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Improved Receiver Design Concepts for Parabolic Dish Direct Solar Cooking Systems

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ABSTRACT

In developing countries, solar cooking technology is considered one of the key measures in dealing with deforestation and environmental pollution. However, their adoption and utilization have been insignificant due to social, cultural, and technical challenges, among others. For parabolic dish direct solar cookers, one of the critical and most important components of the system is a receiver since its performance greatly affects the entire system. This paper presents part of the findings of the study which investigated the prospects of improving the technical performance of parabolic dish direct solar cooking systems by focusing on the identification of prospective heat loss reduction mechanisms on the receiver. The study identified the Insulated (IR), Air-filled (AFR), and Oil-filled (OFR) receivers with Base Circular Rings (BCR) as alternatives to the Conventional Receiver (CR) System. Tests were conducted using procedures and protocols given by the American Society for Agricultural Engineers (ASAE). The test results showed that the average power developed by the systems was 185 W for the IRBCR system, 90 W for the OFRBCR system, 92 W for the AFRBCR system, and 118 W for the CR system. The standardized cooking power for a temperature difference of 50°C, $P_S(50)$, was 291 W for the IRBCR system, 11 W for the OFRBCR system, 272 W for the AFRBCR system, and 142 W for the CR system. The results further revealed that the overall efficiencies were 23% for the IRBCR system, 9% for the OFRBCR system, 12% for the AFRBCR system, and 18% for the CR system. The receiver efficiencies were found to be 27% for a system with IR, 11% for a system with OFR, 14% for a system with AFR, and 21% for a system with CR. The study concluded that the performance improved when the system with the IR was used while the magnitudes of the performance parameters of the AFR and OFR were lower than the CR system.

Keywords: Solar Cooking, Improved Receiver, Receiver Efficiency, Thermal Efficiency, Heat Flow.

1. INTRODUCTION

Lack of access to clean household cooking energy is a globally accepted challenge experienced by many regions of the world with an estimated 2.8 billion people being affected (International Energy Agency, 2017). In developing countries, in Africa for instance, fuelwood scarcity is a major constraint for people in rural and peri-urban regions as this is the main source of cooking, baking and heating energy for the majority of households (Riahi et al., 2018; Asmelash et al., 2014a). Combustion of these fuels leads to many environmental and health problems such as indoor air pollution associated with use of traditional cooking stoves (Tesfay et al., 2019).

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Relentless efforts are therefore being undertaken to devise alternative methods of meeting household energy cooking requirements as a way of averting both the cooking energy requirement challenge as well as the problems associated with use of fuelwood. Solar cooking technology is one of the solutions to the said problems and is currently being promoted in many countries. It is considered as one of the possible solutions in dealing with deforestation and environmental pollution (Asmelash et al., 2014b; Cuce and Cuce, 2013).

The most widely and commonly used solar cookers are the direct types mainly the solar box, panel and the parabolic dish (Asmelash et al., 2014b). The solar box cooker, which mainly consists of an insulated box with a transparent cover (glass or plastic) on the top, is the most common type of solar cooker used for domestic cooking (Kimambo, 2007). The panel cooker is similar to the solar box but has reflective panels at the sides of the top face, which focus the sunlight on a cooking vessel (ibid). On the other hand, the parabolic dish is a concentrating type of solar cookers that works based on the principles of optical concentration. Unlike the solar box and panel cooker, which utilise global solar radiation, the parabolic dish cooker concentrates beam solar radiation on the focus of the parabola on which the receiver is placed and achieves higher temperatures than the former (ibid).

Conventionally, many parabolic dish systems that have been developed for outdoor direct cooking, use a black painted pot as a receiver placed on the fixed focus point. The major problem with such systems is that heat losses become excessive, which are also exacerbated by the winds blowing around the receiver (Kumar et al., 2018). Therefore, replacing this type of receiver with improved designs would greatly improve the overall performance of the parabolic dish solar cooking system. This paper focuses on prospective improved receiver designs for parabolic dish direct cooking systems together with their technical performance.

2. RECEIVER DESIGNS USED IN SOLAR THERMAL SYSTEMS

The receiver is one of the most important components of solar thermal systems. This is where radiation is absorbed and converted into heat. The performance of the receiver greatly affects the entire system (Govender, 2013). In order for the solar cooker receiver to absorb the collected energy by transforming it into heat, transfer the heat from its walls to the heat transfer fluid or the cooking load and increase, as well as retain the temperature of the cooking load; it ought to be designed, optimized and constructed in an appropriate manner (Karathanasis, 2019). Geometric concentration ratio, receiver shape and size, orientation, absorber surface area as well as material strength and thermal properties are some of the key factors that are considered in designing and optimizing receiver systems (Govender, 2013).

The need for the receiver to absorb maximum amount of concentrated radiation for the systems to work at higher efficiencies led to numerous research efforts on the design, analysis and optimization of receiver systems to ensure that minimal energy is lost to the environment (Patil et al., 2018; Govender, 2013). According to Capuano et al. (2017), solar thermal receivers are mainly categorized into three namely: cavity, tubular and volumetric. Cavity receivers are insulated enclosures having an opening (aperture) through which radiation enters and undergoes multiple reflections in the inner walls. Tubular receivers are pipes or tubes, which are made from high thermally conductive materials such as carbon, steel and copper that are used or coiled into a specific shape. The latter are prone to high convective heat losses.

