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The Potential of Steam Generating by The PMMA Fresnel Lens Concentrator for Indoor Solar Cooker Application

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Abstract

Solar power is an alternative energy source that can be used for cooking. It is a simple, secure, and useful way to cook food without using conventional fuels that pollute the air. Solar cookers offer various benefits to the user's health, productivity, and income as well as to the environment. Solar energy is abundant in a tropical country like Indonesia, making it a dependable and sustainable of energy resource. The study's goal is to analyze the potency of steam produced by a solar cooker that uses a Fresnel lens concentrator. The thermal performance of the Fresnel lens concentrator with a conical receiver on the solar cooker prototype is discussed in this research. In the construction of solar cookers, PMMA (Polymethyl-Methacrylate) Fresnel lenses, manual trackers, and conical receiver types are used. The research conducts an experimental analysis of the thermal performance of the prototype solar cooker using a Fresnel lens concentrator with a conical receiver. This empirical approach provides valuable data on the efficiency and effectiveness of the solar cooker design. The experiment result shows the cumulative average solar irradiation, the average collection of solar energy per time of Fresnel lens concentrator, and the heat utilized of steam from conical receiver are 709.09 W/m², 456.14 Watt, and 383.88 Watt, respectively. The results of this study suggest that Fresnel lens concentrators are a promising development for indoor solar cookers and therefore provide a pathway for increased utilization of solar cooking technology.

Keywords

solar energy, indoor solar cooker, Fresnel lens, steam heat

1 Introduction

Fossil fuels have predominantly been employed in Indonesia in recent years to cover the nation's energy needs. It consists of crude oil (27.80%), coal (10.35%), and natural gas (10.55%). On the other hand, the overall energy consumption increased by about 3.4% per year from 2013 to 2019 and decreased by about 5% in 2020. Whereas, in 2021, consumption increased by about 3%, but it was still below levels in 2019 [1]. Therefore, there must be a way to cut back on the use of fossil fuels. One of the most promising renewable energy sources that are accessible in the majority of developing countries, including Indonesia, is solar energy. Additionally, solar energy is typically captured and converted into heat for usage in households (such as for cooking and water heating), industrial sector, and the production of electricity [2–4].

Indonesia is located at latitudes 6° N to 11° S, and 95° to 141° E in the eastern longitude. The dry season in Indonesia runs from June to September, and the wet season is from December to March [5, 6]. The intensity of solar radiation in Indonesia can reach 5.1 kWh/m²/day (in the eastern region) and 4.5 kWh/m²/day (in the western region), with an average of about 4.8 kWh/m²/day in the entire region. Indonesia has duration of sunshine for as long as the season of about 2975 hours, with an average of 8.2 hours every day [7, 8].

According to its geographic locations, most of Indonesia can take advantage of optimal sunshine throughout the year. In addition, the amount of sunshine becoming on a square meter of the surface during peak conditions or when the sun is perpendicular can reach 900 to 1000 Watts per hour. Indonesia has a high potential for solar energy and can be one of the choices for renewable energy sources. However, the large potential of solar energy can-not be utilized optimally. Therefore, knowledge, research, development, and

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national energy policy are needed to use solar energy to be the solution for the country's energy needs [9–11].

Solar thermal energy is regarded as one of the most promising choices for the demands of rural cooking (small scale) and thermal processing (industrial scale). When it comes to using solar energy, solar cooking is an advantageous alternative [12, 13]. Meanwhile, in developing countries, both commercial (i.e., LPG, kerosene, electricity, and coal) and non-commercial (firewood, agricultural waste, and cow dung) energy contribute to the majority of the total energy used for cooking [14, 15].

Suharta et al. [16] presented the first investigation and report on the use of solar energy for residential solar cookers in Indonesia. According to their reports, the sixty-four solar ovens that were field tested in numerous locations of eastern Indonesia showed promising indications of social acceptance. Additionally, the solar oven's design makes it possible to cook a variety of foods effectively [17]. There are several benefits to using solar cookers, including those that relate to user health, economics, usability, suitability for families, and environmental impact [18, 19]. The different designs for solar cookers that have been made, such as box, concentrator, indirect, with and without storage, and many others. In addition to having a wide variety of types, solar cookers also have well-developed, thorough designs, test procedures, theories, and utility [20–23]. Furthermore, several researchers have presented a comprehensive review of solar cookers, including a variety of types, thorough furnace designs, optimization of geometric factors, feasibility analysis, standardized testing methods, and performance analysis [24–26].

