

THE DEVELOPMENT OF FRESNEL LENS CONCENTRATORS FOR SOLAR WATER HEATERS: A CASE STUDY IN TROPICAL CLIMATES

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Abstract

This paper discusses the application of Fresnel Lens Concentrator for Solar Water Heater which is a case study in Indonesia. The purpose of this study was to find an empirical equation of the relationship between Direct Normal Irradiance (I_b) and focal point temperature (T_f). The research location is Latitude: 7.9553 °S and Longitude: 112.6145 °E. The SM-206 solar power meter is used. The Fresnel lenses are made of PMMA material. Its specifications are: diameter = 1000 mm; weight = 2 kg; thickness = 2 mm; groove pitch = 0.5 mm and focal length = 880 mm. The main experimental setup consists of a PMMA Fresnel lens and a receiver. The conical cavity receiver has specifications; geometric concentration ratio, $CR_g = 8$, and $V = 2$ Liters. Temperature measurement is done using a temperature data acquisition system. The K-type thermocouple is used to measure:

- 1) ambient temperature (T_a);
- 2) the focal point temperature (T_f);
- 3) receiver wall temperature (T_r);
- 4) water temperature (T_w).

The experiment obtained the results of the empirical equation for the relationship between Direct Normal Irradiance (I_b) and focal point temperature (T_f). The increase in solar radiation produces a focus temperature, exponentially. At DNI 858 W/m² it can produce a focal temperature of up to 1064 °C. The efficiency of the receiving cavity of the thermal cone which contains 2 litres of water and $CR_g = 8$ under conditions of relatively Direct Normal Irradiance ($\bar{I}_b = 675$ W/m²) is about 10.61 %. Furthermore, the energy that can be generated in heating water is 0.17–0.32 MJ, in 100 minutes. Heat convection and radiation loss can be reduced by adding an insulating layer to the walls and coating the surface with black.

Keywords: Fresnel lens concentrator, solar water heater, conical receiver, thermal efficiency.

DOI: 10.21303/2461-4262.2022.002441

1. Introduction

As an energy source, the Sun is alternative energy. Solar energy is generated from the fusion of the Sun's core, the total energy generated from solar radiation is 3.8×10^{20} MW, equivalent to 63 MW/m² of energy generated by the Sun's surface [1]. This energy is emitted in all directions, and the total solar energy radiation reaching the earth is about 1.7×10^{14} kW [2]. And only 30 % reaches the ground, the earth's energy needs for a year only takes 30 minutes of the energy emitted.

Geographically, Indonesia is at latitude: 11 °S–6 °N and longitude: 95–141 °E. Indonesia has a tropical climate with two seasons, namely the dry season and the rainy season. Indonesia's geographical location, which is on the equator, has great potential for solar energy. That's because it is exposed to the Sun all year round. Indonesia has hours of sunshine per year, about 2975 hours of weather, or 124 days. While the average exposure time is 8.2 hours per day, at peak conditions the sunlight falling on the surface of the Indonesian territory of 1 m² can reach 900 to 1000 Watts per hour. Meanwhile, the average solar radiation intensity is around 4.8 kWh/m² per day [3].

One alternative to reduce energy needs in the household sector is to use solar thermal energy for solar water heaters and solar cookers. Plastic concentrator lenses can be an alternative

application of solar thermal energy collection technology. Therefore, in this study, the concentrator of solar thermal energy is as a large circular Fresnel lens, which is commonly referred to as Solar Beam Radiation (I_b) or Direct Normal Irradiance (DNI). The lens material is PMMA (Poly Methyl Meth Acrylate). The focal point of the lens will be hot, so the lens concentrator is used for solar heaters and solar cookers [4].

Therefore, this study will investigate the potential of Direct Normal Irradiance (DNI) around the research location at the coordinates of Latitude: 7.9553 °S and Longitude: 112.6145 °E hoping to represent the condition of DNI, especially in Malang-Indonesia.

Some thermal applications require energy at high temperatures. The intensity of solar radiation transferred can increase to heat by reducing the area where radiation and heat loss occurs [5]. This can be done by placing an optical device between the radiation source and the energy-absorbing surface [6]. The design types of solar heat concentration are parabolic trough and Fresnel oven. The concept of light concentration consists of two methods, namely refraction and reflection. Method of concentration of solar thermal to produce high-temperature vapour (super-heated) in solar power generation systems [7].

