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Performance analysis of parabolic dish solar cooking system with improved receiver designs

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Abstract. Lack of access to clean energy for cooking and heating applications is one of the challenges faced by households in developing countries. Solar cooking is one of the solutions, but suffers low adoption and utilization due to various challenges including technical limitation. This study investigated initiatives on improving the technical viability of parabolic dish solar system used for direct cooking by focusing on the receiver. Three receiver prototypes namely; Insulated, Oil-filled and Air-filled, all incorporated with a base circular ring, were constructed and their performance was compared experimentally with the conventional receiver. The maximum temperature inside cooking vessels were 154 °C, 99 °C, 141 °C and 128 °C while standardized stagnation temperature and first figure of merit (F_1) were found to be 159 °C, 100 °C, 154 °C and 109 °C; and 0.26, 0.15, 0.54 and 0.17, for systems with insulated receiver, oil-filled receiver, air-filled receiver, and conventional receiver, respectively. The second figure of merit (F_2), overall heat loss factor, heat exchange factor and optical efficiency were determined as 0.36, 0.15, 0.14 and 0.33; 59.7 W/m^2 K, 28.6 W/m^2 K, 20.49 W/m^2 K and 73.4 W/m^2 K; 0.18, 0.75, 0.69 and 0.23; 25%, 4%, 4% and 17%. The study found that the cooking system with Insulated Receiver gave more merits and was established as the best.

Keywords: Parabolic dish solar cooking system / performance test / improved receiver / base circular ring / Bureau of indian standard

1 Introduction

Globally, 38% (2.6 billion people) of the population and almost 50% (3.9 billion people) of the population in developing countries do not have access to clean cooking facilities [1,2]. In Sub-Saharan Africa, around 30% of the population lack access to clean energy cooking facilities and most of these people live in rural areas [3]. Biomass, in form of firewood, charcoal, agricultural residues and animal dung, remains the major source of energy, which accounts for about 80% of total energy consumption [2,4].

In many least developed countries, percentage of population connected to the national electricity grid is overly low. For instance, in Malawi, access to grid electricity is approximated at around 12%. These people, together with those that are not connected, and both living in urban and rural areas, heavily depend on firewood and charcoal as the main source of energy for heating and cooking [5,6]. About 77.4% and 18% of the people use firewood and charcoal respectively [7]. This status is premised on the fact that poverty level is high, coverage of electricity is low and alternative sources of energy are dearth to meet cooking needs of the people [8].

About 95% of energy that is used in the country is derived from biomass, mainly in the form of firewood, charcoal, crop residues and animal dung [9]. Due to population growth and dependence on charcoal and firewood, more pressure is exerted on forests leading to deforestation and environmental degradation. Burning of firewood as a primary energy source for cooking is also a major source of indoor air pollution, which affects the health of people due to smoke produced during cooking [10,11]. People, especially women and children, walk long distances and spend about 3–5 h daily to fetch firewood in order to meet their energy needs [10].

To address the afore-mentioned challenges, governments in developing countries, for several years, have been promoting the use of renewable energy and energy efficient technologies with major focus on biogas and improved biomass cookstoves. Liquefied Petroleum Gas (LPG) stoves, efficient biomass cook stoves, biogas stoves and

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electric cookers are reported as main cooking facilities that are currently being promoted in many countries in efforts to increase access to clean energy for cooking [12]. Access to clean cooking is oftentimes considered separately and not taken into account in programmes that aim at increasing access to energy [13]. Solar cookers are not part of these actions and are not specifically mentioned in government policies and strategies. This is contrary to the documented fact that solar cookers present a realistic solution to cooking fuel and environmental problems that the world is facing [12,14].

In the case of Malawi, as a specific example of developing countries, analysis of various cooking fuel options found that solar energy resource has the potential to provide sustainable energy for cooking [15]. However, few attempts to develop and promote solar cookers through pilot projects were done by government and non-governmental organizations to popularize the technology [16], but their adoption and utilization was insignificant owing to technical, social and cultural challenges, just to mention a few. The afore-explained challenges do not only depict status for Malawi but also for many least developed countries. There is therefore, a need to holistically look into solar cooking technology especially on technical design in order to improve performance and increase acceptance of the technology, which would eventually lead to increased adoption and utilization.