There haven't been many studies done on concentrator solar cookers with as large Fresnel lenses. Until now, several researchers have solely studied parabolic solar concentrators [27]. There are advantages and disadvantages to using concentrator types for domestic solar cookers. It is more quickly for cooking/heating some foods/water since it can reach higher temperatures than other types and high temperatures in a short time. These models' disadvantages include the requirement of regularly refocusing on the direction of the sun (a solar tracker is required), the potential for burning food if abandoned for any period, and the potential for flames and burn if not used carefully [28, 29].

Researchers have been studying the use of solar energy concentrator methods for indoor solar cooker applications, particularly for steam transfer, over the past three years. In a study conducted by Raheema and Bedaiwi [30], it was found that the thermal performance of parabolic solar collectors for steam generation improved with the use of smaller receiver tube diameters. Another study by Houcine et al. [31] introduced a new hybrid photovoltaic parabolic concentrator that used a conical thermal receiver, which significantly improved optical efficiency and steam productivity. Additionally, Kumar et al. [32] designed a household scale parabolic dish concentrator (PDC) that could achieve steam cooking results for certain foods in just 70 minutes with an energy efficiency of 47.74%.

Meanwhile, several researchers have also explored the potential of Fresnel lenses as solar energy concentrator technology for water heating or indoor cooking. Obaid et al. [33] conducted an experimental study of Fresnel lenses for water heating with a heat exchanger receiver. A cone-shaped pipe heat exchanger and a cube-shaped tank are placed at the focus of a Fresnel lens, with the focus continuously adjusted by incoming sunlight. The research results show that the cone-shaped pipe heat exchanger has a thermal efficiency of up to 30% when exposed to a solar radiation intensity of 1159 W/m² and a temperature of around 16 °C. Cuce and Cuce [34] presented a Fresnel lens-driven hot water/steam generator suitable for domestic and industrial use, with a capacity of up to 1696.5 kg of steam in 3 hours. These studies collectively highlight the potential of various solar concentrator technologies for steam generation, providing valuable insights for the development of PMMA Fresnel Lens Concentrators.

The solar cooker based on a Fresnel lens is made to be lighter, more portable, more affordable, more simple and flexible in design, and smaller in size when compared to solar parabolic cookers. However, research on the application of Fresnel lens concentrators for solar cookers is still limited to outdoor solar cookers. An outdoor location is chosen for the cooking installation, which is supported by a stand [35, 36].

Therefore, this research will introduce the use of a large Fresnel lens made of PMMA (Polymethyl-Methacrylate) material to concentrate solar energy on a specially designed stove. This research is also to build a new design of solar cooker based on a large Fresnel lens concentrator with a special receiver unit for steam generation. The steam produced will flow through pipes to cook indoors. In addition, the thermal performance of this Fresnel solar cooker is investigated.

2 Methods and materials

2.1 Experimental setting

The experiments have been done at State Polytechnic of Malang site, Indonesia (Latitude: −7.9434° and Longitude: 112.6136°) on dry season. This research investigates the generation of saturated steam for medium-temperature applications (100 °C – 150 °C) using low-pressure steam (up to 2 bar) [37–39]. The tests were carried out under clear sky conditions with prolonged sunshine duration to achieve stable solar irradiation and maximize the saturation temperature of the water in the receiver. Once this temperature and pressure exceed their saturation points (>100 °C and >1 bar), the water undergoes a phase change to saturated steam. A relief valve then regulates the flow of this steam through a nozzle and into an indoor pressure cooker. The research flowchart for the Fresnel solar cooker (FSC) is shown in Fig. 1.

The solar cooker experiments were conducted during a duration of three consecutive days under clear sky conditions. Every test was conducted from 9:00 am to 3:30 pm. The device used for testing solar irradiation (I_b) is measured by a

