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The effect of solar tracker movement on the thermal performance of solar cooker using the Fresnel lens solar concentrator

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Abstract

Solar energy as renewable energy has great potential to supply the world's energy needs. Solar thermal energy can be used for domestic energy purposes (cooking and water heating). The purpose of this research is to develop, design and analyze the performance of a solar cooker from the concentration of direct normal irradiance (DNI) by the Fresnel lens on the receiver/absorber as a cooking vessel. One form of improving the performance of the Fresnel solar concentrator (FSC) is the addition of an automatic solar tracker installation using hydraulic actuators. The solar tracker is varied, every 5 and 10 minutes, respectively. The solar cooker performance test was conducted outdoors at the Mechanical Engineering Department of State Polytechnic of Malang (7.9553 ^{o}S and 112.6125 ^{o}E) in April 2021. The method used actual experimental research. The measurement of solar radiation uses a solar power meter SPM-1116SD and the tracker's movement. At the same time, the temperature parameters (water temperature, receiver wall temperature, focal point temperature, ambient temperature) are measured by the temperature data logger. The concentrated solar cooker type design uses a fresnel lens with a capture area of 0.785 m2 and a focal ratio of 0.88. The main components of this solar cooker design consist of: a large fresnel lens that functions as a concentrator of sunrays, a cone-shaped cooking stove as a solar collector (receiver), and a hydraulic actuator type solar tracker unit. Initial tests showed that the solar radiation, In = 789.00 W/m^2, obtained the focal point temperature at the receiver, T_f = 930.10°C. Meanwhile, the thermal efficiency (η_{Th}) of a solar cooker with a solar tracker that moves every 10 minutes and 5 minutes is 12.7% and 33.66%, respectively. The increase in the thermal efficiency of the solar cooker is very significant, which is 2.65 times. This shows that the more accurate and continuous movement of the tracker will increase the thermal efficiency of the designed Fresnel solar cooker.

Keywords:
solar energy, concentrator, Fresnel lens, tracker, receiver, focal temperature, solar cooker, thermal efficiency

1. Introduction

International energy demand now mainly relies on fossil fuels. This is because the amount of energy consumed each year is increasing. However, energy supplies are still limited [1]. Similarly, it's happened in Indonesia. The national energy demand in this country is mainly supplied by fossil energy, i.e. crude oil (34%), coal (35%), and natural gas (19.3%). Meanwhile, new and renewable energy only reached 11% [2]. Therefore, a solution must be there to reduce fossil energy consumption. Solar energy is considered one of the most promising renewable energy resources available in most developing countries, including Indonesia.

As one of the tropical countries, Indonesia is located along the equator line (Latitude = 6° N - 11° S and Eastern Longitude = 95° - 141° E). The geographical location allows optimal solar radiation reception in most areas throughout the year. Especially when the peak position of the sun is perpendicular to the earth's position, the sun rays that descend on the ground surface can reach 900-1000 W/m2. As a result, the intensity of solar radiation reaches 5.1 kWh/m2/day (in the East) and 4.5 kWh/m2/day (in the West), with an average of 4.8 kWh/m2/day across the region. The duration of sunlight is ±2975 hours/year, while the average duration of irradiation is 8.2 hours/day [3].

As mentioned above, Indonesia has a large solar energy essential and might be a long-term renewable energy source. However, despite its immense essentials, solar energy in Indonesia has yet to realize its full essentials. The government is skeptical of solar energy, claiming that the region's overcast climate makes it unsuitable for its use. The government is still trailing behind other countries in solar energy development (India or Thailand). Solar thermal energy can be used for various purposes, including domestic applications (e.g. cooking and water heating) and power plant resources. Therefore, the knowledge upgrade, study, research, development and the national energy policy in terms of solar energy utilization are important to fulfill energy needs in this country [4].

Solar thermal energy is one of Indonesia's most promising renewable energy solutions for rural cooking and industrial thermal processing. Cooking is well-known as one of the most vital and required household jobs in any civilization. Therefore, in Indonesia, the utilization of solar energy for domestic solar cookers has been observed and reported first time by Suharta *et. al.* (1998). The reports indicated that the results of outdoor testing of sixty-four units of the solar oven in several regions in eastern Indonesia showed promising tendencies of social acceptance. In addition, the design of a solar oven can cook a variety of foods effectively [5].