This concentration mechanism can be obtained by the reflection or refraction of solar radiation using mirrors or lens [8]. Reflected or refracted light is concentrated in the focus area. This will increase the energy flux at the target receiver [9, 10]. Thermal performance of solar thermal energy collectors called Phase Change Materials (PCM). Where the PCM thermal mass is obtained from direct heating using a Fresnel lens, the result is that the water heating system temperature reaches 60 °C. PMMA Fresnel material is resistant to sunlight, produces a stable temperature up to 80 °C, has good transmissivity of the solar spectrum, and has a refractive index of 1.49 (close to glass). If the lens surface captures the precision, the optical efficiency reaches 96.06 %. PMMA Fresnel geometry with diameter = 900 mm, thickness = 3.17 mm, focal distance = 757 mm can produce a flux density of solar radiation reaching 2664 times. This means that at 1000 W/m² radiation capture, the maximum energy density at the focal point is 264 W/cm² [11, 12].

2. Materials and Methods

The research was conducted outdoors at the energy conversion laboratory of the State Polytechnic of Malang, Indonesia. The research location is Latitude: 7.9553 °S and Longitude: 112.6145 °W. Solar radiation data is retrieved using the SM-206 solar power meter. The test was conducted on a sunny day between 09.00 am – 03.00 pm in August 2020. PMMA Fresnel lens specifications are diameter = 1000 mm; weight = 2 kg; Thickness = 2 mm; Groove pitch = 0.5 mm and Focus distance = 880 mm. **Fig. 1** shows the device design for the application of solar water heaters and solar cookers. The components of this tool consist of a PMMA Fresnel lens and a copper receiver as a conical cavity. The receiver functions as a collector of solar heat. The conical cavity receiver has specifications $CR_g = 8$, and $V = 2$ Liters. Data collection is done every 10 minutes.

The temperature data acquisition system uses a Digi-Sense Channel Scanning Benchtop with four thermocouple channels connected to a computer. *K*-type thermocouples with a temperature range of –200 °C ~ 1350 °C are used for measuring. **Fig. 1** shows the installation of the temperature tool on the test receiver.

The solar thermal energy concentrator employed in this study is a large Fresnel lens with a circular shape. The purpose of this lens is to refract incoming Sun rays in a direction perpendicular to the lens surface, known as Solar Beam Radiation (I_b) or Direct Normal Irradiance. Sun rays can be focused or concentrated in a smaller area due to the lens surface design, as illustrated in **Fig. 1**. Therefore, based on the manufacturer's specs, several performance characteristics of this Fresnel lens can be determined, including: *f*-number or focal ratio, concentration ratio and lens efficiency.

The *f*-number or focal ratio, $f/\#$, is the ratio of the effective focal length of the lens to the diameter of the lens's clear-aperture optical, which is defined by the equation:

$$f/\# = \frac{f_L}{\phi_{CA}}, \quad (1)$$

where f_L – effective focal length of the lens, and ϕ_{CA} – diameter clear-aperture Fresnel lens.

