theoretical model using Fresnel lenses for solar water desalination. Fresnel lenses used in experiments are made of acrylic, with the specifications: $p \times l$=50×70 cm, and the focal length is 0.85 m. The analysis indicates that the collector efficiency of Fresnel lenses on sunny days can reach 70 %. The water heating test results show that the energy received by water is 249.9 W.

The author of the paper [26] designed the use of Fresnel lenses for the indirect solar cooker. A semicylindrical-shaped solar boiler that is insulated is used to produce steam. The solar boiler design is capable of producing 146 °C high-temperature steam and 3.15 barG pressure. Meanwhile, the estimated energy efficiency and maximum exergy results for boilers were 30.18 % and 2.86 %, respectively. According to him, the efficiency of the solar cooker can still be improved by improving the design of the solar boiler. e. g., add baffles, nozzles, or automatic steam injection systems. In addition, the use of solar boilers on a larger scale, steam can be used as a utility in a chemical pilot plant.

In the study [27], the author presents a solar cooker equipped with a fixed focus Fresnel lens solar concentrator. Fresnel lens solar stove design with fixed focus, consisting of the Fresnel lens solar concentrator, cavity receiver, mineral oil circulation system, solar storage system, and cooker unit. The tracker system is made automatically. The fixed focus Fresnel lens solar concentrator allows the receiver of the sun's stove cavity to be stationary during all cooking time. So, the cooking stove can be placed next to the side of the room. The results showed that the average optical efficiency of the three cooking vessel/pot forms studied was 68.49–76.40 %. So when compared to other systems, this fixed-focus Fresnel lens solar cooker has a relatively higher thermal efficiency. It also has the advantage of making solar tracker systems easy and cost-effective.

However, from the above studies, there is no standardization of the performance testing of concentrating solar cookers. The estimation of the solar cooker performance is still based on the concept of heat transfer, the first and second laws of thermodynamics [28–32]. So for application in the field, it is difficult to compare the performance of the solar cooker designed by each researcher.

So far, the use of Fresnel lenses as a solar concentrator for solar cooker applications is still rarely studied. In this regard, it is necessary to develop the performance test methods, and design analysis of Fresnel Solar Cooker (FSC) that can produce the same solar cooker characteristics. In this paper, the study based on field experiments follows the international standards of testing for concentrating solar cookers. So that the thermal performance of the Fresnel solar cooker can be compared with else.

3. The aim and objectives of the study

The aim of the study is the investigation of the thermal performance of solar cooker using a solar concentrator by a spot Fresnel lens.

To accomplish the aim, the following objectives have been set:

– to develop a new design of the cooking pot of solar cooker as an absorber of solar thermal from a spot Fresnel lens;

– to analyze the relationship of several temperature parameters in the cooking pot with the thermal efficiency of the Fresnel solar cooker;

– field-test by heating test and cooling test of water in the cooking pot to obtain a performance characteristic of the Fresnel solar cooker.

4. Materials and methods of the experimental study for investigating the Fresnel solar cooker performance

4. 1. Basic theory of temperature stagnation on solar concentrating system

The form of an absorber/receiver in a solar concentration system is identified as the Geometric Concentration Ratio symbolized by CR_g. This discussion of geometric efficiency requires a temperature parameter called stagnation temperature. Stagnation temperature is the ideal peak/maximum temperature received by the receiver's surface with certain geometric factors. The stagnation temperature is measured in a receiver/absorber/cooking pot in conditions with no load and no losses on the receiver surface (Q_{use}=0). The relationship between the geometric concentration ratio (CR_g) and stagnation temperature (T_{st}) can be analyzed by a simple thermal equilibrium. Fig. 1 shows an illustration of the thermal equilibrium on a Fresnel lens. The energy balance equation that can be seen starts from the formula (1)–(3).

Fig. 1 shows that a Fresnel lens will concentrate beam radiation (Direct Normal Irradiance) with specific lens efficiency. The efficiency of this lens is determined by the quality of the lens material, namely absorptivity (α) and emissivity (ε). These parameters will cause radiation losses on the lens. So the useful energy received by the receiver (cooking pot) is written like the formula (1),

$$q_{useful} = q_{receiver} - q_{radiationloss}, \tag{1}$$

where

$$q_{radiationloss} = \varepsilon \sigma T^4, \tag{2}$$

$$q_{receiver} = \alpha q_{solar}, \tag{3}$$

$$q_{solar} = CR_g . I_b, \tag{4}$$

If we assume q_{useful}=0; α=1; ε=1; $T=T_{st}$, then the stagnation temperature equation (T_{st}) can be written like the formula (5),

$$T_{st} = \left(\frac{CR_g . I_b}{\sigma} \right)^{0.25}, \tag{5}$$

where q=heat flux (W/m²); T_{st}=stagnation temperature (°K); CR_g=geometric concentration ratio; I_b=DNI=direct solar radiation (W/m²); σ=Stefan-Boltzman's constant=5.675×10⁻⁸ (W/m²K⁴).
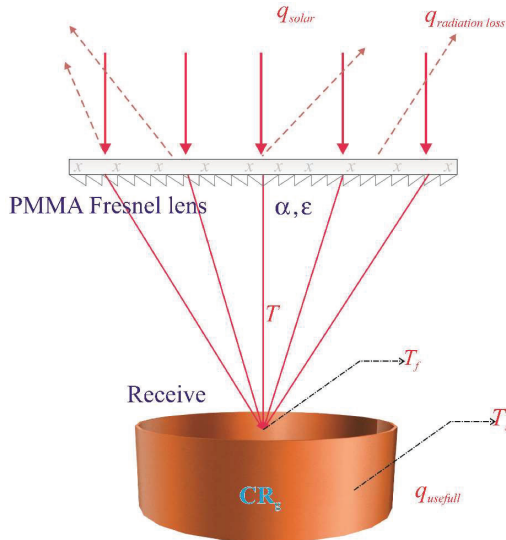
Fig. 1. Thermal balance in a Fresnel lens