Cooking with solar energy is an alternative to using fossil fuels. It's a quick, easy, and handy way to cook food without burning fuel, heating the kitchen, or harming the environment. Solar cookers also provide several advantages in terms of health, affordability, user-friendliness, ease of use, suitability for families, user income, and environmental impact [7-8]. The various types of solar cookers produced for cooking until now are box types, concentrator types, indirect types, as well as with and without storage types. Not only are the different types of solar cookers well developed, but so are the precise design, test procedures, theory, and utility. In addition, a comprehensive review of state the art of solar cookers, such as various types, detailed cooker designs, and optimization of geometry parameters, feasibility analysis, and standard testing approach and performance analyses were presented [9-12].

Many solar collectors now use traditional technologies in terms of design (box) and material (glass). Therefore, a solar collector technology that is lightweight, simple to operate, economical to create, generates heat quickly, and has a high energy density is required [13-14]. One of the solutions to the challenges with solar cookers so far could be the adoption of adequate and efficient solar collectors. Designing a solar thermal energy collector with a plastic lens is one option for building a solar cooker. Plastic Fresnel lenses may be a solution to the aforementioned issues [15]. Fresnel lenses are a type of optical lens that is unique. Now it can be made from plastics such as acrylic or PolyMethylMethAcrylate (PMMA) Fresnel lenses [16-17]. It can reach higher temperatures than other types, and it can reach extremely high temperatures in a short period, making it faster for cooking and heating some foods and water. Therefore, this solar cooker type is promising and economically viable for domestic and industrial applications [18-20].

Solar thermal collectors in a concentrator configuration with plastic lenses are still uncommonly used in research. More glass mirrors were employed as sunray catchers in prior trials. Plastic lenses have a lot of advantages, including being lightweight, inexpensive, and quick to produce, as well as being simple to install. Fresnel lenses can be built with a bigger surface area to effectively concentrate the sunray. Installing a tracker to run this type of concentrator is also less expensive than conventional glass collectors.

The purpose of this study was to determine the effect of variations in the rotation period of the solar tracker on the thermal performance of cooking stove (receiver) for solar cookers. The prototype of a concentrated solar cooker in this study uses a Fresnel PMMA lens concentrator with a single axis solar tracker. Measurement of Direct Normal Irradiance (DNI) at the research site can help determine the amount of solar energy that can be used for cooking. In order to obtain optimal thermal performance from the receiver (cooking container), the effect of the tracking movement time is predicted to affect the focal temperature produced by the fresnel lens. Based on the temperature variables (cooking pot temperature, boiling water temperature), the thermal efficiency of the Fresnel Solar Cooker (FSC) can be determined. The results of this study are expected to produce solar cooker findings that have high performance, and can be applied on a communal scale.

2. Materials and Methods

The development of methods, processes, and analysis of the Fresnel Solar Cooker (FSC) prototype is expected to produce the characteristics of a solar cooker that has high efficiency and effectiveness. Therefore, the focus of this study is to result in optimal thermal characteristics. In addition, to make a proper analysis, basic theories such as conduction, convection, radiation, and the first law of thermodynamics are required.

2.1. Energy balance in receiver (cooking vessel)

In general terms, temperature testing on the receiver with loads (e.g. water) can be performed to measure thermal performance in solar thermal applications. The usage energy in the receiver is sensible heat energy. An analysis of the energy conversion from the sun to the receiver is the method of determining the thermal performance. Therefore, thermal efficiency is the usage of energy to boil water (95°C) divided by the energy received by the cooking vessel. The solar radiation that passes through the Fresnel is then concentrated to the receiver can be illustrated in Fig.1.

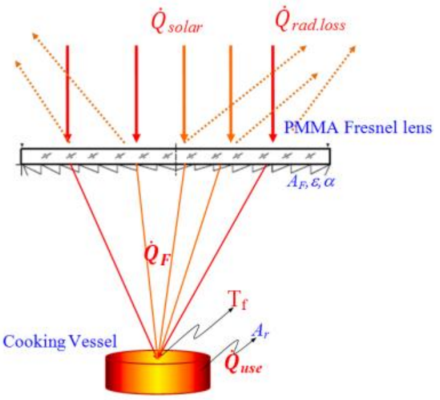


Fig.1. The illustration of energy balance on cooking vessel (receiver)

$$\eta_{th} = \frac{\dot{Q}_{use}}{\dot{Q}_{in}}, \quad (1)$$

Where η_{th} is the instantaneous thermal efficiency of the cooking vessel (receiver), $\dot{Q}_{use}$ is the total power absorbed by water in cooking vessel (W), and $\dot{Q}_{in}$ is the Direct Normal Irradiance (DNI) power absorbed by the cooking vessel (W).