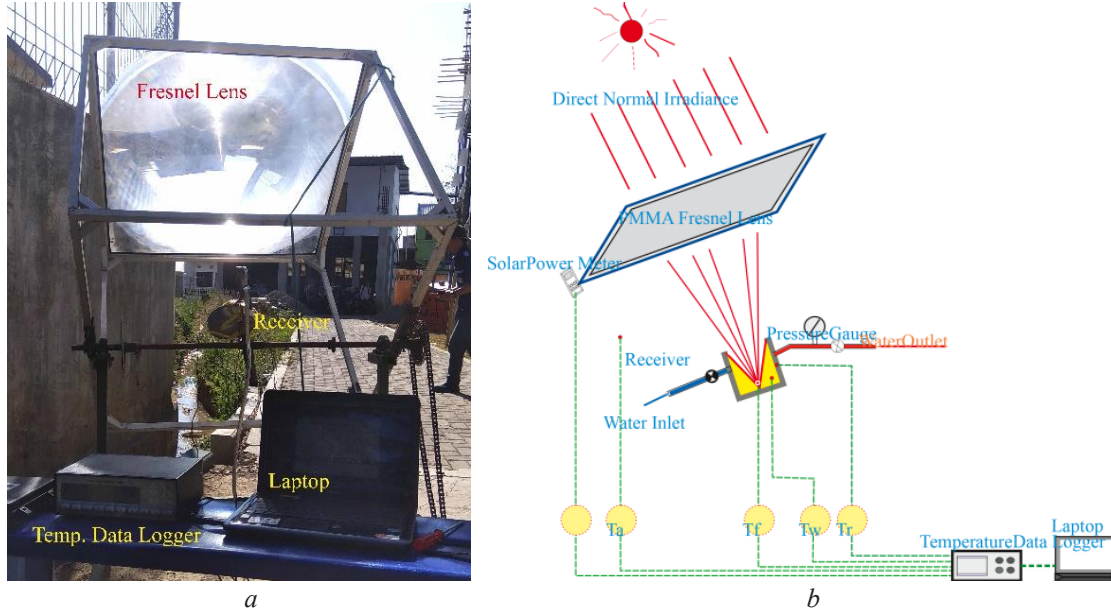


Fig. 1. Experimental setup scheme: *a* – photograph of experimental device installation; *b* – Scheme of temperature test on the receiver by a data acquisition system

The Optical Concentration Ratio is the ratio of the average solar radiation (radiant flux) integrated over the receiver area to the solar radiation of the concentrator opening area. The optical concentration ratio is determined by the reflector's quality [13]. However, many collectors have a receiver surface area greater than the concentrated area of Sun rays. In this regard, the Optical Concentration Ratio, CR_O , of Fresnel lens is determined by the equation:

$$CR_O = \frac{\frac{1}{A_r} \int I_r dA_r}{I_c}, \quad (2)$$

where I_r – solar radiation received by the receiver; I_a – solar radiation entering the Fresnel concentrator; A_r – receiver area.

However, because the intensity of solar radiation varies throughout the day and is difficult to measure, it is not easy to obtain the concentration ratio using equation (2). The concept of geometric concentration ratio is introduced to simplify this analysis, which is defined by the ratio of the Fresnel lens area to the receiver area, i.e.:

$$CR_g = \frac{A_a}{A_f} = \frac{r_{lens}^2}{r_{rec}^2}, \quad (3)$$

where CR_g – the geometric concentration ratio; A_a – the Fresnel lens aperture area; A_f – focus area on receiver. The CR_g shows the ability of the receiver to utilize solar radiation intensity. It has an effect on the stagnation temperature of the receiver surface. The radiation heat loss is affected by decreasing receiver size, which is indicated by an increase in the geometric concentration ratio.

Fig. 2 shows how to prediction of lens efficiency. The efficiency of the lens may be determined using the f-number parameter [14].

It can be observed within **Fig. 2** that the trendline or chart pattern is the same for different focal lengths. As a result of Equation (1), $f/\# = 0.8$, the lens efficiency of the Fresnel lens utilized in this study can be estimated, $\eta_L = 89.9\%$. The receiver performance testing with a load is used to determine the performance of solar thermal applications. For water heater applications, the load parameter is the receiver's usable energy expressed as sensible thermal energy. The receiver's performance is dependent on the utilization of solar energy to generate thermal energy. The solar energy entering the receiver can be illustrated in **Fig. 3**.