Solar cookers are devices that work by converting sun rays into heat which is conducted into the receiver. Based on the way radiant solar energy is used by the cooking system and whether the system includes storage or not, solar cooking systems are broadly classified into two: solar cookers with storage and solar cookers without storage [17]. Solar cookers without storage are further categorized into direct and indirect solar cookers with the former using solar radiation directly in the cooking process and the latter involving the transfer of heat from the collector to the receiver using a heat transfer fluid [18]. Direct solar cookers include solar box (solar oven), panel and concentrators while indirect cookers are all cookers of collector type, which include those with flat plate collector, with evacuated tube collector, with spherical collector and with concentrating collector [18].

The focus of this work is on direct solar cookers but specifically, the Parabolic Dish Solar Cooker (PDSC). The PDSC is a type of solar concentrating cookers that use parabolic reflector material to concentrate direct radiation energy onto the central receiver by utilizing principles of concentrating optics [16,19,20]. Parabolic reflectors (dishes or mirrors) are reflective surfaces which are used to collect, transform and project incoming plane solar radiation waves travelling along the axis into spherical waves converging towards a common focal point known as the focus [19]. These cookers are quite efficient, cook faster and achieve extremely high temperatures [21] suitable for frying [20,22]. However, they require user's attention, have safety problems and must be used carefully because they may cause bodily harm (burns or eye damage) to the user [20]. This work aimed at analyzing performance of parabolic dish solar cooking system incorporated with improved receiver prototypes as initiatives on improving technical viability of the system used for direct solar cooking.

2 Performance comparison of parabolic dish solar cookers

There are numerous experimental investigation study reports on performance of parabolic solar cookers that were undertaken by a number of researchers. These form the basis for comparison of the available solar cooking systems with the current study. Table 1 illustrates findings of some of the cooking systems including those reported by Aramesh et al. [23].

It was observed from reviewed studies that performance of concentrating type solar cookers is affected by a number of factors. Chief among these factors is heat losses on the receiver. As such, various material, geometry, size, tracking and cooker design modifications were tested and proposed to counter the problem, but many of the studies dwelt much on indirect types of solar cooker that incorporate a thermal storage component in the system. Some studies aiming at improving technical performance of parabolic dish solar cooking systems that are used for direct cooking have been undertaken by researchers in many countries using varied solar cooker standards. Despite the fact that some of the studies focussed on the receiver of the system, many of them investigated the conventional receiver (CR), the black painted metal cooking vessel, by looking at effects of different type of metals used, absorber coating materials, receiver shapes, receiver sizes and type of covering, on the overall performance of the cooking system. However, not much work has been done on designing alternative receivers to the CR used in direct solar concentrating parabolic dish cooking systems and establishing the comparability of their performance.

This study, therefore, aimed at addressing this gap by exploring alternative receiver designs for direct use and studying their performance in order to ascertain their effect on improvement of technical performance of parabolic dish solar cooking systems, thus contributing to various studies that have been undertaken on performance enhancement of parabolic dish solar cookers.

3 Materials and methods

3.1 Research design

The design of the research was mainly experimental, but it was guided by literature review which was conducted throughout the research period. A solar cooking system comprising of a concentrator made of fibre and glass mirrors and receiver prototypes were used in this study. The CR, made of aluminium was sourced from the local market; while prospective improved receivers of Insulated, Air-filled and Oil-filled types were fabricated using mild steel.

3.2 Instrumentation, data sources and data collection

Primary data for the study was obtained from experiments, while secondary data was gathered from literature. Pyranometer, anemometer and thermocouples were the main instruments used to measure key variables of insolation, wind speed and temperature, respectively, from which performance parameters were calculated. A microwave

Table 1. Findings of previous studies on performance of parabolic dish solar cookers.