On the other hand, volumetric receivers are characterized by porous solid absorbers crossed by air that is heated by contact with the inner walls and are made using materials such as ceramic foams, grids, honeycombs and pin-fin arrays, metallic mesh, fibres and ceramics, among others (Capuano et al., 2017). Radiation on these types of receivers is allowed to penetrate the absorber material making it possible for heat exchange to occur over a larger area rather than just on the surface of the material (Govender, 2013). Despite these three being the major categories of receivers, there have been several efforts to modify these designs, develop novel designs, and ensure that they are optimized to increase the efficiencies of the systems.

2.1. Previous Studies on Technical Performance of Solar Cooking Systems

Patil et al. (2018) studied alternative designs of an evacuated receiver for a parabolic trough collector, in which tests were made on a Half Insulation-Filled Receiver (HIFR), Air-Filled Receiver (AFR) and Linear Cavity Receiver (LCR). The results were compared with Parabolic Trough Receiver (PTR 70) developed by SCHOTT (Patil et al., 2018). Among others, it was found that at temperatures above 400 °C, HIFR and LCR performed better than PTR70 and at temperatures below 400 °C, their performance was similar to the PTR70 (Patil et al., 2018).

A numerical investigation on the effect of receiver shapes on natural convective heat losses was carried out by Sendhil et al. (2008). Experiments for three shapes of the receiver namely: cavity, semi-cavity and modified cavity receivers for a fuzzy focal solar dish concentrator were conducted and convection losses were estimated by varying the inclination angle of the dish. The conclusion was that the modified cavity receiver was preferable as it gave less convective heat losses compared to other receiver types (Sendhil Kumar and Reddy, 2008).

Craig (2015) developed a stand-alone parabolic dish solar cooking system that tracks the sun in two axes and provides cooking services during off-sunshine hours and at night. The analysed performance was compared to existing cookers. The system was an indirect type that utilized oil as heat transfer fluid through copper tubes to a storage-solar-oven combined system. Convective heat losses on the receiver were tremendously reduced by having the entrance aperture area of the cavity receiver packed with a flat spiral copper tube that had no pitch (gap) (Craig, 2015). The system achieved the requirement for indoor cooking and utilization efficiency of around 47% when used under direct sunlight, and around 27% when used for late-hour cooking (ibid).

Yadav et al. (2017) also did a study on solar cookers, but this mainly focused on a system that would be capable of providing cooking power only at night by using a parabolic dish solar cooker with dual thermal storage. The study separately investigated solar cooker receivers with inner space filled with sand, stone pebbles, iron grits and iron balls. The results showed that it was feasible to use the cookers with the inner space filled with sand and stone pebbles as they achieved higher temperatures of 83.5^{o}C and 82.9^{o}C; and successfully cooked the food. Kumar and Singh (2018) experimentally evaluated the performance of parabolic dish solar cookers with cylindrical cooking vessels made of aluminium and galvanized iron sheets. The values of heat loss factor, optical effectiveness factor, cooking power, sensible cooking time, average cooking efficiency and exergy efficiency were used to evaluate the performance. The aluminium cooking vessel attained a maximum temperature of 123^{o}C while the galvanized iron cooking vessel attained a maximum temperature of 105^{o}C. Time taken to boil water in the aluminium vessel was less than the galvanized iron sheet. Therefore, aluminium was considered a better material for performance enhancement.

Das et al. (2019) analysed the performance of a parabolic dish cooker under steady state conditions and unsteady state conditions. The aim was to quantify the heat transfer in the system. The analysis was conducted on a concentrating cooker of aperture area 1.54 m^2 made of anodized aluminium film having 85% reflectivity. The receiver, made of aluminium and painted black with an outer surface area of 0.212 m^2, was placed at the focal point. The observation was that thermal efficiency of the cooker was as low as 7% compared with the predicted thermal efficiency of 54%. This was attributed to very high energy losses on the receiver coupled with unfavourable climatic conditions for operation of the system.

Mekonnen et al. (2020) conducted an experimental study on the performance of the SK14 parabolic solar cooking system that was fabricated in Ethiopia using locally accessible tools and materials. The stagnation test results were found to be 212◦C when air was used as a heat transfer fluid, and 100 ◦C when water was used as heat transfer fluid. The study determined that the solar cooker had a cooking power of 635 W, first figure of merit (F_1) of 0.22 ◦C/W/m^2 and second figure of merit (F_2) of 0.625 which confirmed that the prototype was in line with standards. Kumar et al. (2019) carried out an experimental investigation of a 16 m^2 Scheffler concentrator system and its performance assessment for various regions of India. The study, among others, concluded that by using silicon based high temperature coating in the receiver, instead of the black paint-based receiver, the optical efficiency of the system increased by 15%. Moreover, the study revealed that there was a scope for further improvement in the heat loss coefficient of the system by using better insulation, shape and structure of the receiver.

Onokwai et al. (2019) designed and fabricated a solar box-parabolic dish cooker by using locally available materials in Nigeria on which modelling, and analysis of exergy and energy efficiencies were done. The receiver, which was not an integral part of the dish, was made of an insulated wooden box with a glass cover and a cooking pot, painted black placed inside. The results showed that on average, energy and exergy efficiencies of the system were about 39% and 44% respectively. Instability of energy efficiency was noted, and this was observed to occur because of optical and thermal losses from the reflector and receiver, as well as the varying environmental conditions.