4. 2. Theoretical study of performance characteristics in Fresnel solar concentrating cooker testing

Another method for calculating heat losses that occur in solar cooker performance testing can be done by heating and cooling tests. In general, the effect of heat loss that occurs in receivers is due to conduction, convection, and radiation. Therefore, in practical field experiments a practical equation is developed that combines the thermal efficiency equation with the energy balance of the receiver to obtain a performance parameter in the solar cooker concentrating test, namely the heat removal factor, $F'U_L$ and the optical efficiency factor, $F'\eta_o$. Where $F'\eta_o$ is also called the second figure of merit, F_2 [28, 31]. Thus, the heat removal factor equation can be written,

$$F'U_L = \frac{m_w c_w + m_{cu} c_{cu}}{A_r \tau_o}, \tag{6}$$

where m_{cu}=mass of a receiver made from copper (kg), c_{cu}=specific heat capacity of copper=385 J/kg·K, τ_o=time required for the cooling process from water temperature of 95 °C to ambient temperature (cooling test). While the optical efficiency factor equation is,

$$F_2 = F'\eta_o = \frac{F'U_L}{CR_g} \left[\frac{\dfrac{T_{wo}-T_a}{I_b} - \dfrac{T_{wi}-T_a}{I_b} e^{\frac{\tau}{\tau_o}}}{1 - e^{\frac{\tau}{\tau_o}}} \right], \tag{7}$$

where τ=the heating time needed for water from ambient temperature to 95 °C (heating test). While the average thermal efficiency of a solar cooker can be predicted by the equation,

$$\eta_{Th} = F'\eta_o - \frac{F'U_L(\overline{T}_w - \overline{T}_a)}{CR_g \cdot I_b}. \tag{8}$$

This water heating time (τ_b) is obtained from eq. (7), so that it becomes,

$$\tau_b = \tau = -\tau_o \ln \left[\frac{F'\eta_o - \left(\dfrac{F'U_L}{CR_g} x \dfrac{T_{wo}-T_a}{I_b} \right)}{F'\eta_o - \left(\dfrac{F'U_L}{CR_g} x \dfrac{T_{wi}-T_a}{I_b} \right)} \right]. \tag{9}$$

Furthermore, to determine the characteristics of the Fresnel concentrating solar cooker, a relation is made to the parameters of the water heating time (τ_b) to the parameter ((T_{avg}-T_a)/($I_b A_r$)). Performance characteristics in solar cooker testing, especially using solar collectors or concentrators (Fresnel lens) in general, are shown with two graph models. First, it is a graph of the relationship between boiling water temperature (τ_b) with a combination of temperature, solar radiation, and receiver area parameters. Second, namely the relationship of efficiency with a combination of temperature parameters, solar radiation, and receiver area. In connection with the presentation of the combination of parameters $f(T_w, T_a, I_b, A_r)$, this can be in the form of $\ln(T_{wo}-T_a);(T_{wo}-T_a)/I_b$ and $T_{avg}-T_a/(I_b A_r)$.

4. 3. Experimental test of Fresnel solar cooker performance

The experimental test was conducted at Brawijaya University (7.9553°S, 112.6145°E), East Java, Indonesia. Experimental testing on the Fresnel Solar Cooker (FSC) was carried out during clear days in August – September 2019. The Fresnel lens is operated manually according to the azimuth at intervals of 10 minutes to concentrate direct normal irradiance (DNI). Solar radiation (DNI) is measured using the SM 206 Solar Power Meter. It uses a K-type thermocouple temperature sensor connected to the Digi-Sense 12 CH-Scanning Benchtop Thermometer with a range from −270 °C to 1372 °C. The tool is set for a data recovery time of 0.5 seconds. Next, four thermocouples are installed in the cooking pot, with the following positions:

1) ambient temperature (T_a);
2) cooking pot temperature (T_r);
3) focus point temperature (T_f);
4) temperature of water in the tube receiver (T_w).

Measurement of wind speed (v_w) by ABH-4224 cup anemometer is done every 10 minutes, with a height of 2 meters above ground level. Research procedures refer to international standards. The photograph of the experimental setup is shown in Fig. 2, while the setting of measurement instrumentation of Fresnel solar cooker performance is shown in Fig. 3.

Fig. 3 shows the location of several measuring parameters needed for testing the performance of a Fresnel Solar Cooker (FSC). It is essential to measure the concentration temperature or focus temperature (T_f) produced by the Fresnel lens. It is necessary to determine the potential of solar energy in the form of a radiation spectrum that can be converted into thermal energy. The focus temperature depends on the DNI. It was entering through the Fresnel lens, focal concentration ratio, focal distance accuracy, and tracker accuracy.