References	Focus	Findings
[24]	Performance analysis of SK 14 solar cooker under Ethiopian climate	Stagnation temperature inside the pot and first figure of merit were 188 °C, and 0.22 °C/W/m^2. Second figure of merit, optical efficiency and heat loss factor were 0.63, 0.39 and 51.59 W/m^2 K, respectively.
[25]	Performance analysis of glazed and unglazed receiver of Scheffler Dish	Glazing enhanced the performance. The overall heat loss coefficient without glazing was 41.8 W/m^2 K and with glazing was 6.04 W/m^2 K.
[26]	Experimental performance analysis of an improved receiver for Scheffler solar concentrator	The overall heat loss coefficient from the stagnation test was estimated to be 109 W/m^2 K
[27]	Receiver coating material	Silicon based system preferable
[28]	Parabolic dish solar cooker with aluminium black coated receiver	Efficiency of 7% was realized
[29]	Insulated wooden box receiver with glass cover and black painted pot placed inside	Efficiency of 39% was registered
[30]	Material for cooking vessel (aluminium and galvanized iron) for parabolic solar dish	Aluminium achieved higher temperature and Less cooking time
[31]	Comparison of two modes of the system (cooker and water heater)	Cooking/heating power and efficiency for both modes increased
[28]	Water and thermal oil as heat transfer fluids for parabolic trough collector	Thermal oil achieved higher temperatures than water
[32]	Spiral copper tube cavity receiver	Efficiency of 26.6% was determined
[33]	Comparative tests of SK 14 and PRINCE 15 solar concentrators of same aperture area but different geometries	PRINCE 15 performed well than SK 14. SK 14 had first figure of merit of 0.38 and second figure of merit of 0.65 where as PRINCE had first figure of merit of 0.42 and second figure of merit of 0.72
[34]	Shape of receiver	Modified cavity receiver was preferable
[20]	Reflectors for parabolic dish concentrator	Glass mirror attained highest temperature of 96 °C in 90 minutes than polished and unpolished aluminium reflectors

oven was used for drying silica gel for the Pyranometer and weight measurements were done using an analog scale. Table 2 gives a description of the instruments.

3.3 Data analysis

Microsoft Excel, MadgeTech software and Picolog software were used to organize and analyse the collected data. The collected data was also used to calculate performance parameters for solar cooking systems of the three receiver design prototypes and the CR.

3.4 Fabrication of the concentrator

The solar concentrator, shown in Figure 1 and with the parameters given in Table 3, was fabricated using the existing mould framework and expertise at the Centre for Agriculture Mechanisation and Rural Technology (CARMATEC) in Tanzania and it was used in this study.

3.5 Fabrication of receivers

3.5.1 Conventional receiver (CR)

A cylindrical aluminium alloy cooking vessel, coated with ceramic material was used in this work as a CR. It consists of a metal container and a glass cover as shown in Figure 2.

3.5.2 Insulated receiver with a base circular ring (IRBCR)

This was fabricated using mild steel, painted black and the annular space was filled with fibreglass wool as insulation material to restrict thermal losses from the side walls of the cooking vessel. The cooking pot was inserted into the receiver shell as shown in Figure 3.

3.5.3 Air-filled receiver with a base circular ring (AFRBCR)

This was also fabricated using mild steel, painted black and the annular space was filled with air to inhibit heat losses

Table 2. Specifications of instruments used in the study.

No.	Name and model	Manufacturer	Sensitivity value/ instrument type	Measurement range/accuracy
1	Eppley Black and White Pyranometer Model 8-48	Eppeley Laboratory, Inc.	10.08 μV/W/m^2	–20 °C to +40 °C
2	Wind101A System (3 cup anemometer and data logger)	MadgeTech	1 Pulse/ 0.655m/s	1.5 MPH to 100 MPH
3	T-C 08 Thermocouple Data Logger	Pico Technology Limited	N/A	–270 °C to +1820 °C, ±50 mV, ±500 mV, ±5 V and 4–20 mA for the single channel terminal board
4	K-Type Thermocouples	Guangzhou Logoele Electronics Technology Co., Ltd	K – Special Limits	–270 °C to +1260 °C
5	Microwave	Panasonic	N/A	0 °C to 200 °C
6	Analog Measuring Scale	Salter Housewares	N/A	Maximum of 100 kg