Saini et al. (2016) experimentally investigated a solar cooker based on parabolic trough collector with thermal storage, which was expected to be used during sunshine and off-sunshine hours. Water and oil were used separately as heat transfer fluids. Unlike, the study by Craig (2015), which used an external pump, the circulation of the fluids in the collector-cooker system was by thermosiphonism. It was found that the temperature of thermal oil was 10-24°C higher than that of water as the working fluid. The system was found to be more efficient and faster in evening cooking (using stored heat) compared to cooking during mid-day time. The use of thermal oil as the working fluid achieved higher temperatures compared to water.

Tibebu and Hailu (2021) designed, constructed, and evaluated the performance of dual-axis sun-tracking parabolic solar cooker and compared the cooker with firewood, charcoal, kerosene, and electricity in terms of cooking time and energy cost of cooking. The study found that the output energy, input energy, efficiency and power of the parabolic solar cooker were 0.182 kW, 1.691 kW, 10.75%, and 0.3 kW/hr, respectively. The solar cooker showed best results in cooking Nefro and Shero wet at a short time compared to other fuels. Further, the cooker performed well in boiling water for a short time next to firewood and charcoal despite taking too long to cook other foods such as eggs and potatoes.

A design and simulation study of a parabolic dish solar cooker was conducted by Dasin et al. (2011), in which temperatures were predicted at various components of the cooker system (absorber, pot cover, cooking fluid and air gap). A maximum boiling temperature of 95^{o}C was achieved in 1 hour of heating 1 kg mass of fluid at a beam radiation of 540 W/m^2 and wind speed of 0.98 m/s, which theoretically took around 2 hours 15 minutes to reach the same temperature at the same climatic conditions. It was concluded that the designed cooker compared well with conventional cookers and therefore could substitute the traditional methods of cooking. Chima (2017) constructed a solar box cooker using locally available materials and conducted performance tests on it in Malawi. The study revealed that the thermal efficiency of the cooker and the cooking power were 39% and 766 W respectively. It attained a maximum water temperature of 76 ^{o}C in 5 hours. However, the study suggested the need to improve the design by incorporating reflectors to achieve higher temperatures.

Asmelash et al. (2014a) carried out a performance test study of Parabolic Trough Solar Cooker for Indoor Cooking. The system had two separate parts, the cooker, and the collector. The cooking section was placed 0.5 m from the collector with a series of pipes with soya bean oil, as a heat transfer fluid, conveying the heat from the collector to the cooker. The study found that maximum temperatures of 191^{o}C and 126^{o}C were obtained under no load conditions using a 16 mm diameter copper pipe as an absorber. A maximum temperature of 119^{o}C was achieved at the cooking pot when the cooking pot was loaded with water, eggs and potato. Further, the study showed that the cooker can efficiently cook from 11:00 am to 16:30 pm and the efficiency of the cooker was found to be 6%.

Kimambo (2007) carried out experimental tests for a group of box cookers, reflector cookers and a panel cooker. The tests were done on cookers with different surface areas. The performance of the box cookers (sun stove and wooden box) was found to be comparable as they both attained a maximum temperature of 78^{o}C at an insolation of 1000 W/m^{2} and wind speed of 2.54 m/s. It was shown that double glazing of the box cooker improved the thermal performance and that the use of glass cover instead of transparent polyvinyl cover improved further the performance as it provided good sealing. Parabolic dish cookers (polished aluminium reflector, unpolished aluminium reflector and glass mirror as reflectors) attained higher temperatures with the cooker using glass mirrors as reflector being highest, with a maximum temperature of 96^{o}C attained in 90 minutes. The shape of the parabola was also found to influence the performance of the cooker, with the glass reflector and shallow parabola exhibiting high performance than the one with deep parabola.

3. IMPROVED RECEIVER DESIGN CONCEPTS

This work came up with three receiver design concepts namely, Insulated Receiver with Base Circular Ring (IRBCR), Oil-filled Receiver with Base Circular Ring (OFRBCR) and Air-filled Receiver with Base Circular Ring (AFRBCR) which were theoretically and experimentally analysed and compared with the Conventional Receiver (CR) as discussed in section 3.1.1 and section 5.

3.1. Sizing of Receiver

The receiver is a component of the solar concentrating system, where concentrated radiation is absorbed and converted to other forms of energy. It includes the absorber, insulation and the associated covers (Duffie and Beckman, 2013). In this work, the receiver was designed using volumetric and gravimetric methods, in which the calculations were based on the amount of energy expected to cook 1 kg of rice per cooking time. The volume of rice to be cooked (V_{r1}) was determined using Equation (1).

$$V_{r1} = \frac{m_{r1}}{\rho_{r1}} \tag{1}$$

Where, V_{r1} is the volume (m^3) of rice before cooking, m_{r1} is the mass (kg) of rice before cooking and ρ_{r1} is the density of rice (kg/m^3) taken as 812 kg/m^3. The volume of rice before cooking was therefore 0.0013 m^3. When rice is cooked in a solar cooker, the volume of water required is double the volume of rice i.e. a rice to water ratio of 1:2 by volume (Mahavar et al., 2013).

$$V_{w1} = 2\,V_{r1} \tag{2}$$

$$V_{w1} = 0.0024\,m^3$$

The total volume of the food before cooking (V_{f1}) was therefore determined as the sum of the volumes of water and rice before cooking.