Furthermore, in the case of concentrated solar power technology, the accuracy of the solar tracker is one of the critical factors for increasing the thermal efficiency of the receiver. The FSC frame is mounted with an upright sun-tracking device called a sundial. This tool serves to maintain the stability of the orientation of the focus point on the receiver, which is done manually. All temperature measurements (T_a, T_f, T_r and T_w) are variables in the calculation of the thermal efficiency of the receiver/cooking pot. The thermal efficiency of this water-filled cooking pot is used to determine the performance of the designed FSC. Furthermore, the wind speed around the location becomes a variable in the convection loss experienced by the cooking pot.
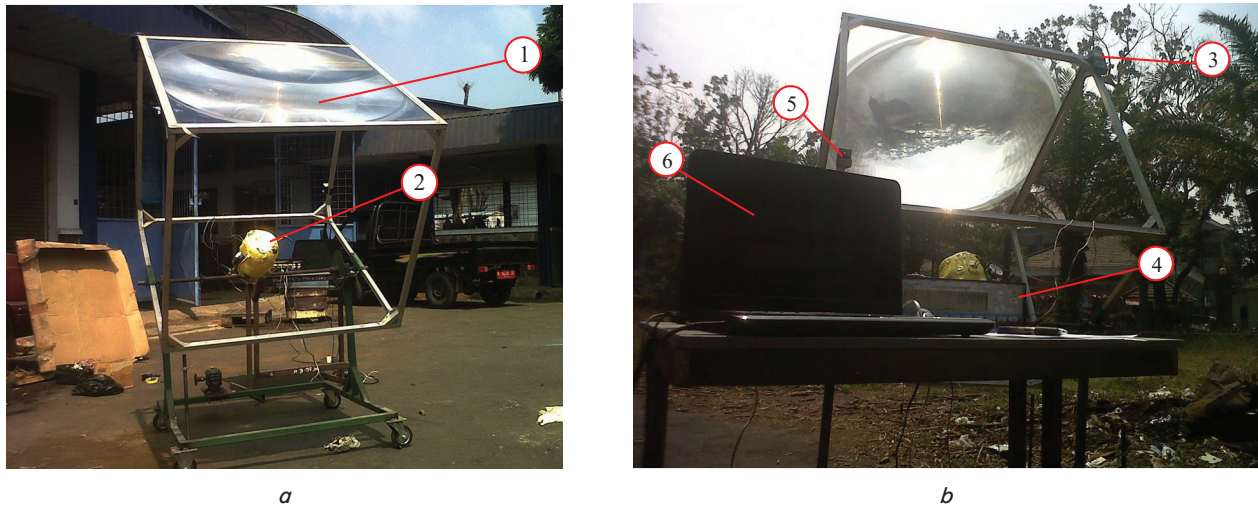
a   *b*

Fig. 2. Photograph of the experimental setup: *a* — installation of Fresnel solar cooker; *b* — instrumentation setting; 1 — PMMA Fresnel lens; 2 — insulation cooking pot with conical cavity receiver; 3 — solar power meter; 4 — data logger; 5 — sundial; 6 — laptop
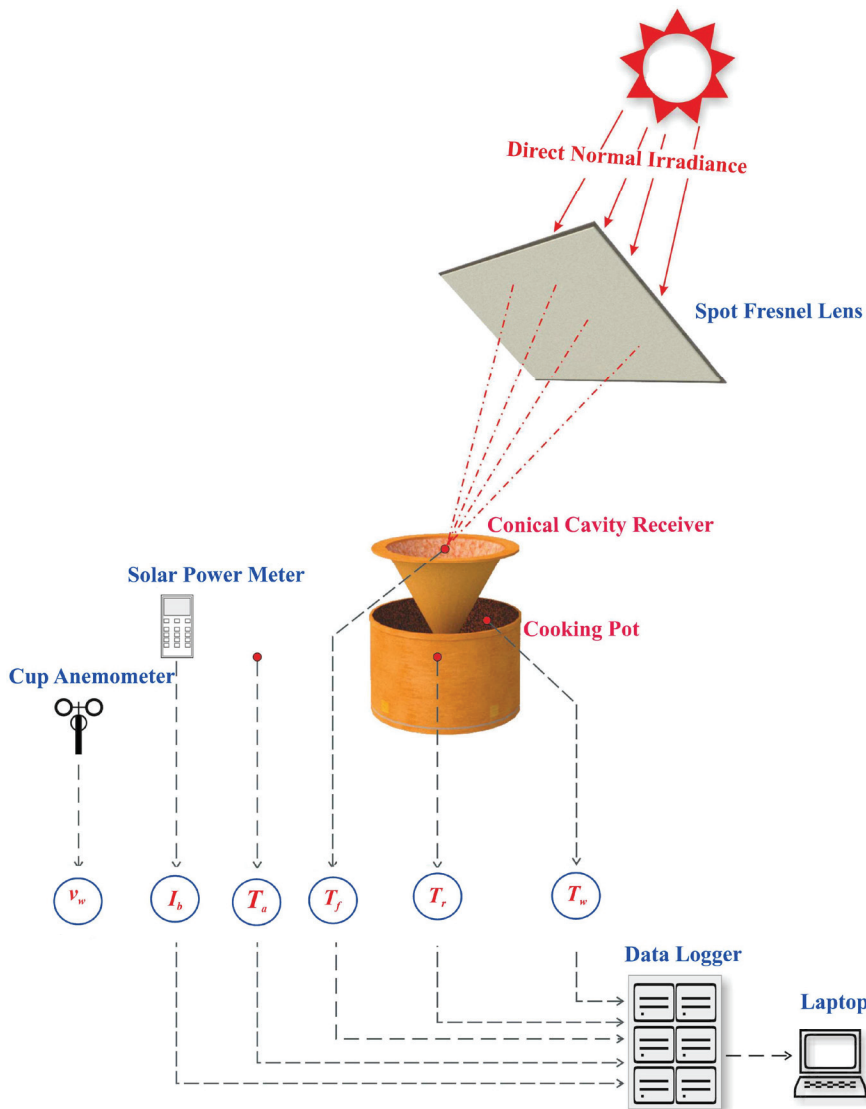

Fig. 3. The setting of measurement instrumentation of fresnel solar cooker performance

cooking. It is in the form of a tube (cooking pot) that uses copper. The capacity of the cooking pot, m_w=2 kg of water. All sides of the cooking pot were isolated using a 10 mm thick layer of glass wool. The cooking tools are placed at the focal point of the Fresnel lens (88 cm) on the surface under the Fresnel lens concentrator. The specifications of Fresnel lenses are shown in Table 1.