Whereas the heat absorbed by the cooking vessel during testing is direct solar irradiance or beam radiation, which is concentrated by the Fresnel lens for the period so that the formula of input power (Q ̇_in) can be written [21],

$$\dot{Q}_{in} = \dot{Q}_F = \eta_o . A_F . \int_0^t I_b . dt, \quad (2)$$

Where $\dot{Q}_F$ is the power of solar radiation received by cooking vessel (W), η_o is optical efficiency of Fresnel lens, I_b is the direct normal irradiance (DNI) or beam radiation (W/m^2); A_F is the aperture area of Fresnel lens (m^2), and *dt*is the duration of test (s).

The total direct normal irradiance received by the cooking vessel throughout the test period is a sensible heat condition that can be utilized to bring water to a boil (±95°C). As a result, the formula for useful power in this system is [22],

$$\dot{Q}_{use} = \frac{m_w c_w (T_o - T_i)}{\Delta t}, \quad (3)$$

Where m_w is mass of water in cooking vessel (kg), c_w is specific heat capacity of water at constant pressure (4186,8 J/kgK), T_o is final temperature of water (°C), and T_i is initial temperature of water (°C). So from Eq. (2) and Eq. (3), the formula of the thermal efficiency of cooking vessel can be written,

$$\eta_{th} = \frac{m_w c_w (T_o - T_i)}{\eta_o . A_F . \int_0^t I_b . dt}, \quad (4)$$

2.2. The experimental Setup

The performance of the Fresnel solar cooker was tested outdoors in April 2021 at the Mechanical Engineering Department of the State Polytechnic of Malang (7.955°S and 112.612°E). The Fresnel lens used in this study has the following specifications: size= 1000 x 1000 mm; thickness= 3 mm; Weight= 2 kg; Focus distance= 880 mm [20]. Furthermore, the cone-shaped cavity receiver is used to enable cooking vessel made of copper material. The capacity is m= 2 kg. Solar radiation was measured using an SPM-1116SD solar power meter. A K-type thermocouple is used to measure temperature, coupled to a Digi-Sense 12 CH-Scanning Bench top data logger and a PC/laptop.

Fig. 2 shows an experimental setup for testing the thermal performance of a fresnel solar cooker, where the data taken in this study are independent variables, namely the time period for the movement of the tracker (t), solar radiation data (I_b) and local time (hour: minute). At the same time, the dependent variable is the focal/focus temperature (T_f) which is measured exactly at the focal point on the surface of the receiver, the temperature of the water (T_c) and the wall temperature (T_s) of the receiver. Fig. 3 shows the position of the thermocouple on the conical cavity receiver used for the cooking vessel. The Fresnel Solar Cooker (FSC) test was carried out on a clear day. This test investigates the focal temperature (T_f) of concentrated solar radiation by a Fresnel lens. The ambient temperature (Ta), cooking vessel temperature (T_s), and water temperature (T_c) were also recorded.

Fig. 2 also shows a block diagram of a single axis solar tracking system that uses a hydraulic actuator. Power supply DC motor driving the hydraulic actuator, taken from the 50 Wp PV module.