$$V_{f1} = V_{w1} + V_{r1} \tag{3}$$

The mass of the water before cooking (m_{w1}) is equal to the product of the density of water and the volume of water before cooking.

$$m_{w1} = V_{w1} * \rho_{w1} \tag{4}$$

Where, ρ_{w1} is the density of water at room temperature taken as 997 kg/m^3. So, m_{w1} was 2.4 kg. Total mass of the food before cooking (m_{f1}) was therefore 3.4 kg from Eq. (5).

$$m_{f1} = m_{w1} + m_{r1} \tag{5}$$

The volume of cooked rice (V_{f2}) (rice including water) expands to about 3.2 – 3.5 times the volume of uncooked rice after completion of the cooking process (Mohammed, 2013). The average value of 3.4 was therefore used as a design factor in this work.

$$V_{f2} = 3.4\,V_{r1} \tag{6}$$

$$V_{f2} = 0.0042\,m^3$$

In order to maintain the cooking vessel to be similar to the conventional pots, the cylindrical shape was adopted for this system with the internal volume of the vessel (V_i) taken as being equal to the volume of cooked food (V_{f2}), having internal diameter, external diameter, internal height, external height and thickness of D_i, D_e, h_i, h_e and t_c respectively. D_i was taken to be equal to $2h_i$. For optimum design of the absorber, the thickness was taken to be equal to 0.002 m same as the thickness of mild steel sheet.

The internal height of the receiver (h_i) is obtained from the volume of the cooked load (V_{f2}) as stated in Equation (7), where A_{ar} is the area of the absorber of the receiver.

$$V_{f2} = A_{ar} * h_i \tag{7}$$

$$h_i = 0.11\, m$$

$$D_i = 0.22\, m$$

The external dimensions are;

$$D_e = D_i + 2t_c \tag{8}$$

$$D_e = 0.224\, m$$

$$h_e = h_i + t_c \tag{9}$$

$$h_e = 0.114\, m$$

Therefore, the total area of the absorber (A_{tar}) was 0.0394 m^2 found using Equation (10).

$$A_{tar} = \frac{\pi D_e^2}{4} \tag{10}$$

$$A_{tar} = 0.0394\, m^2$$

The geometric concentration ratio (CR_g), defined as the ratio of the aperture area of the concentrator to the absorber area of the receiver was determined as;

$$CR_g = \frac{A_a}{A_{tar}} \tag{11}$$

$$CR_g = 64$$

3.1.1. Receiver Design Conceptualisation and Material Selection

The following designs of the receiver were conceptualized, designed, and fabricated.

Concept 1: Conventional Receiver (CR)

Aluminium cooking vessel was selected as the best Conventional Receiver (CR), due to its readily availability, affordability, light weight and good heat absorption properties (Govender, 2013). A cylindrical aluminium alloy cooking vessel, coated with ceramic material, which is commonly available on the local market was chosen to be used as a CR in this work. It consists of a metal container and a glass cover with dimensions fitting the ones calculated in Section 3.1 and as shown in figure 1.

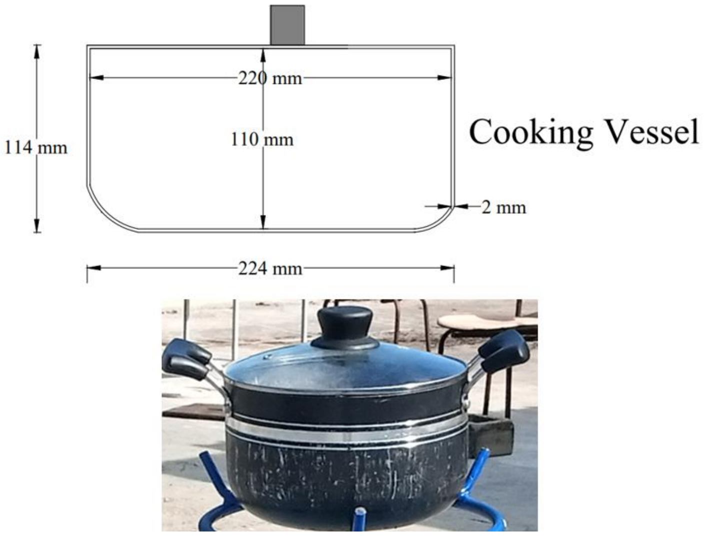

Figure 1. Schematic and Pictorial Diagram for CR.

Concept 2: Insulated Receiver with a Base Circular Ring (IRBCR)

This concept has a receiver that consists of a shell made of mild steel with an annular space filled with fibreglass wool as insulation material to restrict thermal losses from the side walls of the cooking vessel. The cooking vessel having a glass cover (CR) is inserted into the shell, making sure that the two bottom surfaces are in firm contact to facilitate heat transfer to the cooking load as illustrated in figure 2. The base of the receiver is painted black to enhance heat absorption and fitted with a circular ring to shield the absorber from the effects of wind so that convective heat losses are reduced. The annular space (a_s) of 0.02 m was used in the design. Using the same procedure as stated in Section 3.1, the following dimensions of the receiver shell were determined: inner diameter (D_{is}) of 0.23 m, outer diameter (D_{os}) of 0.26 m, internal height (h_{is}) of 0.10 m, outer height (h_{os}) of 0.21 m, the height of the circular ring (h_{cr}) of 0.11 m. The total surface area of the absorber of 0.042 m^2.