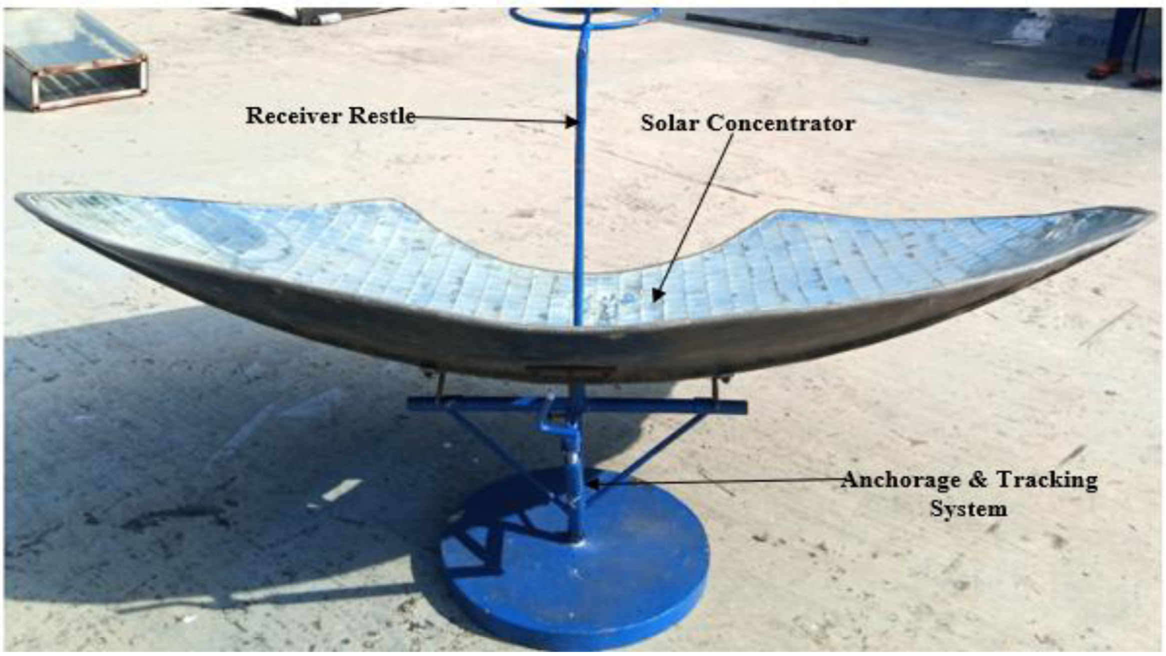

Fig. 1. Parabolic solar cooking system fabricated for the study.

from the cooking vessel which was inserted inside the reciever as shown in Figure 4.

3.5.4 Oil-filled receiver with a base circular ring (OFRBCR)

This was also fabricated using mild steel and painted black but the annular space was filled with thermal oil to inhibit heat losses from the cooking vessel, stabilise the teperature in the receiver-cooking vessel and enable heat storage within the receiver. Figure 5 shows pictorial diagram for the receiver-cooking vessel configuration.

4 Experimental setup

The setup of the experiment comprised of the solar concentrator, together with supporting and tracking components; solar receivers; data measuring and recording

Table 3. Physical parameters of the fabricated solar concentrator.

No.	Dimension	Value	Unit
1	Major axis	2.33	m
2	Minor axis	1.32	m
3	Major axis of constricted section	0.95	m
4	Minor axis of constricted section	0.30	m
5	Number of arc bars	3	No.
6	Focal length	0.75	m
7	Diameter of focal point	0.28	m

Fig. 2. Pictorial diagram for CR.

instruments (computer, data loggers, pyranometer, cup anemometer and thermocouples). Figure 6 shows pictorial diagrams of the set-up of the experiment.

When conducting tests, the solar concentrator was tracked manually to follow the sun's azimuth and altitude. The tracking frequency for both was subjectively done but it was observed that it varied depending on the time of the day and it ranged from 15 to 20 min.

5 Solar cooker performance determination results

Evaluation of performance of cooking systems was conducted based on the load and no-load tests, by using test standards and procedures outlined by Mullick et al. [35,36]. Table 4 shows an extract of measured, theoretical and calculated data; and tests are described thereafter.

5.1 No load test (stagnation temperature test)

The ability of solar cookers to develop and retain maximum temperature is depicted by the cooker's stagnation temperature, which indicates the quality of the design and performance [24,35]. The test also determines the first figure of merit (F_1), which together with standardised stagnation temperature is used to compare and ascertain quality of designs and performance of solar cookers [37].