From the design results obtained by the volume and surface area of the cooking pot, respectively, V_r=2 L of water and A_r=0.1051385 m^2=1051.39 cm^2. Receivers with conical-shaped catching surfaces are very suitable to be applied as solar thermal collectors using Fresnel lens. The conical cavity has the best thermal performance because the value of the convective loss is small compared to other forms [33].

The shape of the surface of the Fresnel lens (circular or square) has an important role in knowing the efficiency of the lens. In this study, the surface shape of the Fresnel lens used is a circular Fresnel lens aperture. It has small reflection so that the lens efficiency is higher than that of a square one. While the material of this lens is a type of acrylic specifically called polymethylmethacrylate (PMMA).

Furthermore, the important parameter in a solar thermal concentrating system is the geometric concentration ratio. The geometric concentration ratio (CR_g) is based on the comparison of the area of the Fresnel capture lens (A_{FL}) with the surface area of the cooking pot/receiver(A_{cp}). The formula of CR_g cooking pot is:

Fig. 4 shows the design of the cooking pot in this experiment. It consists of a conical cavity as a solar thermal absorber/receiver and tube shape as the bottom vessel for

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$$CR_g = \frac{A_{FL}}{A_{cp}}, \qquad (10)$$

where, the aperture area of a Fresnel lens, A_{FL}=7,850 cm^2 and the surface area of cooking pot/receiver (A_{cp}) is 1051.39 cm^2. Hence, CR_g=7.48$\cong$8x.
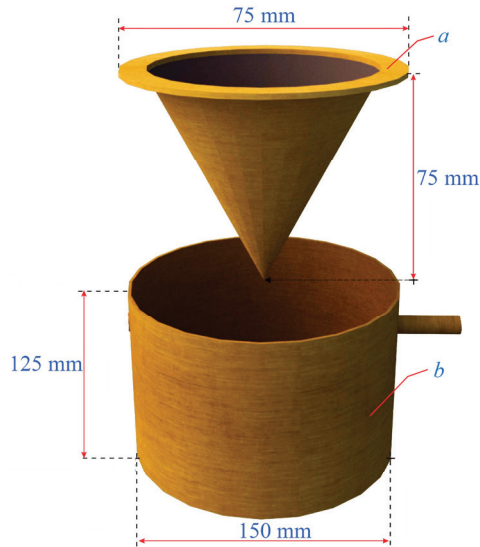

Fig. 4. Design of solar cooker pot: a — receiver-type conical cavity; b — bottom pot for cooking

Table 1

PMMA specifications of Fresnel lenses

Manufacturer	Wuxi Bohai Optical ApparatusElectronicCo. Ltd (China)
Prod.code	BHPA880-2
Material	PMMA (Polymethyl-Methacrylate)
Type	Circular Fresnel Lens Aperture
Diameter (mm)	1,000
Surface (m^2)	0.785
Weight (kg)	2
Thickness (mm)	3
Groove pitch (mm)	0.5
Focal distance (mm)	880
Circular focus diameter (mm)	20
Solar radiation concentration	2,500x
Lens efficiency, η_L (%)	89.9

tion temperatures. The calculation of stagnation temperature (T_{st}) is based on equation (5) and (10).

Table 2

Calculation of stagnation temperature based on Direct Normal Irradiance measurement

Cooking pot specification	Test	Data value	DNI W/m^2	T_{st} ^{o}C
Receiver type: conical cavity A_r: 1051.39 cm^2 V_r: 2 liter CR_g: 8	12/08/2019	Min	108.75	78.94
		Max	787.50	304.34
		Avg	602.06	253.20
	13/08/2019	Min	678.75	283.28
		Max	789.00	304.61
		Avg	743.56	295.99
	15/08/2019	Min	76.28	49.08
		Max	857.39	316.74
		Avg	566.97	244.33
	15/09/2019	Min	155.11	111.61
		Max	799.28	306.48
		Avg	703.65	92.11

Fig. 5 shows that CR_g and DNI influence the stagnation temperature. The higher the CR_g value, the higher the stagnation temperature (T_{st}). The average stagnation temperature received on the cooking pot surface for various DNI is 267.35 °C. Therefore, the CRg factor is used to determine the estimated temperature of the solar cooker.
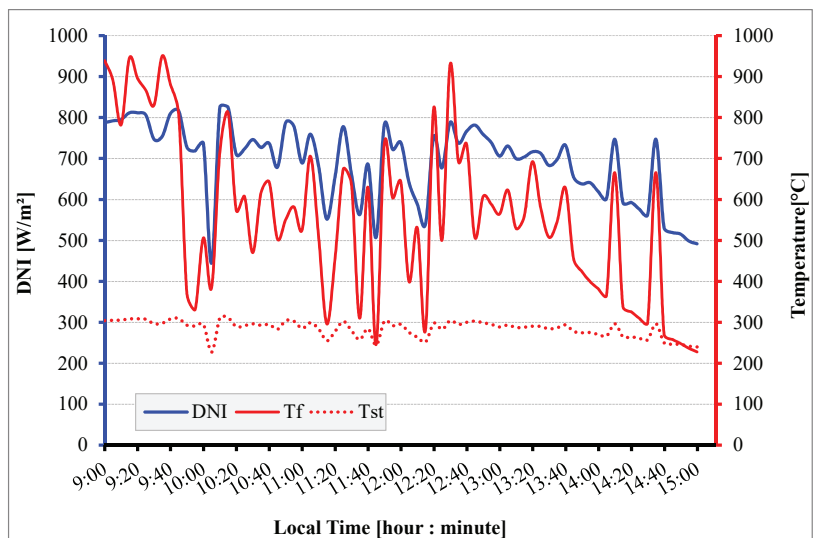

Fig. 5. The measurement of DNI, focus temperature (T_f), and stagnation temperature (T_{st}) versus

5. Results of experimental study of Fresnel solar cooker performance

5. 1. Results of stagnation temperature calculation of FSC cooking pot

Table 2 shows the results of the calculation of temperature stagnation. Fig. 5 shows the relationship between DNI (I_b), stagnation temperature (T_{st}), and temperature of the focus point (T_f), for the value of CR_g=8.