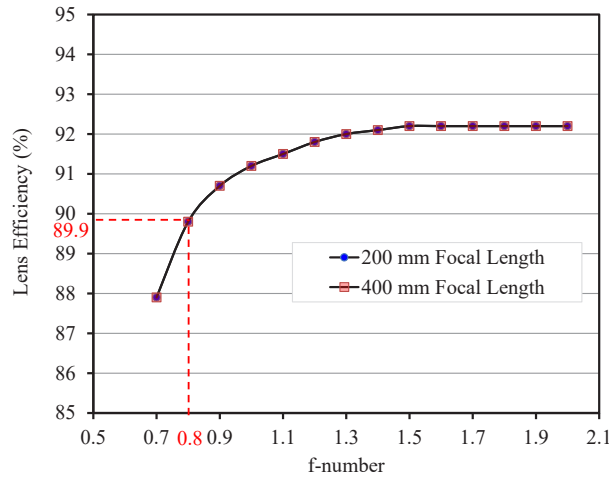


Fig. 2. Relationship of focal length, f-number and lens efficiency

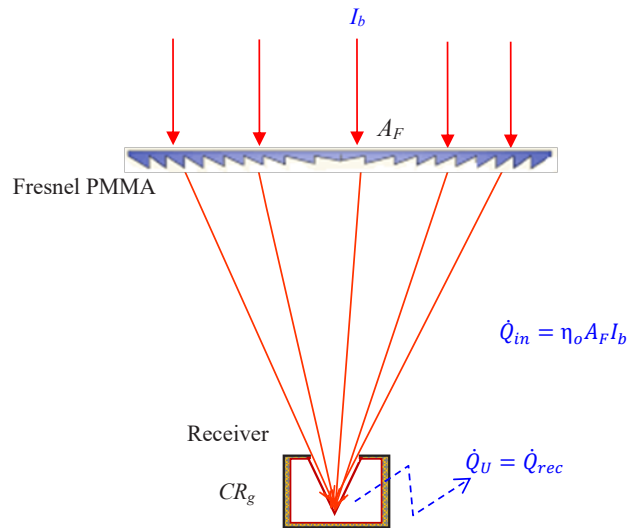


Fig. 3. Energy balance of conical receivers for solar water heater applications

Thermal efficiency, η_{Th} , is defined as the ratio of the power used by the receiver to the energy entering the receiver (**Fig. 3**), where the equation can be written:

$$\eta_{Th} = \frac{\dot{Q}_U}{\dot{Q}_{in}}, \quad (4)$$

where \dot{Q}_U – the energy used by the receiver; \dot{Q}_{in} – the energy entering the receiver. Meanwhile, the incoming energy, \dot{Q}_{in} , is the refractive energy of the Fresnel lens, \dot{Q}_F . The equation can be written:

$$\dot{Q}_{in} = \dot{Q}_F = \eta_o I_b A_F, \quad (5)$$

where η_o – optical efficiency; I_b – direct normal irradiance; A_F – aperture area of the Fresnel lens.

The power used by the receiver depends on its use. In solar water heater applications, the receiver power equation is:

$$\dot{Q}_U = \dot{Q}_{rec} = \frac{m_w c_w \Delta T}{\Delta t}, \quad (6)$$

where m_w – mass of water in the receiver (kg); c_w – the specific heat capacity of water at constant pressure (4186.8 J/kg $^{\circ}$ K); ΔT – difference in initial and final water temperature ($^{\circ}$ C); Δt – time duration of water heating (s).

The initial water temperature and the final water temperature were measured in this investigation. As a result, the thermal efficiency of solar water heaters can be expressed as:

$$\eta_{Th} = \frac{m_w c_w (T_o - T_i)}{\eta_o \int_0^t I_b A_F dt}, \quad (7)$$

where η_{Th} – the thermal efficiency of solar water heater; T_o – the initial water temperature (°C); T_i – the final water temperature (°C).

Therefore, the overall heat transfer coefficient, U_L , is determined according to [15] by the equation:

$$U_L = \frac{\dot{Q}_{in} - \dot{Q}_U}{A_r (T_r - T_a)}, \quad (8)$$

where T_r – receiver surface temperature (°C); T_a – the ambient temperature (°C).

3. Results and Discussion

3.1. Correlation of Direct Normal Irradiance (I_b) and Focal Point Temperature (T_f)

It is essential to measure the concentration temperature or focus temperature produced by a Fresnel lens. It is to determine the extent to which solar energy's potential is in the form. The solar radiation spectrum can be converted to thermal energy. The focus temperature depends on the DNI entering through the Fresnel lens, focal concentration ratio, the accuracy of the focus distance and accuracy of the solar tracker. Therefore to get accurate measurement data, needed more in-depth research, both simulations or indoor and outdoor research. Tests conducted in this study are outdoor with a simple method, from the specifications of existing Fresnel and measurements at a focal distance of about 80 cm. Then the results can give an idea of DNI. They correlate with the focal temperature produced by the Fresnel lens. The results of the focus temperature testing on this receiver surface are shown in Fig. 4.