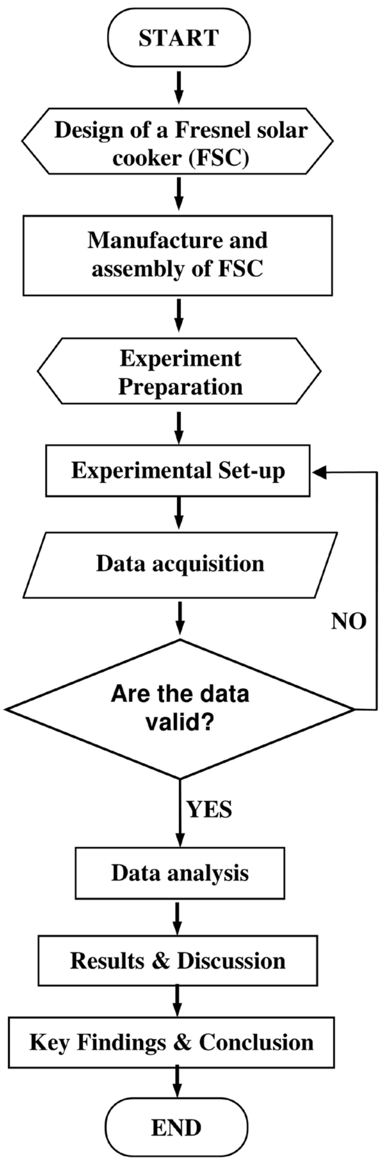

Fig. 1 Flowchart of the Fresnel solar cooker experiment

Solar Power Meter SM 206, with an accuracy of ±10 W/m²; sensor type: silicon cell; measuring range: 1–3999 W/m². The temperature was measured using a K-type thermocouple connected to a data logger multi channel.

Furthermore, the data logger connected to a computer was used to record the output temperature. This thermometer has an accuracy of ±0.3 °C for temperature measurements ranging from −50 °C to 1200 °C. It is utilized for measuring the temperature at the focal point (T_2) of solar radiation concentration on the receiver surface, water temperature (T_1) in the conical receiver, the surface temperature at the conical receiver's side/wall (T_3), and ambient temperature (T_s). All data were collected at 10-minute intervals. The pressure gauge and safety valve are mounted on the receiver's outflow. The safety valve allows to regulation the operating pressure at which it should open and release the generated steam. Because the safety valve only opens at a predetermined pressure, it is possible to keep the desired pressure inside the receiver.

The experimental set-up of a Fresnel lens concentrator for an indoor solar cooker is shown in Fig. 2.

2.2 Main devices of Fresnel solar cooker

A comprehensive description of the main parts of the Fresnel Solar Cooker (FSC) consists of;

1. Fresnel lens concentrator; solar radiation was concentrated using a Fresnel lens composed of high-quality acrylic (poly-methyl methacrylate, PMMA). The Fresnel lens used has a circular Fresnel lens aperture (A_f) of 0.785 m² with a diameter of 0.9 m. This lens has a focal length (f) of 0.88 m. Furthermore, the Fresnel lens is mounted on an aluminum frame of the solar cooker installation, as shown in Fig. 3.
2. Single-axis tracker with an actuator hydraulic system; Fresnel lenses were moved by an automatic solar tracking-single axis mechanism. The Fresnel was automatically oriented according to azimuth at 10-minute intervals, to concentrate the energy of solar radiation. Single-axis tracking from east to west ensure the orientation of the Fresnel lens.
3. The conical receiver; a conical receiver collects concentrated solar energy. The conical receivers are made of copper plates with a thickness (t) of 2 mm. It has the properties of thermal conductivity, k = 385 W/m °C, and the density of the plate material, ρ = 8954 kg/m³. Furthermore, the conical receiver design consists of two-volume variations: 2 liters and 0.5 liters.