In this work, the test was conducted using an empty cooking vessel as a CR and by placing the empty cooking vessel inside alternative receivers; and monitoring the change in temperature inside the cooking vessel. A thermocouple was fixed at the centre of the cooking vessel, while letting it not to touch the bottom. Air temperature inside the cooking vessel, ambient temperature, wind speed and solar radiation were recorded at intervals of 10 seconds and retrieved from data loggers at both 10 seconds and 10 minutes intervals. Standard stagnation temperature (SST) and first figure of merit F_1 were determined using equations (1) and (2), in which 850 W/m^2 was used as average theoretical insolation, I_m was average horizontal insolation during the test period in W/m^2, H_s was calculated horizontal insolation in W/m^2 at time of stagnation, T_s was maximum air temperature reached, and T_p was maximum temperature attained by solar cooker absorber plate and T_a was ambient temperature at stagnation [36,38].

$$\mathrm{SST} = \left[\frac{T_s - T_a}{I_m}\right] 850, \tag{1}$$

$$F_1 = \frac{(T_p - T_a)}{H_s}. \tag{2}$$

The results of the test are presented in Table 5 and shown graphically in Figures 7 and 8.

The results in Table 5 and Figure 7 show that maximum stagnation temperature inside the cooking vessels for IRBCR, OFRBCR, AFRBCR and CR were 154 °C, 99 °C, 141 °C and 128 °C which were reached in 40 min, 80 min, 60 min and 50 min respectively. Using equations (1) and (2), standardised stagnation temperature (SST) and first figure of merit (F_1) were determined as 159 °C, 100 °C, 154 °C and 109 °C; and 0.26, 0.15, 0.54 and 0.17 for systems with IRBCR, OFRBCR, AFRBCR and CR respectively. As it can be observed, figures of merit varied significantly between receivers and this was attributed to properties of receivers as well as climatic conditions under which they were operating.

Figure 8 shows variation of global solar radiation with time of day at the test site during testing period. It is seen that global solar radiation varied throughout the testing periods and maximum values were not obtained at solar

Fig. 3. Pictorial diagram for IRBCR.

Fig. 4. Pictorial diagrams for ARBCR.

Fig. 5. Pictorial diagram for OFRBCR.

Fig. 6. Experimental setup.

noon as expected since the days were partly cloudy with intermittent radiation around the solar noon. This climatic parameter has significant effect on intensity of heat accumulation inside receivers as well as time taken to reach stagnation.

Figure 9 shows variation of wind speed with time of day at the test site during the 3 days testing period for each system. The average maximum wind speeds were 0.31 m/s, 0.36 m/s, 0.23 m/s and 0.32 m/s during the tests for the IRBCR, OFRBCR, AFRBCR and CR respectively. This climatic parameter has significant effect on the intensity of the heat lost from the periphery of receivers.

5.2 Load tests (water heating and cooling tests)

Load tests for solar cooking systems for all receivers were conducted by using 3 kg of water. These tests were undertaken immediately after completion of stagnation tests by allowing the concentrated solar radiation to heat water from the initial temperatures to boiling point, which was chosen to be 90 °C. Thereafter, the concentrator was taken off the focus and receivers were kept under shade to allow them to cool for 2 h and/or until water temperature approaches the initial reading. Other studies use either ambient temperature or temperature midway of the test as initial temperature. However, this work used the first reading as initial temperature of water. As explained by Mullick et al., [38], in this work, the upper limit was selected and fixed at 90 °C because of the known observation that as water temperature approaches 100 °C, the rate of variation of temperature approaches zero, giving a major uncertainty in deciding the end point of the test. Figures 10 and 11 present results of water heating tests for all systems and the variation of wind speed during water heating tests, while Figures 12 and 13 depict results of cooling tests, including their comparison to the fitted linear regression lines.

Figure 10 shows that it took about 61 min to heat and raise water temperature in the CR from 55 °C to the boiling temperature. It took about 54 min and 97 min for the IRBCR and AFRBCR to raise water temperature to the boiling point from 43 °C and 47 °C respectively.

Table 4. Theoretical, measured and calculated data for the tests.