Table 2 shows the results of DNI measurements carried out for four days. Furthermore, DNI measurement results and cooking pot specifications can be calculated at stagna-

5. 2. Results of water heating test in the FSC cooking pot

Based on the heating test, the water boiling point in the isolated cooking pot by glass wool is obtained, as shown in Table 3. The graph of DNI, time, and temperature can be made, as shown in Fig. 6.

The main parameters needed in this boiling test analysis are direct solar radiation (I_b), water temperature (T_w), ambient temperature (T_a), and time (t). Therefore, from the results of tests conducted on 15/09/2019, up to 95 °C water temperature testing is taken. Table 3 and Fig. 6 show the results of boiling tests conducted on the water in cooking pots up to a temperature of 95 °C.

Table 3

Boiling test measurement data

Time t (minutes)	D.N.I. I_b (W/m^2)	Water Temp. T_w (ºC)	Receiver Temp. T_r (ºC)	Ambient Temp. T_a (ºC)
0	556	34.5	35.1	30.0
5	757	39.5	40.1	30.1
10	752	44.5	45.1	30.2
15	747	49.5	50.1	30.3
20	741	54.5	55.1	30.4
25	730	59.5	60.1	30.4
30	720	59.7	61.5	30.6
35	650	61.7	62.8	31.6
40	704	64.8	64.1	32.2
45	763	78.2	73.8	33.0
50	695	85.0	82.8	33.4
55	760	90.1	88.4	33.5
57	740	95.1	94.6	33.6
Avg	716	64.8	64.9	31.5

The descriptive statistics in Table 4 provides an overview of the sampling data from the cooling test results. These results can be used to estimate the cooling time from boiling temperature (95 °C) to ambient temperature (33 °C). The data distribution in this cooling test obtained a standard error, $SE=0.141$. So from Fig. 7 below, it is found that the relationship between temperature and cooling time has a strong correlation level, which is indicated by the coefficient of determination, $R^2=0.88$.

In the cooling test, the influence of ambient temperature and wind speed became the dominant factor in the cooling process, where the wind speed at the time of testing was 0.87 m/s. Fig. 7 is the result of measuring the cooling test concerning time.

Fig. 7 shows the equation of the relationship between cooling time (τ_o) and water temperature (T_w), °C, where the equation can be written,
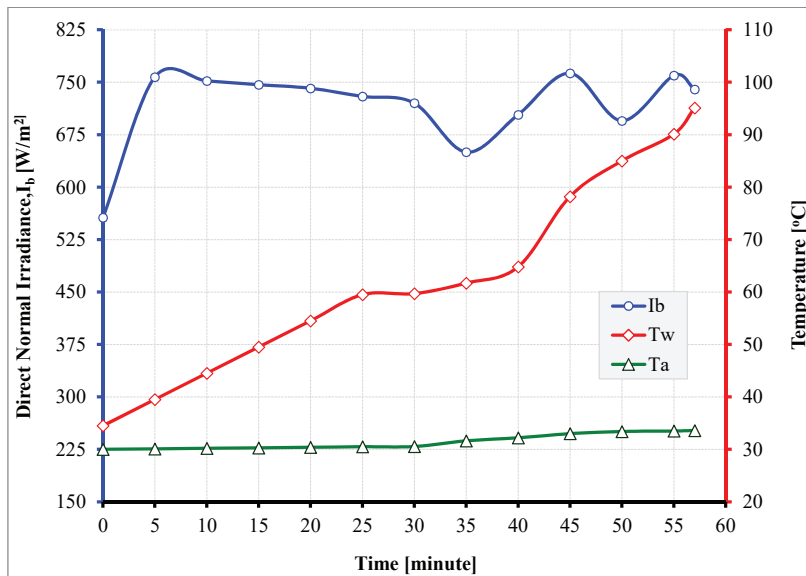
$$\tau_o = 787.1 - 185\ln(T_w). \tag{11}$$

Fig. 6. Water heating test of FSC cooking pot ($CR_g=8$; $m_w=2$ kg)

Table 4

Descriptive statistics of water temperature cooling test

Descriptive statistics	Cooling Test
Mean	63.4
Standard Error	0.141
Median	62.7
Mode	66.5
Standard Deviation	3.22
Sample Variance	10.34
Kurtosis	−1.20
Skewness	0.06
Range	13.9
Minimum	56.7
Maximum	70.6
Sum	33021.8
Count	521

Based on Fig. 6, the boiling time is obtained, $\tau=57$ minutes. Under average of DNI conditions, $I_b=716$ W/m^2 and ambient temperature, $T_a=31.5$ °C.

5. 3. Results of water cooling test in the FSC cooking pot

The general cooling test method is carried out when the temperature of the water in the cooking pot has reached 95 °C–100 °C. Furthermore, the concentrator is closed so that sunlight does not enter, then the movement of temperature reduction and cooling time are measured until the water temperature reaches ambient temperature. Table 4 shows the results of the descriptive statistics of temperature data from the water cooling test in the receiver. The measurement data of temperature and time is recorded by a data logger every 4 seconds, which is carried out for 35 minutes (12:23−12:59 p.m.)