Mild steel was used in fabricating receiver shells because of its wild availability and ease of use. The radiation receptor side of the shell was also painted black to enhance heat absorption. The cooking vessel was inserted into the shell, making sure that the two bottom surfaces are in firm contact to facilitate heat transfer to the cooking load as shown in figure 3. Fibreglass wool was used in this work because it was readily available. Low-cost insulation materials will have to be used for mass production to reduce the cost and make the receiver affordable.

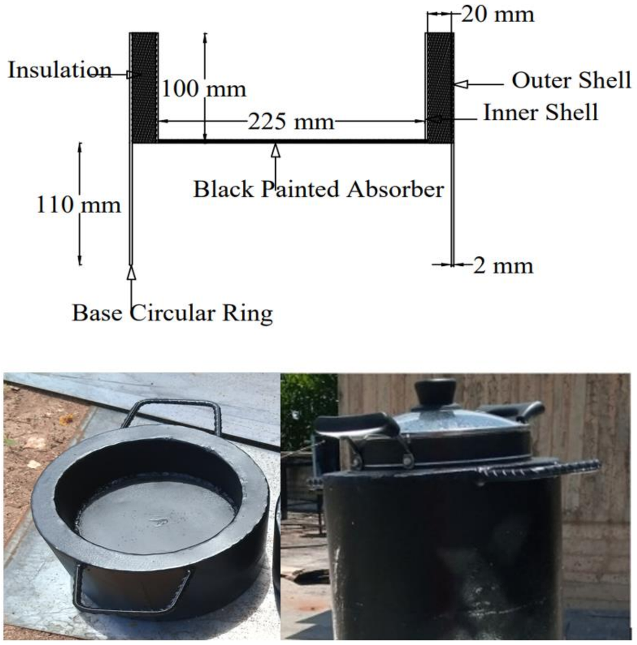

Figure 2. Schematic and Pictorial Diagram for IR.

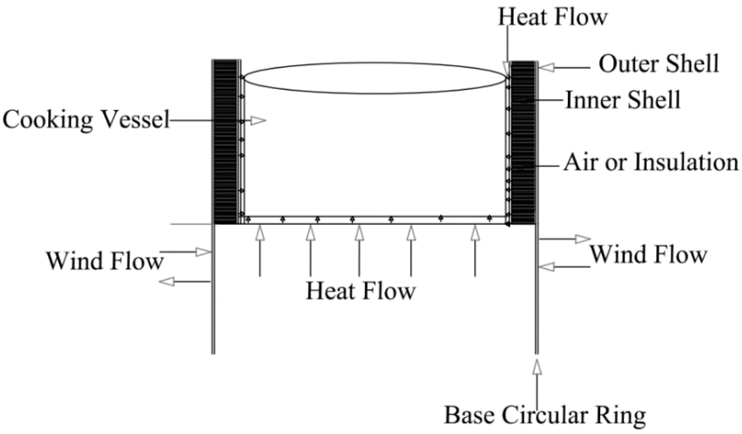

Figure 3. Heat Flow in Insulated Receivers.

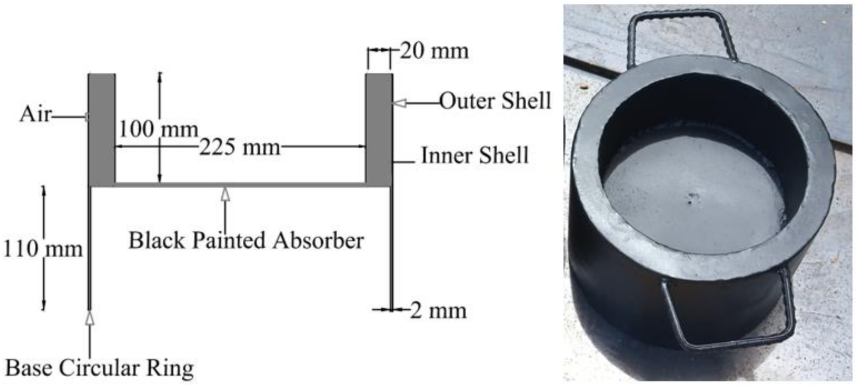

Figure 4. Schematic and Pictorial Diagrams for AFRBCR.

Concept 3: Air-filled Receiver with a Base Circular Ring (AFRBCR)

The design configuration, dimensions and heat flow mechanism are similar to Concept 2 but instead of having the annular space filled with insulation material, it is filled with air to inhibit heat losses from the cooking vessel, which is placed inside the receiver shell. Figure 4 shows the configuration of the concept and its fabricated pictorial diagram.

Concept 4: Oil-filled Receiver with a Base Circular Ring (OFRBCR)

The design configuration and dimensions are similar to concepts 2 and 3 but the annular space is filled with oil to retain thermal energy and facilitate heat transfer through conduction. The oil is placed in between two insulation layers on the sides and heat is exchanged from the oil and the cooker interiors through the bottom contacts as shown in figure 5. Figure 6 depicts the schematic and pictorial diagram of the fabricated receiver and how the vessel is inserted into the shell.