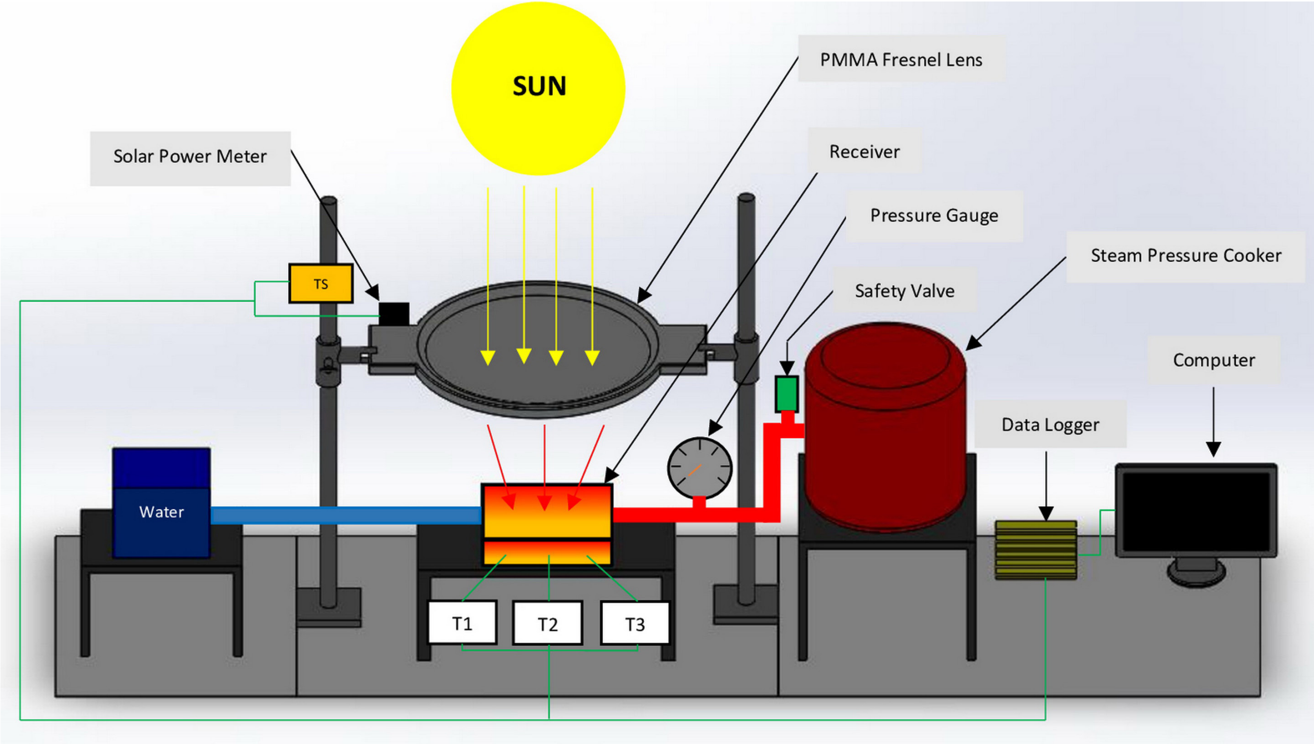

Fig. 2 Schematic diagram of the test set-up used in the experiment

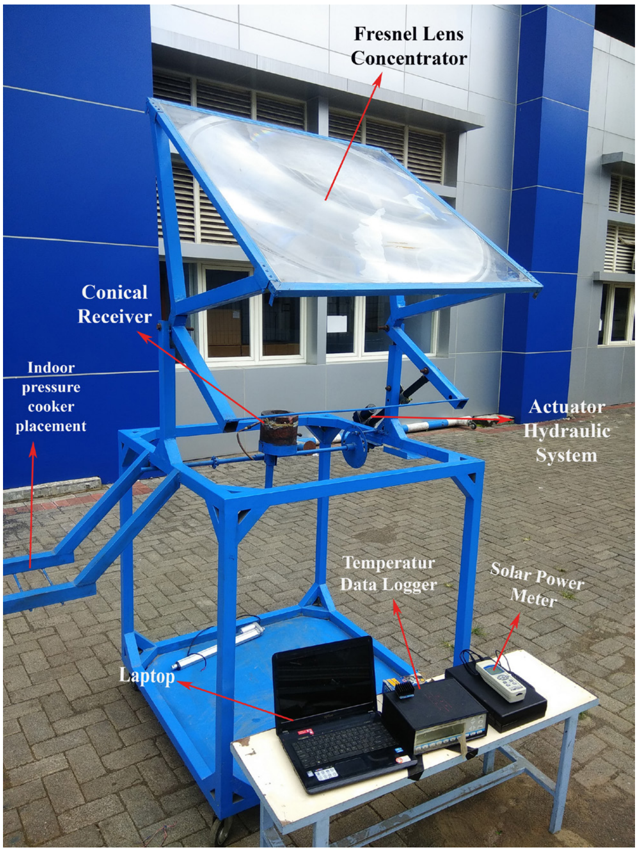

Fig. 3 The Installation of Fresnel lens solar cooker

2.3 The energy balance of receiver

The energy balance from solar radiation in the conical receiver is shown in Fig. 4.

Energy refraction from the Fresnel lens influences the concentration of energy arriving at the receiving surface. The conical receiver's energy can be written by Eq. (1) [36]:

$$Q_f = \eta_o \cdot A_f \cdot \int_0^t I_b \cdot dt, \tag{1}$$

where, Q_f is solar energy received (kJ); η_o is optical efficiency; I_b is the solar irradiation (kW/m²); A_f is the aperture area of circular Fresnel lens (m²); t is the time of measurement (s).

Energy balance at dish receiver can be estimated by using the following Eq. (2):

$$\dot{Q}_{\text{rec}} = \dot{Q}_f - \dot{Q}_{\text{cond.loss}} - \dot{Q}_{\text{conv.loss}} - \dot{Q}_{\text{rad.loss}} \tag{2}$$

As a result, the instantaneous thermal efficiency can be expressed by Eq. (3):

$$\eta_{th} = \frac{\dot{Q}_{\text{rec}}}{I_b A_r} = \eta_o - \frac{U_L (T_r - T_a)}{I_b C R_g}, \tag{3}$$

where, Q_{rec} is the useful energy delivered by the conical dish receiver; U_L is the coefficient of overall heat loss; A_r is the area of conical receiver; T_a is the ambient temperature; T_r is the mean temperature of the receiver surface; T_{av} is the average operating temperature of working fluid, and the geometric concentration ratio (CR_g) is defined as the ratio of the Fresnel lens aperture area (A_f) to the surface area of the receiver (A_r).