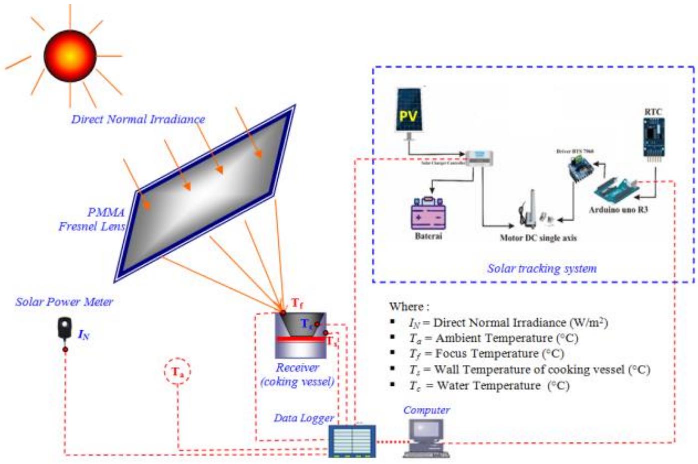


Fig. 2. Experimental setup of fresnel solar cooker by single axis tracker

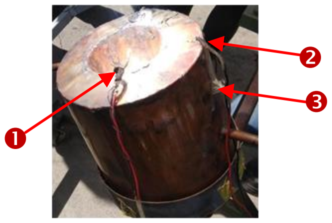


Fig 3. The position of temperature measurement by a thermocouple on the receiver: 1–focal temperature; 2–wall temperature of receiver; 3–water temperature.

Fresnel lens movement will be controlled via the RTC module. This module is used as a parameter when it performs the motor movement so that the surface of the Fresnel can be perpendicular to the sun's rays. RTC program is as an input on Arduino. The software design for application programming used is Arduino IDE on a laptop. RTC will input data to Arduino in hours, minutes and seconds. The setting of speed variations, direction, and duration, will instruct the motor driver to move the DC motor (actuator). Therefore, the Fresnel lens can move perpendicular to the sun to get the maximum normal radiation; the actuator used is a single axis movement.

The photograph of the instrumentation setting for measuring the Fresnel solar cooker performance and collecting data is shown in Fig. 4.

Fig 4. Photograph of experimental setup: 1–Fresnel lens; 2–hydraulic actuator for solar tracker single-axis; 3–cooking vessel (receiver); 4–Laptop;5–Digi-Sense 12 CH-Scanning Bench top data logger; 6–SPM-1116SD solar power meter.

3. Results and Discussion

3.1. The measurement of performance data parameter on the cooking vessel (receiver)

Table 1 shows the results of data measurement at a 10-minute of the solar tracker's movement. The data parameters consist of local time (hours: minutes), DNI/direct normal irradiance (W/m2), tracker movement duration (minutes) and temperature parameters mentioned above. It's an essential thermal parameter to consider while analyzing the performance of the cooking vessel.

Table1. Measurement of data every 10 minutes

t (hh:mm)	T mnt	DNI W/m2	T_f °C	T_s °C	T_c °C	T_a °C
11:40	0	714	629.9	35.0	33.0	32.5
11:50	10	782	736.0	36.5	35.8	32.5
12:00	20	739	642.9	42.4	38.7	32.8
12:10	30	737	692.8	47.8	44.7	32.6
12:20	40	753	823.5	52.1	48.2	33.1
12:30	50	788	930.1	55.8	53.6	33.2
12:40	60	767	734.4	60.3	58.4	33.4
12:50	70	759	606.7	63.8	63.6	33.6
13:00	80	789	793.5	67.4	67.2	32.5
13:10	90	700	529.3	72.9	72.3	31.2
13:20	100	716	692.4	73.4	71.2	31.4

Furthermore, the measurement data in Table 1 is presented in graphical form as shown in Fig. 6. Table 2 and Fig. 7 show the results of data measurement at 5-minute of the solar tracker's movement.

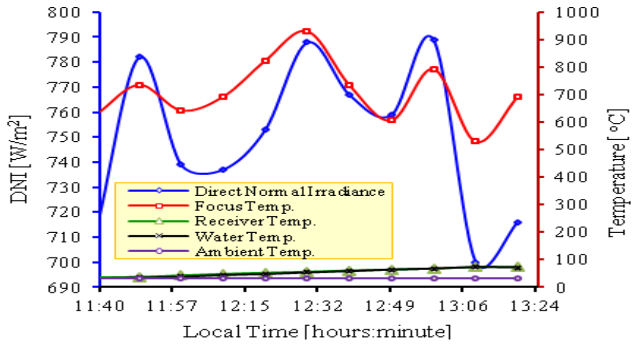


Fig 6. Graph of the relationship between local time, DNI and temperature for the movement of the solar tracker every 10 minutes.