y = -185ln(x) + 787.1
R² = 0.880
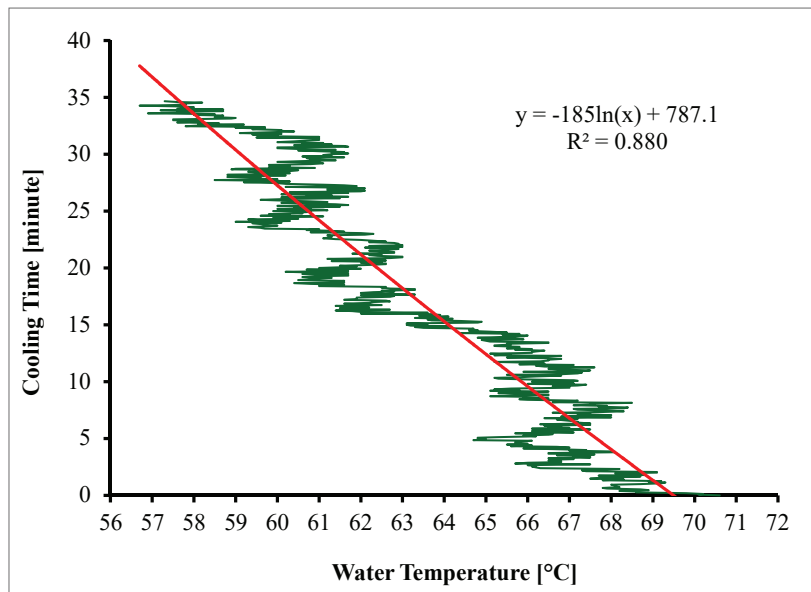
Fig. 7. Water cooling test of FSC cooking pot ($CR_g=8$; $m_w=2$ kg)

The maximum temperature reference point to (0) is 70.6 °C. When using ambient temperature, T_a=33 °C, time (t_1)=140.25 minutes is obtained, if the boiling temperature=95 °C, time (t_2)=−55.37 minutes is obtained. So that the cooling time (τ_o) can be reformulated into,

$$\tau_o = t_1 - t_2. \tag{12}$$

τ_o=140.25−(−55.37)=195.62 minutes.

The next calculation results are plotted in the graph to get a complete picture of the cooling process. Fig.8 shows a cooling test from 95 °C to an ambient temperature of 33 °C in a water-filled cooking pot with a mass of 2 kg.
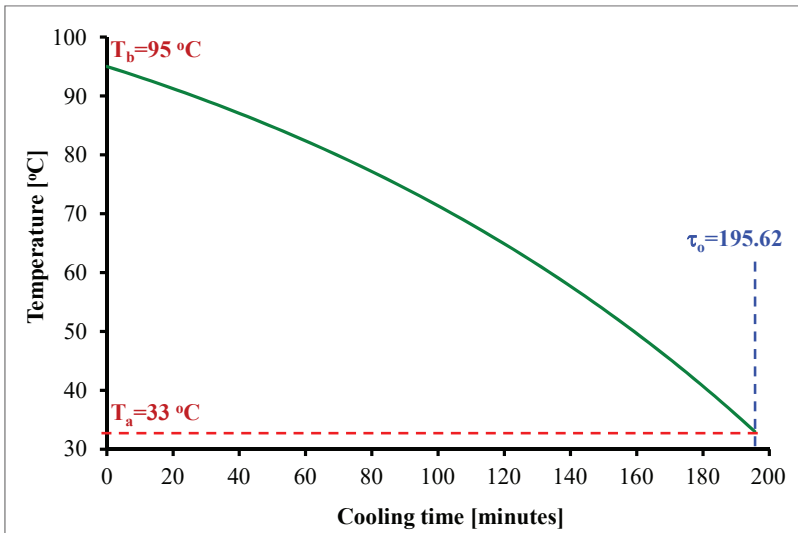

Fig. 8. Relationship of water temperature (T_w) vs. cooling time (τ_o)

The cooling test in this study was carried out by new methods, namely by the method of taking sampling data, which then made patterns/trend graphs to obtain an equation of temperature and cooling time (Fig. 8). This method is done with the assumption:

1) the isolated cooking pot by glass wool with a thickness of 10 mm;
2) the wind speed when testing is below 1 m/s, where the test data on-site show that the average wind speed from 09.00 to 15.00 at a local time is 0.87 m/s.

From these two conditions, it can be predicted that thermal losses due to convection are small. All this time, the process of cooling water takes hours. That is why the data sampling method is needed so that the testing process is more time-efficient.

5. 4. Results of calculation of heat removal factor

The formula for calculating this heat loss factor ($F'U_L$) is,

$$F'U_L = \frac{m_c c_w + m_{cu} c_{cu}}{A_r \tau_o}, \tag{13}$$

where m_w=mass of water (kg), c_w=specific heat capacity of water (J/kg·K), m_u=mass of copper (kg), c_{cu}=specific heat capacity of copper (J/kg·K), A_r=surface area of cooking pot/receiver (m²), τ_o=cooling time. While cooper mass (m_{cu}) of cooking pot follows the formula (14),

$$m_{cu} = A_r t_r \rho_{cu}, \tag{14}$$

m_{cu}=0.105×0.002×385=1.88 kg,

where t_r=copper plate thickness (m) and ρ_{cu}=copper density (kg/m³).

Then from eq. (13) and (14), the heat loss factor can be calculated,

$$F'U_L = \frac{(2 \times 4{,}186.8) + (1.88 \times 385)}{0.105 \times 11{,}737},$$

$$F'U_L = 7.38 \ \text{W/m}^2 \cdot \text{K},$$

where $F'U_L$ is the heat removal factor or heat loss factor of the cooking pot, W/m²·K.