Fig. 5 shows the application of the first principles of the first law of thermodynamics in the conical receiver.

The useful energy (Q_u) delivered from a receiver can also be written as rate of specific heat gained by the fluid, shown by Eq. (4):

$$\dot{Q}_u = \dot{Q}_{\text{rec}} = \dot{Q}_s + \dot{Q}_L \tag{4}$$

The heat energy required to raise the sensible temperature of water to 100 °C (sensible heat) can be written by Eq. (5):

$$\dot{Q}_s = \dot{m}\left(h_o - h_i\right) \tag{5}$$

$$\dot{Q}_s = \int_{T_i}^{T_o} \dot{m} c_p dT \tag{6}$$

$$\dot{Q}_s = \dot{m}_w c_p \left(T_o - T_i\right) \tag{7}$$

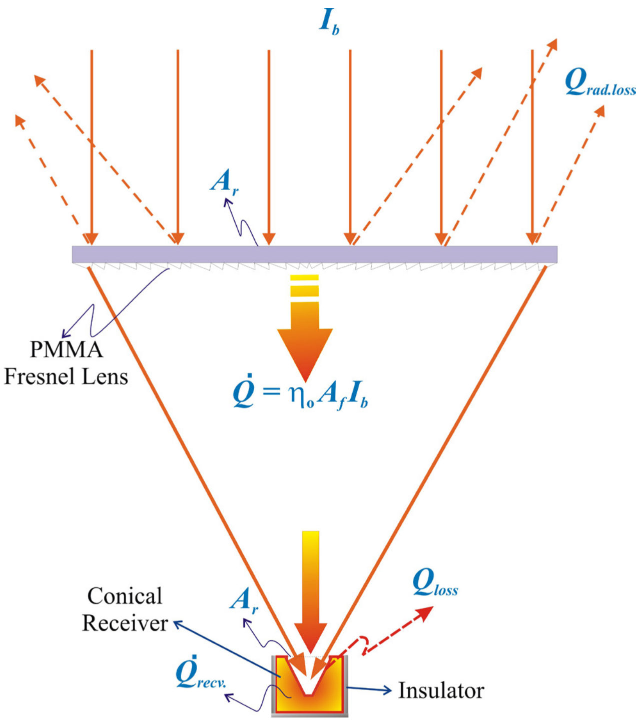

Fig. 4 The Illustration of energy balance of receiver

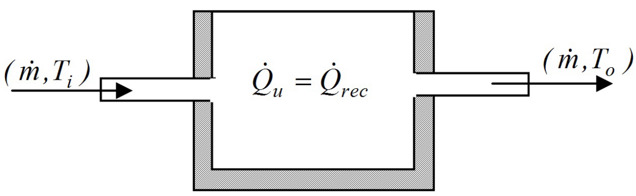

Fig. 5 The usefull energy in conical receiver

The heat energy required to convert of water at 100 °C to steam (latent heat) can be written by Eq. (8):

$$\dot{Q}_L = \dot{m}_w h_{fg}, \tag{8}$$

hence,

$$\dot{m}_w c_p \left(T_o - T_i\right) + \dot{m}_w h_{fg} = \eta_{\text{rec}} \eta_o A_f I_b, \tag{9}$$

where, Q_w is energy absorbed by the water flow; $\dot{m}$ is the mass flow rate of water (kg/s); c_p is the specific heat capacity at constant pressure of the water (4186.8 J/kg K); T_i is the water inlet temperature; T_o is the steam outlet temperature; h_{fg} is the specific latent heat of the vaporization of water is 2.257 × 106 J/kg at constant saturated pressure and temperature.

3 Results and discussions

Experiments were carried out on a prototype Fresnel lens concentrator for solar steam cooker applications. In this regard, the load or volume of water in the conical receiver has been designed differently, viz. 2 liters and 0.5 liters, respectively. Whereas the data consisting of local time, pressure, temperature parameters, and solar radiation were measured, periodically.

3.1 Measurement of solar irradiation

Fig. 6 shows on the graph a typical solar irradiation (I_b) profile during three days in clear sky conditions. Fig. 5 shows that the average solar irradiation recorded on day-1, day-2, and day-3 was 709.19 W/m², 700.32 W/m², and 717.14 W/m², respectively. Therefore, the cumulative average solar irradiation was 709.09 W/m². In addition, the maximum solar irradiation obtained during the test was 850 W/m², which depends on local solar time.