Table. 2 Measurement data every 5 minutes

t (hh:mm)	*T* mnt	*DNI* W/m²	T_f °C	T_s °C	T_c °C	T_a °C
9:00	0	556	301.5	35.1	34 ,5	30.7
9:05	5	757	699.6	40.1	39.5	30.6
9:10	10	752	683.9	45.1	44.5	30.8
9:15	15	747	668.8	50.1	49.5	30.3
9:20	20	741	654.3	55.1	54.5	30.6
9:25	25	730	623.1	60.1	59.5	30.4
9:30	30	720	620.0	61.5	59.7	30.5
9:35	35	650	600.0	62.8	61.7	31.6
9:40	40	704	558.6	64.1	64.8	32.2
9:45	45	763	715.9	73.8	78.2	33.0
9:50	50	695	600.0	82.8	85.0	33.4
9:55	55	760	706.3	88.4	90.1	33.6
10:00	60	740	649.9	99.6	102.1	33.6
10:05	65	789	798.7	101.2	104.4	33.8
10:10	70	723	606.0	108.0	108.5	33.6
10:15	75	771	740.3	109.7	111.2	33.6
10:20	80	792	809.8	113.8	114.8	34.1
10:25	85	789	798.9	120.1	118.3	34.0
10:30	90	772	744.8	117.0	122.0	34.0
10:35	95	789	797.6	120.7	124.9	33.6
10:40	100	796	821.7	125.6	126.1	34.3

The tabulation of measurement data in Table 2 will be shown in the graph (Fig. 7) to get a better understanding of the investigation results.

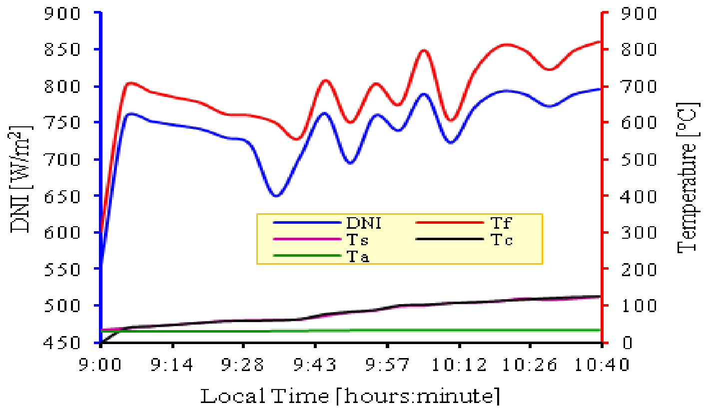


Fig 7. Graph of the relationship between local time, DNI and temperature for the movement of the solar tracker every 5 minutes.

Fig. 6 and 7 shows fluctuations in solar radiation affect the focal temperature at the receiver. In addition, the test results show that the focal point of the concentration of solar radiation by the Fresnel lens can reach a temperature of T_f = 930.1°C at *DNI* = 788 W/m^2. The temperature of the cooking vessel and the temperature of the water inside tend to increase almost equally. It's because the receiver is not covered with an insulator. This will cause radiation losses on the receiver. So, within 100 minutes, the water cannot reach the boiling temperature (±95°C). In addition, the instability of incoming solar radiation is also the cause of the deceleration of water heating.

3.2. The thermal performance of receiver with solar tracker movement every 10 minutes

Testing of the receiver performance can be used to determine the performance of the solar cooker [23-25]. The effect of the tracker movement period on the performance of the solar cooker is carried out on the receiver (cooking vessel) containing water, *m* = 2 kg. The test is carried out for 100 minutes to get the boiling point of water at 95 C (boiling test). Therefore, Fig. 8 shows the effect of solar radiation on temperature parameters. (T_f, T_s, T_c, T_a) on the receiver.

The experimental result (Fig. 8) shows that the water temperature could not reach the boiling point (95°C) after a 100th-minute test. The highest water heating temperature was 72.3°C.

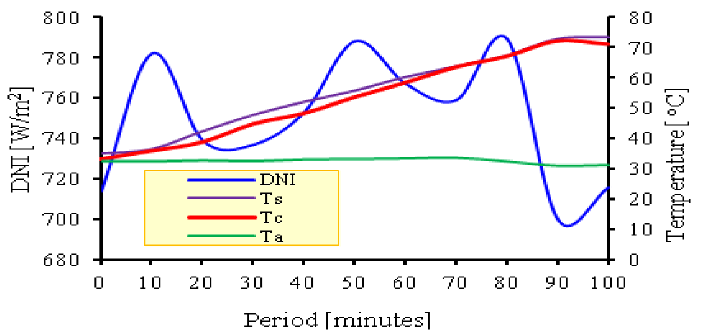


Fig. 8. Relationship of *DNI*, T_s, T_c, T_a versus tracker movement period every 10 minutes

Weather factors can create fluctuations in incoming solar energy. As a result, the previously increasing temperature of the water in the cooking vessel will decrease. The decline in water temperature is also caused by convection heat loss on the receiver wall. Furthermore, the focal point disorientation/ degradation caused by the solar tracker's inaccuracy is the reason for the unstable thermal energy transfer in the receiver.