5. 5. Results of calculation of optical efficiency factor and thermal efficiency of the FSC cooking pot

The optical efficiency factor ($F'\eta_o$) is calculated by the formula:

$$F'\eta_o = \frac{F'U_L}{CR_g} \times$$

$$\times \left[\frac{\dfrac{T_{wo} - T_a}{I_b} - \dfrac{T_{wi} - T_a}{I_b} e^{-\frac{\tau}{\tau_o}}}{1 - e^{-\frac{\tau}{\tau_o}}} \right] \tag{15}$$

or

$$F'\eta_o = \left(\frac{F'U_L}{CR_g} \right) \times$$

$$\times \left[\frac{\left(\dfrac{T_{wo} - T_a}{I_b} \right) - \left(\dfrac{T_{wi} - T_a}{I_b} \times e^{-\frac{\tau}{\tau_o}} \right)}{1 - e^{-\frac{\tau}{\tau_o}}} \right], \tag{16}$$

where T_{wo}=final water temperature (°C), T_{wi}=initial water temperature (°C), τ=water heating time, τ_o=water cooling time. Equation 16 becomes,

$$A = \frac{F'U_L}{CR_g}, \tag{17}$$

$$B = \frac{T_{wo} - T_a}{I_b}, \tag{18}$$

$$C = \frac{T_{wi} - T_a}{I_b}, \tag{19}$$

$$D = e^{-\frac{\tau}{\tau_o}}. \tag{20}$$

So equation (16) can be written:

$$F'\eta_o = A \left[\frac{B - (C \times D)}{1 - D} \right]. \tag{21}$$

The optical efficiency factor ($F'\eta_o$) can be calculated namely;

$$A = \frac{7.38}{8} = 0.92,$$

$$B = \frac{(95 - 31.5)}{716} = 0.09,$$

$$C = \frac{(34.5 - 31.5)}{716} = 0.004,$$

$$D = e^{\frac{57}{195.6}} = 0.75.$$

So $F'\eta_o$ results are obtained,

$$F'\eta_o =$$
$$= 0.92 \left[\frac{0.09 - (0.004 \times 0.75)}{1 - 0.75} \right] = 0.3202.$$

Furthermore, from the calculated heat removal factor ($F'U_L$) and optical efficiency factor ($F'\eta_o$). The formula of the thermal efficiency (η_{Th}) of the cooking pot during testing can be calculated,

$$\eta_{Th} = F'\eta_o - \frac{F'U_L(T_r - T_a)}{CR_g \cdot I_b}, \qquad (22)$$

where,

$$T_r = \frac{(T_{ro} - T_{ri})}{2}, \qquad (23)$$

where T_{ro}=final temperature of the cooking pot wall (°C), with T_{ri}=initial temperature of the cooking pot wall (°C), T_a=average ambient temperature (°C), I_b=average direct normal irradiance (W/m²). So the thermal efficiency of the Fresnel solar cooker is,

$$\eta_{Th} = 0.3202 - \frac{7.38(64.9 - 31.5)}{8 \times 716} = 27.72\,\%,$$

where η_{Th} is the thermal efficiency of the Fresnel solar cooker, %. The calculation results of the thermal efficiency from the cooking pot/receiver can be used for performance analysis of the Fresnel solar cooker. Where in eq. (22) above T_r can be replaced by T_w (average temperature of water). The efficiency value from the calculation is not much different, because the T_w and T_r values are almost the same. From the calculation, the thermal efficiency of the Fresnel solar cooker η_{Th} is 26.93 %.

6. Discussion of performance characteristics of Fresnel solar cooker

Performance characteristics in testing solar cookers, especially using solar collectors or concentrators, in general are shown with two graph models. First, it is a graph of the relationship between water heating temperature (τ_b) with a combination of temperature, solar radiation, and receiver area parameters (Fig. 9). Second, namely the relationship of efficiency with a combination of temperature parameters, solar radiation, and receiver area (Fig. 10).

Fig. 9 shows a trend exponential relationship, with a strong correlation coefficient R^2=0.845. The correlation between heating/boiling water with several variables in this study (T_w, T_a, I_b, A_r) is τ_b=5.039$e^{6.932k}$. These results indicate

a relationship between the time of boiling water (τ_b) with the k-factor (x-axis). Where k-factor consists of output water temperature (T_w), ambient temperature (T_a), direct normal irradiance (I_b), and cooking pot surface area (A_r).
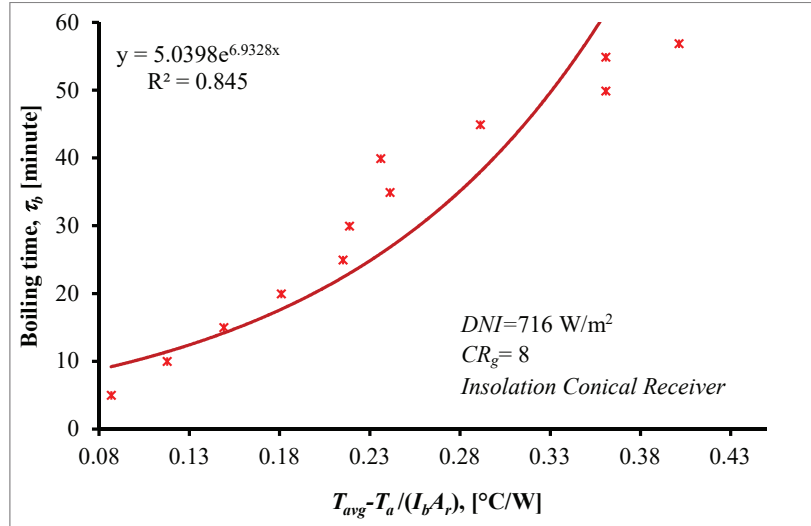

Fig. 9. Characteristic of water heating time of isolated cooking pot (CR_g=8; m_w=2 kg)

The curve (Fig. 9) shows an insulated receiver's performance characteristics, where sensible heat scaling is affected by changes in solar radiation and ambient temperature variables. So by knowing some of these parameters, the time required (boiling time) by the conical cavity receiver (CR_g=8) to boil water as much as 2 kg to boiling (95 °C) can be predicted. Using the merit method will be obtained.