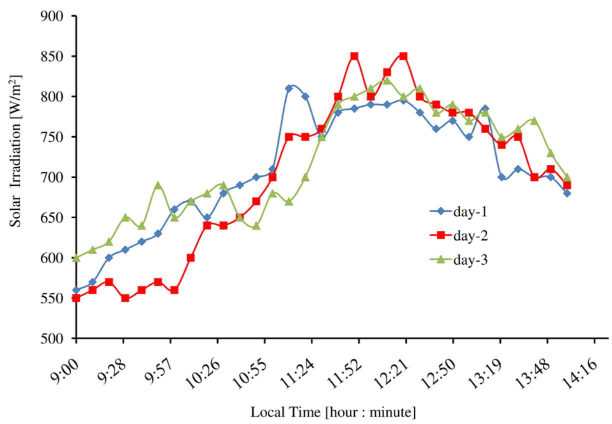

Fig. 6 The solar irradiation variation as a function of time

The average collection of solar energy per time, can be calculated by Eq. (10):

$$\dot{Q}_f = \eta_o \cdot A_f \cdot I_b = 0.83 \cdot 0.785 \ \text{m}^2 \cdot 700.09 \ \text{W/m}^2 = 456.14 \ \text{Watt}, \tag{10}$$

where, $\dot{Q}_f$ is refraction power of Fresnel lens (W), I_b is solar irradiation (W/m²), A_f is *aperture area* of Fresnel (m²), η_o is optical efficiency is 83% [40]. This calculated result shows that Fresnel lens concentrator can be used to solar cooker.

3.2 Measurement of temperature

Solar radiation was concentrated at the focal point by the Fresnel lens, increasing the density of solar energy in this region. Therefore, the conical receiver (T_r) is installed at the location of the Fresnel lens focal point in this Fresnel Solar Cooker (FSC) prototype. Figs. 7 and 8 show the results of temperature measurement parameters in the experiment with water volumes of 2 liters and 0.5 liters, respectively.

Fig. 7 shows that the focal temperature has the same pattern as solar irradiation (I_b). The increase in solar irradiation is also accompanied by an increase in concentrating solar thermal or the focal temperature (T_f). In addition, local time cannot be used as a parameter, that the higher the solar irradiation during the day, this is because the weather conditions (cloudy) dominantly affect the size of the solar irradiation received by the Fresnel lens.

According to the data distribution, an average sun irradiance and focal temperature are 611 W/m² and 484 °C, respectively. While the maximum values of I_b and T_f are 700.09 W/m² and 954.2 °C. Fig. 6 above also shows that a receiver with a volume of 2 liters of water takes up to 3 hours to produce steam (water temperature up to 100 °C). The extent of time required is due to fluctuations in the heat energy entering the receiver. This energy instability is caused by several factors, namely wind speed, overcast clouds, inaccuracy of the solar tracker, and loss of energy in the receiver.

Several factors affect receiver performance consists of solar irradiation received by the Fresnel lens, the characteristics of the PMMA Fresnel lens concentrator, receiver shape and material, receiver treatment (insulator and surface coating), initial and final water temperature, ambient temperature, receiver surface temperature, and wind speed [41].

Fig. 8 shows the temperature behavior of a conical receiver containing 0.5 liters of water.

Test result shows that water heating process in conical receiver by Fresnel lens concentrator is very fast occurs at volume 0.5 liter (Fig. 8) compared with volume 2 liter (Fig. 7). The temperature and rate of change of sensible and latent heat will increase with increasing solar radiation. Thus, cooking, heating, and steaming can all be done at this high temperature [42, 43].

3.3 Measurement of steam pressure

The effectiveness of the steam generation is one of the variables affecting the receiver's ability to generate useful steam energy quickly. So that this steam can be used as a power supply for indoor cooking. Fig. 9 compares the ability of the large and small receivers to produce steam at a saturation pressure of 2 bar. Several studies suggest that using Fresnel lenses in solar cookers significantly reduces costs compared to traditional glass mirror concentrators. This advantage is further enhanced by employing receivers with high geometric concentration ratios, which not only achieve high