The thermal efficiency of the solar cooker system, due to the movement of the solar tracker every 10 minutes, can be determined using the results of testing the parameter data in Table 1 and Fig. 6. Furthermore, Equations 1 to 4 can be utilized to determine the thermal performance of the Fresnel solar cooker.

Power input on the cooking vessel ($\dot{Q}_{in}$)

$$\dot{Q}_{in} = \eta_o . \bar{I}_b . A_F , \quad (5)$$

$$\dot{Q}_{in} = 0.7544 \times 749.5 \times 0.785 = 443.86 \text{ W}$$

Where, $\bar{I}_b$ is the DNI average during the test (100 min), W/m²; A_F is aperture area of fresnel lens, m²; η_o is optical efficiency of Fresnel lens = 0.7544 [20].

The usage power by the cooking vessel ($\dot{Q}_U$)

The power consumption of a receiver to heat 2 kg of water for 100 minutes≈ 6000 second is,

$$\dot{Q}_{use} = \frac{m_w c_w (T_o - T_i)}{\Delta t}, \quad (6)$$

$$\dot{Q}_{use} = \frac{2 \times 4186.8(73.4-33)}{6000} = 56.38 \text{ W.}$$

Where, m_w = mass of water in the cooking vessel (kg), ρ_w = density of water (kg/m³), c_p = specific heat capacity of water at constant pressure (J/kgK), T_o = final water temperature (°C), T_i = water temperature initial (°C), Δt = time duration of water heating (s).

The thermal efficiency (η_{th}) of the receiver can be calculated by Eq.(1),

$$\eta_{th} = \frac{\dot{Q}_{use}}{\dot{Q}_{in}} = \frac{56.38}{443.86} = 0.127$$

As a result, the Fresnel solar cooker with a solar tracker that moves every 10 minutes has a thermal efficiency of 12.7 %.

3.3 The thermal performance of receiver with solar tracker movement every 5 minutes

Fig. 9 is a graph of test results with a solar tracker treatment that moves every 5 minutes, with a test duration of 100 minutes. The results of the measurement data obtained are the average DNI, and the maximum water temperatures are 703 W/m², and 126.1 °C, respectively.

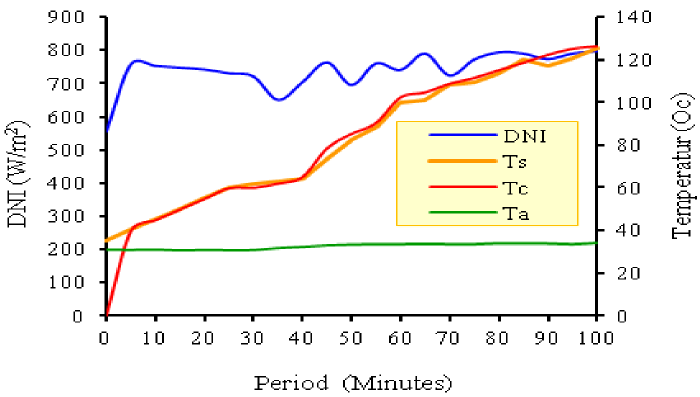


Fig. 9. Relationship of *DNI*, T_s, T_c, T_a versus tracker movement period every 5 minutes

The receiver's performance can be determined by the amount of sensible heat used. Sensible heat is used to heat water from an initial point to a boiling point (95°C). With the movement of the solar tracker every 5 minutes, fig. 9 shows the results of the boiling water test in a cooking vessel that can be achieved in the 60th minute. Hence, the performance of the solar cooker can be determined in the same way as in the previous calculation.