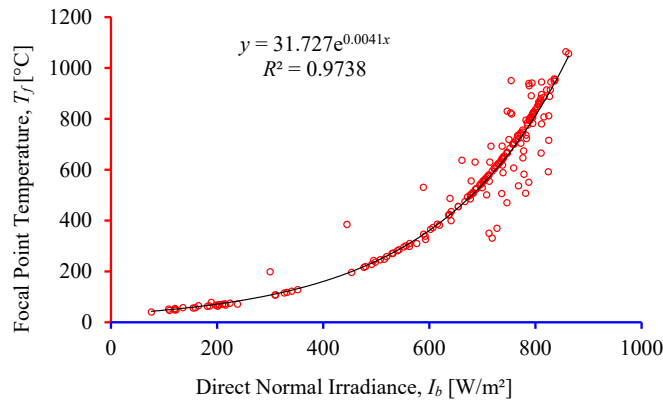


Fig. 4. Effect of direct normal irradiance on the point focal temperature at the receiver surface

From all the result data of the experiment, it is obtained that DNI and average focus temperature (T_f) is 611 W/m² and 484 °C, respectively. While the maximum values of DNI and T_f are 858 W/m² and 1064 °C. **Fig. 4** shows the distribution of DNI data to the receiver's focusing temperature. The regression analysis results show that the trendline has a correlation coefficient (R^2) = 0.973. It shows that DNI has a significant correlation to the focal temperature produced by the PMMA Fresnel lens. Thus the exponential pattern relationship that occurs between DNI or symbolized (I_b) W/m² with focus temperature (T_f) °C. The equation below shows the relationship between DNI and receiver focus temperature:

$$T_f = 31.72e^{0.004x(I_b)}. \quad (9)$$

Thus it can be concluded that the PMMA Fresnel lens has a diameter specification $\phi = 1000$ mm, surface area $A_a = 0.785$ m², and focus distance $f = 880$ mm can produce temperatures at the focal point, reaching 1064 °C.

3. 2. Performance of Fresnel Solar Water Heater

Fig. 5 shows a receiver with a volume of 2 litres of water in 100 minutes capable of reaching temperatures above 70 °C. Whereas, the test results that show a decrease in temperature are the test on 12/08/2020 (green). The main factor in decreasing water temperature is cloudy weather so that the DNI drops during testing. **Table 1** shows the calculation of various performance parameters of the thermal receiver.

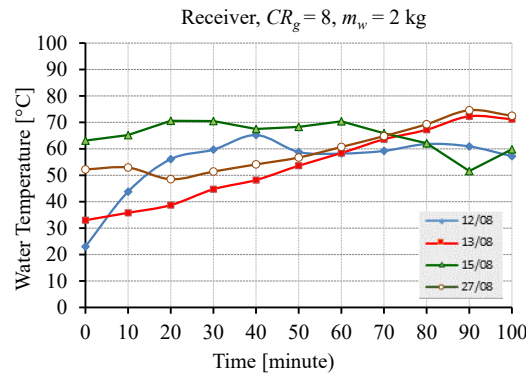


Fig. 5. Comparison of the performance of water heating temperature by the Fresnel lens on the receiver

Table 1

Calculation of thermal receiver performance parameters of testing

Date	I_b (W/m ²)	Q_{in} (Watt)	Q_u (Watt)	η_{Th} (%)	U_L (W/m ² ·C)
12/08/2020	690	408.9	47.73	11.67	130.12
13/08/2020	749	443.8	53.31	12.01	163.24
27/08/2020	587	358.7	28.33	8.16	92.02

The performance characteristics of the receiver during testing can be seen in **Fig. 6**. In this regard, the relationship between the efficiency of the sensible thermal η_{Th} of receiver's with a group of variables that affect efficiency is shown by the equation (2):

$$\eta_{Th} = \frac{T_{avg} - T_a}{A_r I_b}, \quad (10)$$

where, $T_{avg} = (T_o + T_i)/2$. Based on tests on 12 and 13 August 2020, the efficiency distribution is between 10 % to 15 %. This proves the stability of the incoming DNI. Meanwhile, the distribution of test data on June 27 fluctuates, which results in instant efficiency results. To show a representation of the overall performance of the receiver, the efficiency taken is the average efficiency.