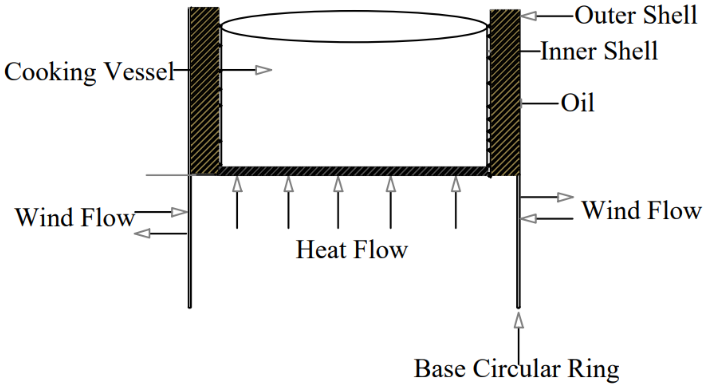

Figure 5. Heat Flow in Oil-filled Receiver.

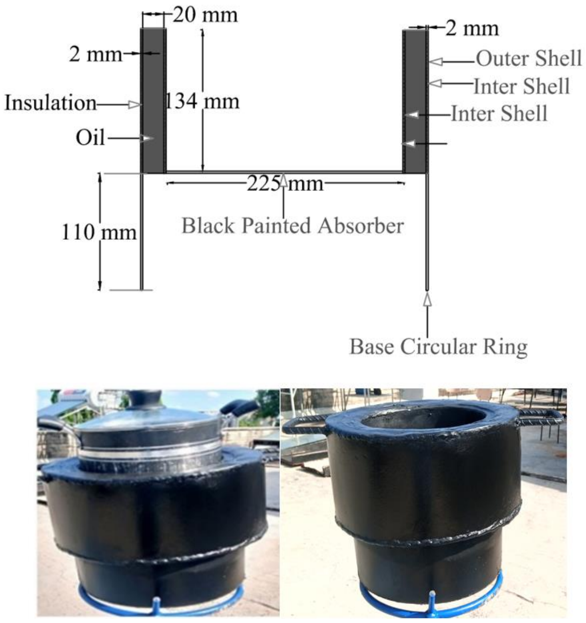

Figure 6. Schematic and Pictorial Diagram for OFRBCR.

4. METHODOLOGY

4.1. System Performance Tests Conditions

The tests were undertaken under the conditions described below as adapted from ASAE 2013 and based on the observations at the site during the time of testing:

- **i.** In this work, the maximum and minimum instantaneous global solar radiation at the site during the test period were 616 W/m^2 and 306 W/m^2.
- **ii.** During the whole period of testing, 0.91 m/s was the maximum wind speed registered.
- **iii.** The ambient temperature at test site varied between 31°C and 35°C.
- **iv.** Using the daily online weather updates for Dar es Salaam and own observation, no precipitation was registered but the average cloud cover ranged from 19% to 44% during the test days.
- **v.** A cooking vessel of aluminium type was used as a CR while the alternative receivers were made from mild steel and were painted with black oil paint on the absorber
- **vi.** The solar concentrator was tracked manually to follow the sun's azimuth and altitude. The tracking frequency for both were subjectively done but it was observed that it varied depending on the time of the day and it ranged from 15 to 20 minutes.
- **vii.** Time of tests were between 11:00 a.m. and 01:00 p.m. local time.
- **viii.** Cooker test load of 3 kg of water was used in this study.

4.2. Solar Cooker Performance Calculations

The following cooking system's performance parameters were calculated based on the load tests by using protocols from Funk (2013); and Kundapur and Sudhir (2009).

(i) Cooking Power (P_i)

The cooking power for each time interval was calculated using Equation (12), in which M_w was the mass of water in the cooking vessel in kg, C_w was the specific heat capacity of water taken as 4186 J/kg^{o}C, T_{wi} was the initial temperature of water in the cooking vessel in ^{o}C, T_{wf} was the final temperature of water in the cooking vessel in ^{o}C and t was the time interval taken as 10 minutes (600 s) for interval calculations and sensible heating time for overall cooking power calculations.

$$P_i = \frac{M_w C_w (T_{wf} - T_{wi})}{t} \qquad (12)$$

(ii) Standardised Cooking Power (P_s)

The standardized cooking power was determined by correcting the cooking power for each interval to a standard insolation of 700 W/m^2 (Funk, 2013). This was done by multiplying the interval cooking power by 700 W/m^2 and dividing by the interval average solar beam radiation (I_{bi}) that was recorded during the corresponding time interval.

$$P_s = P_i * \frac{700}{I_{bi}} \tag{13}$$

(iii) Thermal Efficiency (η_t)

The thermal efficiency was calculated using Equation (14) as given by (Kundapur and Sudhir, 2009), in which A_a is the aperture area of the solar cooker (m^2), Δt is the time required to achieve the maximum temperature of the cooking load (s) and the other parameters as defined before.

$$\eta_t = \frac{M_w C_w (T_{wf} - T_{wi})}{A_a I_{bi} \Delta t} \tag{14}$$

(iv) Receiver Efficiency (η_r)

The efficiency of receivers were calculated using Equation (15) as given by (Kumar et al., 2018), in which Q_u is the useful heat gained by the cooking load (W) and Q_R is the heat gained by the receiver material (W).

$$\eta_R = \frac{Q_u}{Q_R} \times 100\% \tag{15}$$

5. RESULTS AND DISCUSSION

The load tests for the solar cooking systems for all receivers were conducted by using 3 kg of water. These tests were done by allowing the concentrated solar radiation to heat the water from the initial temperatures to the chosen upper limit boiling point of 90°C, which when reached, the experiment was stopped.