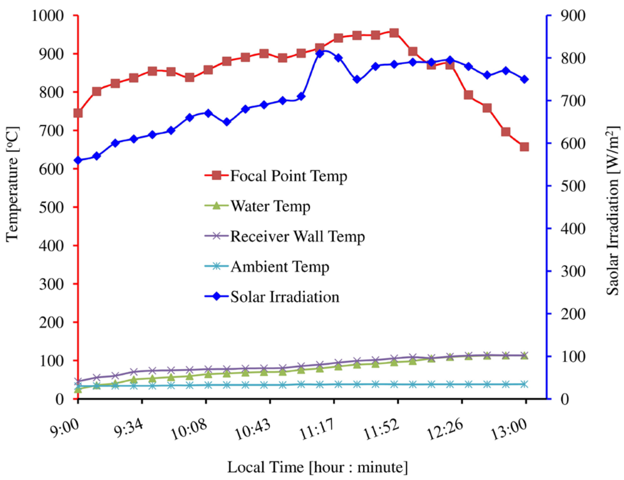

Fig. 7 The variation of solar irradiation and temperature as a fuction of time at conical receiver, V = 2 liter.

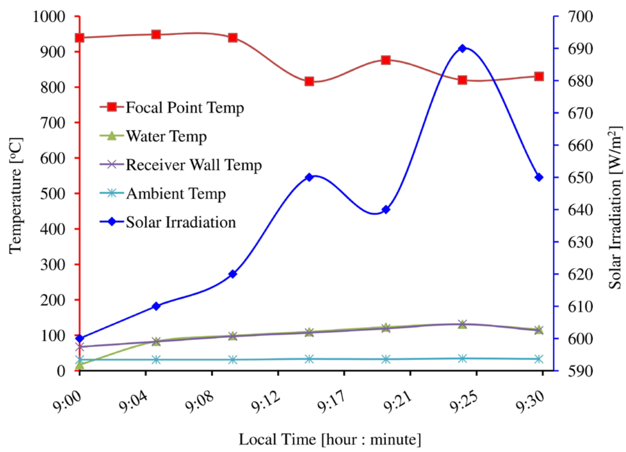

Fig. 8 The variation of solar irradiation and temperature as a function of time at conical receiver, V = 0.5 liter

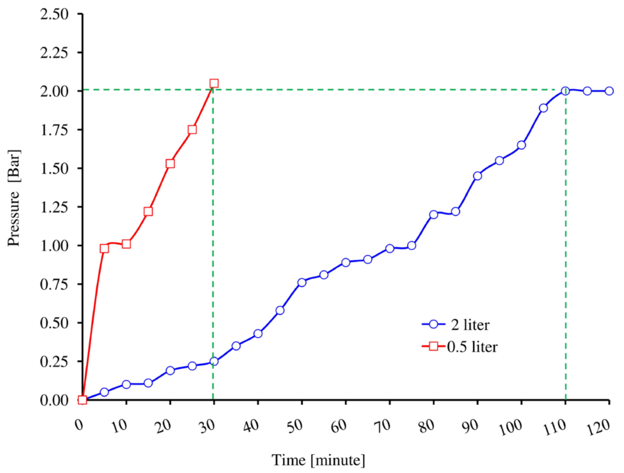

Fig. 9 The pressure variation at conical receiver as a function of time

temperatures but also maintain good efficiency [39, 44, 45].

Based on the reviews above, this experiment compares receivers with large and small volumes. The goal is to find a receiver capable of functioning as a mini boiler so that it can generate steam.

Receiver requirements can be developed for indoor solar stoves with the steam transfer method if this receiver can function as a boiler. The mini boiler can produce steam (latent heat) in a short duration, so the steam produced can be used as a source of cooking energy [35].

The receivers used in this study consisted of two types of geometric concentration ratio (CR_g), namely 8× for large receivers (V = 2 l) and 30× for small receivers (V = 0.5 l). According to Kribus [46] the temperature distribution throughout the receiver surface ranges from 250 °C – 750 °C, which can be produced by receivers with $CR_g < 50$. The high-concentration temperatures increase the rate of heat transfer into the receiver.

3.4 The rate of heating the water

The initial estimate, the energy loss is assumed to occur on the conical receiver surface is η_{rec} = 85% [40]. Thus, the thermal energy absorbed by water in the conical receiver,

$$\dot{Q}_w = \eta_{rec}\dot{Q}_f = 0.85 \cdot 462.01 = 392.71 \text{ Watt}, \quad (11)$$

hence,

$$\dot{m}c_p\left(T_o - T_i\right) = \eta_{rec}\eta_o A_f I_b \quad (12)$$

where $\dot{Q}_f = \eta_o A_f I_b$ = 462.01 Watt, T_o = 100 °C, T_i = 25 °C, C_p is the specific heat capacity of the water, at constant pressure (4186.8 J/kg K), h_{fg} = 2.257 · 10⁶ J/kg).