The average total thermal efficiency for the three tests under conditions of relatively normal solar radiation for 675 W/m² is 10.61 %. Meanwhile, the energy generated by the receiver to heat water with a duration of 100 minutes (12, 13, and 27 August 2020) is 0.29 MJ each, 0.32 MJ and 0.17 MJ.

The study's limitations and disadvantages include its low efficiency, which is estimated to be around 10 %. As a result, various treatments and modifications to this solar water heater mechanism are required, including: 1 – the treatment of the receiver surface by adding an insulating layer to the wall and coating the surface with black. This will reduce convection and radiation heat loss so that thermal efficiency will increase. 2 – the shape and dimensions of the receiver need to be developed to get high-efficiency heat collector performance. 3 – the characteristic of the Fresnel

solar concentrators has high efficiency if the direction is always perpendicular to the Sun's rays. So it is necessary a solar tracker with dual axes, which can follow the movement of the Sun precisely.

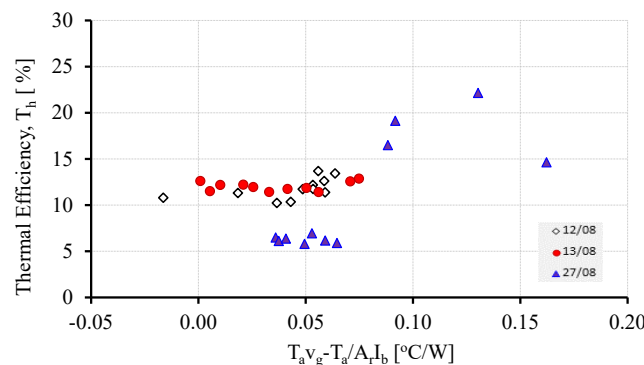


Fig. 6. Effect of variable $f_{(A,LT)}$ on the sensible thermal efficiency of the receiver

The use of large Fresnel lenses in solar thermal applications has the potential to be developed for a communal scale (e.g. school dormitories and hotels). The advantages of Fresnel lenses are lightweight, not easy to break, simple construction, inexpensive compared to glass materials and easy to maintain. Therefore, the use of Fresnel lenses for solar water heaters is an alternative to replace the previous technology, namely the flat-plate type or glass tube.

4. Conclusion

The PMMA Fresnel lens used in this study has a diameter specification $\phi = 1000$ mm; surface area, $A_a = 0.785$ m², focal distance, $f = 880$ mm and lens efficiency, $\eta_L = 89.9$ %. The measurement results show the relationship between Direct Normal Irradiance (I_b), and focal point temperature (T_f). Therefore the effect of DNI on the focal temperature of the Fresnel lens concentration is exponential. The test results for the DNI 850 W/m², can produce a focal point temperature of up to 1064 °C. The lightweight Fresnel lens design has the potential for solar water heating applications or to meet household thermal energy needs.

The thermal efficiency of the conical cavity receiver, which contains 2 litres of water and $CR_g = 8$ under relatively normal solar radiation conditions ($\bar{I}_b = 675$ W/m²), is about 10.61 %. The energy produced to heat water within 100 minutes ranges from 0.17–0.32 MJ.

Increasing the concentration of solar heat with Fresnel lenses can be done with a treatment receiver. Heat loss and convection radiation can be reduced by adding an insulating layer to the walls and coating the black surface. The accuracy of the solar tracker will improve the performance of the Fresnel lens solar concentrator.

Acknowledgments

We are very grateful to the Department of Mechanical Engineering, State Polytechnic of Malang, Indonesia to provide equipment support and be more mature in conducting an analysis.

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Received date 13.08.2021

Accepted date 26.05.2022

Published date 31.05.2022

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How to cite: Asrori, A., Susilo, S. H. (2022). The development of Fresnel lens concentrators for solar water heaters: a case study in tropical climates. *EUREKA: Physics and Engineering*, 3, 3–10. doi: <https://doi.org/10.21303/2461-4262.2022.002441>