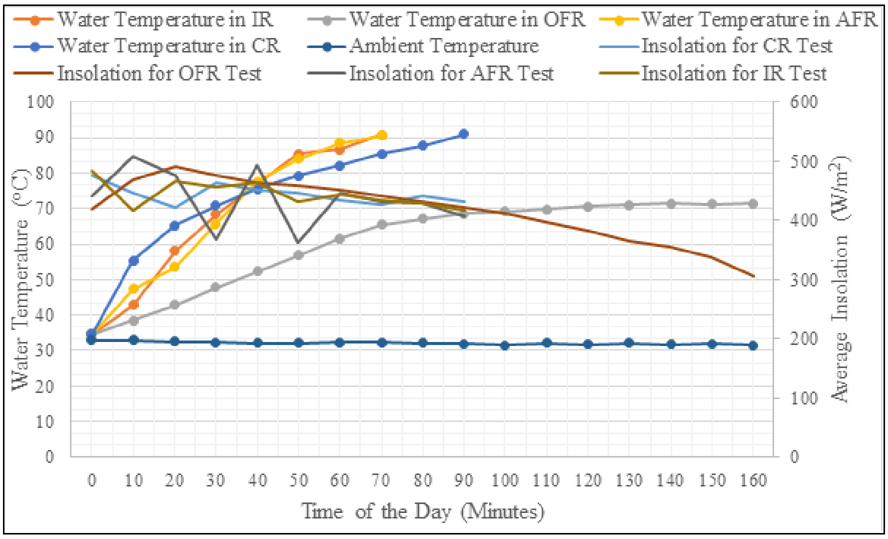

Figure presents the results of the water boiling tests for all the receivers.

Figure 7. Water Heating Tests of Solar Cooking Systems for Different Receivers.

Figure 7 shows that it took about 90 minutes to heat and raise the water temperature in the CR from 35^{o}C to the boiling temperature. It took about 70 minutes for the IRBCR and AFRBCR to raise the water temperature to the boiling point from 35^{o}C. The temperature of water in the OFRBCR did not reach the boiling point but attained a maximum temperature of 71.2^{o}C from an initial temperature of 35^{o}C after 160 minutes. Thereafter, the temperature started to fall. The low temperature achieved is attributed to the effect of the added thermal mass of the oil which acted as heat storage.

5.1. Cooking Power of the Systems

The cooking (heating) power for the solar cooking systems with each of the receivers was determined using Equation (12), with the mass of water in the cooking vessel of 3 kg and the other parameters as defined in Section 5. According to Funk (2013), the cooking power for solar cookers is calculated using the average water temperatures recorded at intervals not exceeding ten minutes.

The cooking power for each ten minute-interval for the system configurations varied from 109 to 320 W for the IRBCR system, 11 to 102 W for the OFRBCR system, 60 to 255 W for the AFRBCR system and 52 to 206 W for the CR system. The variation of the cooking power for each ten minutes interval is attributed to the effects of variability of the climatic conditions at the testing site during the testing days. The average power developed by each of the systems was determined and found to be 185 W for the system with IRBCR, 90 W for the OFRBCR system, 92 W for the AFRBCR system and 118 W for the CR system.

The standardised cooking power of the four alternative cooker configurations was calculated using Equation (13) and found to be 345, 162, 172 and 221 W respectively. These findings indicate that based on the power developed by the cookers within the respective sensible heating times, the IRBCR system is the best, followed by the CR system. The standardised cooking power of the systems for 10 minutes sensible heating intervals are presented in figure 8.

It is observed from figure 8 that the coefficients of determination (R-Squared values) for the standard cooking power regression lines are 0.87, 0.80, 0.65 and 0.08, for the IRBCR, CR, OFRBCR and AFRBCR systems respectively. The value of standardised cooking power, P_S (50), for a temperature difference of 50°C, was estimated from standardised cooking power regression lines and found to be 291 W for the IRBCR system, 11 W for the OFRBCR system, 272 W for the AFRBCR system and 142 W for CR system.