$$\begin{aligned}\dot{m}_w &= \frac{\eta_{rec}\dot{Q}_f}{c_p\left(T_o - T_i\right) + h_{fg}} \\ &= \frac{462.01(0.85)}{4186.8(100-25) + 2.257 \cdot 10^6} \\ &= 0.000157 \text{ kg/s} = 0.5652 \text{ kg/h}\end{aligned} \quad (13)$$

3.5 Boiling time of water

The estimation of boiling time for 0.5 liter of water can be calculated by Eq. (14):

$$\begin{aligned}t &= \frac{\rho_w V_w}{\dot{m}_w} = \frac{997.97 \cdot 0.0005}{0.000157} \\ &= 3178.25 \ s \approx 52 \text{ minutes.}\end{aligned} \quad (14)$$

3.6 The heat utilized of steam

Equation (15) shows how the thermal energy in the steam receiver is used to heating of water from ambient tempera-ture to saturation temperature (the sensible heat) before it vaporates at saturation pressure (the latent heat of vapori-zation),

$$\dot{Q}_{vap} = \dot{m}_{vap}c_p(T_o - T_a) + \dot{m}_{vap}h_{fg}, \quad (15)$$

where, $\dot{m}_{vap}$ = rate of generated steam (kg/h), T_o = operating temperatur (saturation temperatur) at saturation temperature (°C), T_a = ambient temperature (°C), h_{fg} = vaporization's latent heat at saturated pressure (J/kg), c_p = specific heat capacity of the water at constant pressure (J/kg K).

If known; $\dot{m}_{vap} = \dot{m}_w$ = 0.54 kg/h, c_p = 4186.8 J/kg K, T_a = 31 °C, T_o = 100 °C, h_{fg} = 2.257 · 10⁶ J/kg. Thus, the output vapor energy per cycle from conical receiver,

$$\begin{aligned}\dot{Q}_{vap} &= \dot{m}_{st}\left[c_p(T_o - T_a) + h_{fg}\right] \\ &= 0.54\left[4186.8(100-31) + 2257000\right] \\ &= 1381.98 \text{ kJ/h} = 383.884 \text{ Watt.}\end{aligned} \quad (16)$$

According to the calculations above, it can be concluded that a Fresnel lens can be used as a steam generator or boiler when combined with a suitable receiver. In a concentrated solar cooker application, the receiver can also be used as a cooking vessel.

The investigation of the receiver performance for the Fresnel solar cooker application shows that direct/indoor solar cookers can use the system. This prototype would be very advantageous if it were made on a larger scale, so that it could be utilized in communal areas like dormitories, hotels, public kitchens, etc.

Concentrated solar cookers using Fresnel lenses and vapour transfer are a promising technology for cooking with solar energy. However, they have some limitations that need to be considered.

One such limitation is the concentration ratio. Current Fresnel lens technology has a lower concentration ratio than parabolic reflectors. This is due to the cost of materials and manufacturing, which limits the dimensions of the Fresnel lens. As a result, the focal temperature area of the Fresnel is limited and receiver dimensions cannot be maximized.

Another limitation is the non-uniform heat distribution. Due to the design of the lens, the focused sunlight creates a non-uniform heat distribution on the receiver, which can potentially cause thermal losses.

In addition, Fresnel lenses require continuous tracking of the sun on two axes to maintain focus. However, the Fresnel solar cooker designed in this study uses a single axis (east-west) and moves intermittently. Therefore, the resulting temperature may not be optimal.

Finally, similar to other solar technologies, the performance of concentrated Fresnel lens solar cookers depends on clear skies and direct sunlight, limiting their usefulness in cloudy weather. Unstable sunlight can cause steam to condense within the system, leading to potential pressure fluctuations and requiring additional components to mitigate.

4 Conclusion

The results show that small receivers are more effective than large ones. It's brought on by several factors, includeing increased efficiency, the potential for faster steam generation due to short cycle times, the load on small receivers being lighter than that on large receivers, and the risk of large receivers not being able to produce steam due to the long time it takes to reach saturation pressure.

The Fresnel lens can focus sunlight, which is a cheap and renewable source of energy. In tropical countries such as Indonesia, the solar energy is plenty and therefore it be-comes a reliable and sustainable source of energy. Fresnel lenses can accelerate and increase the concentration of heat. The prototype Fresnel solar cooker's test findings indicate that an indoor solar cookers could potentially developed with a Fresnel lens concentrator.

Limitations of the Fresnel solar cooker include the limited concentration ratio, continuous double-axis solar tracking, unstable focal temperature distribution, the receiver requiring an insulator, weather influence, steam pressure fluctuations, and thermal losses in steam transfer.

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