Fig. 10 shows the thermal efficiency performance of the receiver/cooking pot/Fresnel solar cooker. The slope shows the average heating temperature with ambient temperature, causing a decrease in the receiver's thermal efficiency. Relationship of thermal efficiency (η_{Th}) of a cooking pot with the cone-shaped cavity receiver (CR_g=8). The experimental results show that Fresnel lens concentrator produces a focal point temperature (T_f) of 1,064 °C at DNI ±850 W/m². The calculation results are a heat removal factor ($F'U_L$) of 7.39 W/m²°C, and an optical efficiency factor ($F\eta_o$) of 0.312. Therefore, the thermal efficiency (η_{Th}) of the Fresnel solar cooker is 27.72 %.

Several authors have conducted studies on thermal performance of the receivers for concentrated solar cooker applications. The results show a decrease in thermal efficiency to an increase in the difference between fluid/water temperature and ambient temperature. Table 5 shows the results of the comparison of the performance of the concentrated solar cooker from several authors using a figure of merit methods.

Table 5 provides a comparative overview of the results of the thermal performance test of the concentrating solar cooker. Although, in the technical specifications it is not equal. However, with the standard test method, it can be seen that the similar comparison results are optical efficiency factor ($F'\eta_o$), heat removal factor ($F'U_L$) and thermal efficiency (η_{Th}). From direct normal irradiance (I_b) and almost the same variation in input parameters, the three results in Table 5 show that the thermal efficiency of the solar cooker design is less than 30 %. Although the thermal efficiency from using a Fresnel lens for the solar cooker is not very significant when compared to the glass parabolic concentrator. However, it has advantages in terms of light weight, low cost and easy installation and maintenance.
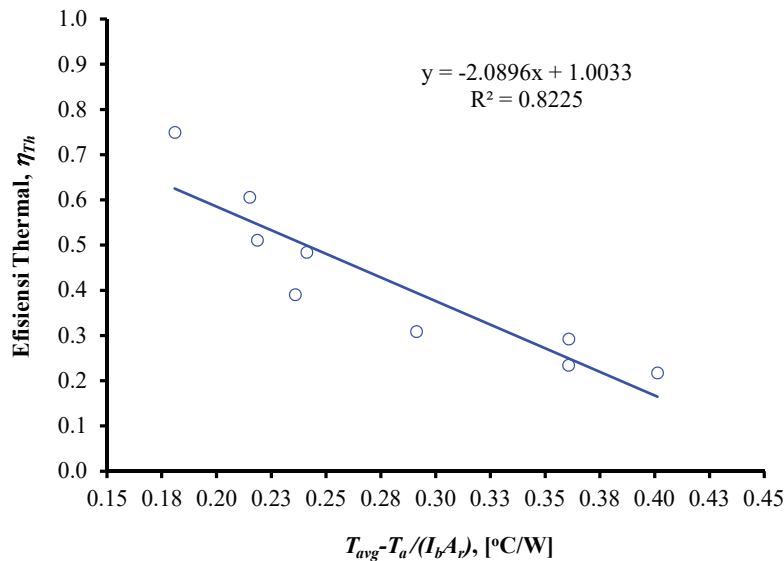
Fig. 10. Characteristic of thermal efficiency of fresnel solar cooker

Table 5

Comparison of thermal performance of the receiver for concentrating solar cooker

Author	Technical Specification	I_b [W/m²]	τ_b [mnt]	τ_o [mnt]	$F'U_L$ [W/m².°C]	$F'\eta_o$	η_{Th}
Asrori, et al. (2020)	PMMA Fresnel: A_p=0.785 m² CR_g=8 m_w=2 kg	716	57	196	7.39	0.312	0.269
Kalbande, et al. (2008)	Glass Parabolic : ϕ_p=1.3 m CR_g=6.03 m_w=1.5 kg	710	29	54.46	9.78	0.428	0.29
Mullick, et al. (1991)	Glass Parabolic: A_p=0.58 m² CR_g=7.25 m_w=1 kg	715	55	52	17.2	0.454	N/A

The limitations and disadvantages of this study are that the performance is relatively low, namely less than 30 %. Therefore, it is necessary to treat the receiver in the application of solar thermal concentration, especially for medium temperature (<150 °C). The treatment of receiver/cooking-pot by increasing the thickness of the insulator, and a black paint coating of the wall surface. This can reduce heat loss because of convection and radiation. Therefore, the thermal efficiency can be improved.

This prototype is very useful to be developed in a larger capacity. So that it can be used for mutual interests such as a kitchen in a dormitory, boarding school, or hotel. Fresnel solar cooker requires additional tools, an automatic solar tracking mechanism to make it more efficient. Moreover, the concept of Indirect Solar cookers can be an addition to harnessing thermal energy from the sun. The solar cooker device can be combined with solar cell applications so that even in cloudy or night conditions it can still cook with electrical energy stored from battery storage.

7. Conclusions

1. The receiver type with a conical cavity whose walls are insulated by glass wool has the potential as a cooking pot for direct Fresnel solar cooker applications.

2. The cooking pot with CR_g=8 and the solar energy input (DNI) of ±850 W/m² can be obtained: a focal point temperature (T_f) of 1,064 °C, a temperature stagnation of 267.35 °C, a heat removal factor ($F'U_L$) of 7.39 W/m².C, and an optical efficiency factor ($F\eta_o$) of 0.312. So the thermal efficiency (η_{Th}) of the Fresnel solar cooker is 27.72 %.

3. The slope of performance characteristics shows that the higher difference of the water heating temperature and the ambient temperature will cause a decrease in the thermal efficiency of the Fresnel solar cooker. The thermal efficiency tends to decrease until the end of the process due to the influence of the optical efficiency factor $(F\eta_o)$.

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