Power input on the cooking vessel ($\dot{Q}_{in}$)

$$\dot{Q}_{in} = \eta_o . \bar{I}_b . A_F , \quad (7)$$

$$\dot{Q}_{in} = 0.7544 \times 716.4 \times 0.785 = 424.25 \text{ W}$$

Where, $\bar{I}_b$ is the DNI average during 60 minutes (W/m²), A_F is aperture area of fresnel lens (m²), and η_o = 0.7544.

The usage power for boiling water test ($\dot{Q}_U$) during 3600 second is,

$$\dot{Q}_{use} = \frac{m_w c_w (95 - T_i)}{\Delta t} , \quad (8)$$

$$\dot{Q}_{use} = \frac{2 \times 4186.8 \times (95 - 33.6)}{3600} = 142.82 \text{ W}$$

So from calculations Eq.7 and 8, it can be determined that the thermal efficiency of the cooking vessel is,

$$\eta_{th} = \frac{\dot{Q}_{use}}{\dot{Q}_{in}} = \frac{142.82}{424.25} = 0.3366$$

Thus, the calculation results above show that the Fresnel solar cooker with a solar tracker that moves every 5 minutes has a thermal efficiency of 33.66 %.

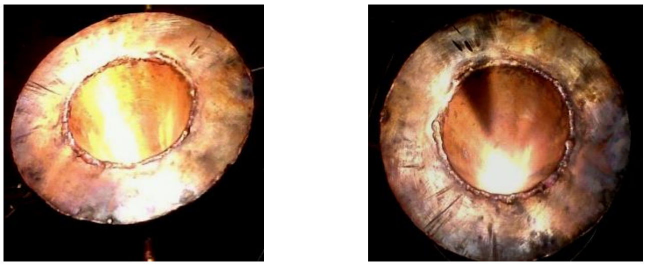
The results of the movement of the solar tracker every 10 and 5 minutes obtained a thermal efficiency of 12.7% and 33.66%, respectively. The thermal efficiency of the Fresnel solar cooker will be increased with more accurate and continuous movement in terms of the tracker following the perpendicular direction of the sunray (DNI). The increase in thermal efficiency from a tracker move every 10 minutes to a tracker move every 5 minutes is significant, at 2.65 times.

The above results indicate that the rotation period of the tracker will improve the performance of the solar cooker. This performance improvement can be further enhanced used by the continuous solar tracker. Intermittent tracking causes disorientation of the focal point, resulting in degradation and loss of heat received by the receiving wall.

3.4. Effect of focal point position on temperature distribution at receiver

The experimental results show that the focal temperature and DNI have a similar pattern. An increase in focal temperature also accompanies the rise in DNI. Furthermore, the heat absorbed by the cooking vessel will be affected by the focal temperature. In addition, it appears that local time cannot be used as a parameter, generally. Weather conditions (cloudy or clear sky) are very dominant in influencing the stability of solar radiation received by the Fresnel lens. Hence, in concentrated solar technology, tracking accuracy is crucial for increasing the thermal efficiency of the receiver. Fig. 10 shows the position of the focal point of the concentration of sun rays by a Fresnel lens.

Fig. 10.a shows the tracer's inaccuracy in changing the surface of the Fresnel lens in the correct direction perpendicular to the solar beams. As a result, the receiver's focal point becomes distracted. The spread of the focus point on the receiver will obstruct thermal energy absorption. The magnification of the spot/focus region also contributes to the rise in radiation and convection losses. The exact focal point in the conical receiver's centre is shown in Fig. 10b. If the incoming DNI is stable, this focus position can improve receiver performance due to the stability of thermal absorption in the receiver.



a. b.

Fig. 10. The location of the focal spot on the cooking pot: *a*–focus spot disorientation; *b*–focus spot is exactly at the receiver cone's end

4. Conclusions

Fresnel lenses have great potential for application in solar cooker systems. The high-temperature concentration captured by the receiver can be used for heat generation systems.

The accurate design of the solar tracker and continuous movement will increase the stability of the transfer of solar energy to the receiver surface area so that an increase in the performance of the solar cooker will be found.

The tracker's inaccuracy in following the movement of sun rays can cause the focal point to expand. This can disrupt the heat transfer in the receiver resulting in heat loss to the walls of the cooking vessel (receiver).

Improving the performance of the receiver can be done by adding an insulator to the wall of the cooking vessel.

Acknowledgments

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