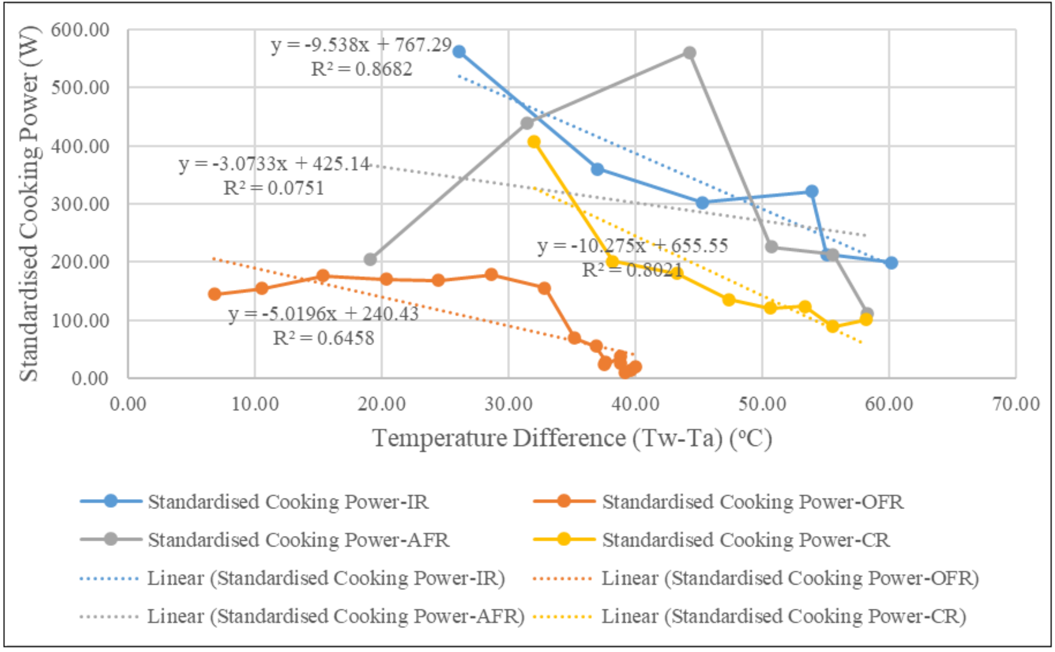

Figure 8. Standardized Cooking Power for Solar Cooking Systems.

According to ASAE protocol, the acceptable value of coefficient of determination for the standardised cooking power is required to be greater than 0.75 and that the standardised cooking power at the temperature difference of 50°C be used as a single measure of performance of solar cookers. It is therefore observed, from the calculated values, that the IRBCR and the CR systems have R-squared values greater than 0.75 and both qualify as good system configurations. However, the latter has a lower standardised cooking power than the former at the temperature difference of 50°C. This leads to the conclusion that the IRBCR system is the best of all the systems that were developed and analysed in this study.

5.2. Thermal Efficiency of Solar Cooking Systems

The overall thermal efficiencies (η_t) of the systems and receivers were calculated by using Equations (14) and (15). These were determined to be 23% for the IRBCR system, 9% for the OFRBCR system, 12% for the AFRBCR system and 18% for the CR system. The efficiencies of the receivers were found to be 27% for the IRBCR system, 11% for the OFRBCR system, 14% for the AFRBCR system and 21% for the CR system. These results indicate that the IRBCR system is the only one, among the proposed options, which provides efficiency increase of the CR system by about 28% and the efficiency of the receiver by about 29%.

6. CONCLUSION

In this work, prospective improved receivers for parabolic dish direct solar cooking systems were identified after a thorough review of the available literature. These were fabricated using locally available materials and their technical performance was compared with the conventional receiver. The present work described results based mainly on the procedures and protocols given by American Society for Agricultural Engineers (ASAE).

The performance parameters showed that the average power developed by the systems were 185 W for the IRBCR system, 90 W for the OFRBCR system, 92 W for the AFRBCR system and 118 W for the CR system. The standardised cooking power for a temperature difference of 50 °C, P_S (50), was 291 W for the IRBCR system, 11 W for the OFRBCR system, 272 W for the AFRBCR system and 142 W for the CR system.

Further, the results showed that the overall efficiencies were 23% for the IRBCR system, 9% for the OFRBCR system, 12% for the AFRBCR system and 18% for the CR system. On the receivers, their efficiencies were found to be 27% for the IRBCR system, 11% for the OFRBCR system, 14% for the AFRBCR system and 21% for the CR system. From these, the IRBCR system was determined as the best.

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8. CONFLICT OF INTERESTS

No conflict of interests.

9. REFERENCE

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APPENDIX

SYMBOLS, NOMENCLATURE AND UNITS

Symbol	**Nomenclature**	**Unit**
A_a	Aperture Area of the Solar Cooker	m^2
A_{tr}	Total Surface Area of Receiver	m^2
C_r	Specific Heat Capacity of Receiver	J/kg°C
C_w	Specific Heat Capacity of Water	J/kg°C
I_a	Average Theoretical Insolation	W/m^2
I_b	Beam Radiation	W/m^2
I_m	Measured Beam Radiation	W/m^2
M_r	Mass of Receiver	kg
M_w	Mass of Water	kg
Q_R	Heat gained by the Receiver Material	W
Q_U	Useful Heat gained by the Cooking Load	W
t	Time Interval	s
T_a	Ambient Temperature	°C
T_{max}	Maximum Temperature	°C
T_{wi}	Initial Temperature of Water	°C
T_{wf}	Final Temperature of Water	°C
η_R	Receiver Efficiency	%
η_t	Thermal Efficiency	%
τ_o	Time constant	min
e	Euler's Number	Unitless

ACRONYMS AND ABBREVIATIONS

AFR, Air-filled Receiver; AFRBCR, Air-filled Receiver with Base Circular Ring;
ASAE, American Society of Agricultural Engineers; BCR, Base Circular Ring;
CR, Conventional Receiver; CR_g, DHRMD, Department of Human Resource Management and Development; Geometric Concentration Ratio; HIFR, Half-Insulation Receiver;
IR, Insulated Receiver; IRBCR, Insulated Receiver with Base Circular Ring;
LCR, Linear Cavity Receiver; MGSF, Malawi Government Scholarship Fund;
OFR, Oil-filled Receiver; OFRBCR, Oil-filled Receiver with Base Circular Ring;
PTR, Parabolic Trough Receiver;
P_S (50), Standardised Cooking Power at Temperature Difference of 50°C