Parameter	Oil-filled	Air-filled	Insulated	Conventional
Ambient Temperature during Water Boiling Tests (°C)	32.25	34.00	32.29	31.62
Ambient Temperature during Stagnation Test (°C)	32.19	32.04	32.23	31.32
Maximum Air Temperature during Stagnation Test (°C)	90.07	119.44	124.22	92.69
Maximum Absorber Plate Temperature during Stagnation Test (°C)	98.75	141.24	128.19	153.96
Initial Temperature of Water (°C)	35.58	37.45	41.23	34.69
Final temperature of water (°C)	71.52	90.03	90.18	90.62
Theoretical average beam radiation (W/m^2)	850.00	850.00	850.00	850.00
Calculated average global radiation (W/m^2) during stagnation test	496.19	491.12	480.16	468.94
Calculated average global radiation (W/m^2) during water boiling test	458.27	441.27	439.86	440.65
Calculated beam radiation (W/m^2) during water boiling test	389.53	375.08	374.55	381.02
Measured beam radiation at stagnation (W/m^2)	366.95	171.60	417.41	400.13
Mass of water (kg)	3.0	3.0	3.0	3.0
Mass of cooking vessel (kg)	1.1	1.1	1.1	1.1
Mass of receiver (kg)	14.0	5.9	6.9	1.1
Specific heat capacity of water (J/kg °C)	4187	4187	4187	4187
Specific heat capacity of cooking vessel (J/kg °C)	887	887	887	887
Specific heat capacity of receiver (J/kg °C)	510.90	510.90	510.90	887
Surface area of receiver (m^2)	0.16	0.15	0.14	0.16
Area of absorber (m^2)	0.04	0.04	0.03	0.04
Aperture area of solar concentrator (m^2)	2.50	2.50	2.50	2.50
Diffuse radiation factor	0.15	0.15	0.15	0.15
Time taken to boiling (s)	5100	5820	3677	3210
Ratio of aperture area to absorber area	15.60	16.70	17.90	15.60
Optical efficiency	0.85	0.85	0.85	0.85
Specific heat capacity of oil (J/kg °C)	568	N/A	N/A	N/A
Mass of oil (kg)	3.50	N/A	N/A	N/A

The temperature of water in OFRBCR did not reach boiling point but attained a maximum temperature of 71.2 °C from an initial temperature of 36 °C after 85 min. Thereafter, temperature started to fall. The low temperature achieved was attributed to the effect of added thermal mass of the oil which acted as heat storage and not heat transfer medium as conceptualised.

Figure 11 depicts how wind speed varied with time of the day during the test periods for each system. As can be seen in the graph, the average maximum wind speed for all test days was 0.25 m/s.

The results for cooling tests as shown in Figure 12, indicate that time constants for IRBCR, CR, AFRBCR and OFRBCR were 130 min, 120 min, 130 min and 110 min respectively. These were determined from respective curves as the temperature difference between water and ambient ($T_w - T_a$) fell to about 37% of respective initial water temperatures. This factor indicates the capability of receivers to retain heat and the duration of the receivers to keep the cooked load warm. The capability to retain heat would also assist to reduce time taken for the next cook, since energy required to heat the cooking vessel before transferring the heat into the vessel interior would be reduced. Despite the fact that all curves have R-Squared values of more than 97%, the results led to the conclusion that IRBCR and AFRBCR would be preferable than CR and OFRBCR.

In Figure 13, the natural logarithm of the temperature differences was plotted against cooling times. The cooling curves for all receivers were compared and it was observed that slopes of CR, IRBCR, AFRBCR and OFRBCR were 0.1079, 0.0680, 0.0684 and 0.08 respectively. The slopes of

Table 5. Stagnation temperature test of solar cooking systems.

Parameter	Receiver type			
	Insulated (IR)	Oil-Filled (OFR)	Air-Filled (AFR)	Conventional (CR)
Ambient temperature (°C)	31.32	32.19	32.04	32.23
Maximum wind speed (m/s)	0.72	0.91	0.61	0.68
Calculated average horizontal insolation during stagnation test (W/m^2)	496.19	491.12	480.16	468.94
Measured horizontal insolation at stagnation (W/m^2)	470.74	431.71	201.88	557.45
Average beam radiation (W/m^2)	398.60	421.76	417.45	408.13
Maximum absorber temperature during stagnation test (°C)	124.22	90.07	119.44	92.69
Maximum air temperature during stagnation test (°C)	153.96	98.75	141.24	128.19
Standard stagnation temperature (SST) (°C)	159.14	100.18	154.72	109.59
First figure of merit (W/m^{2}K)	0.26	0.15	0.54	0.17

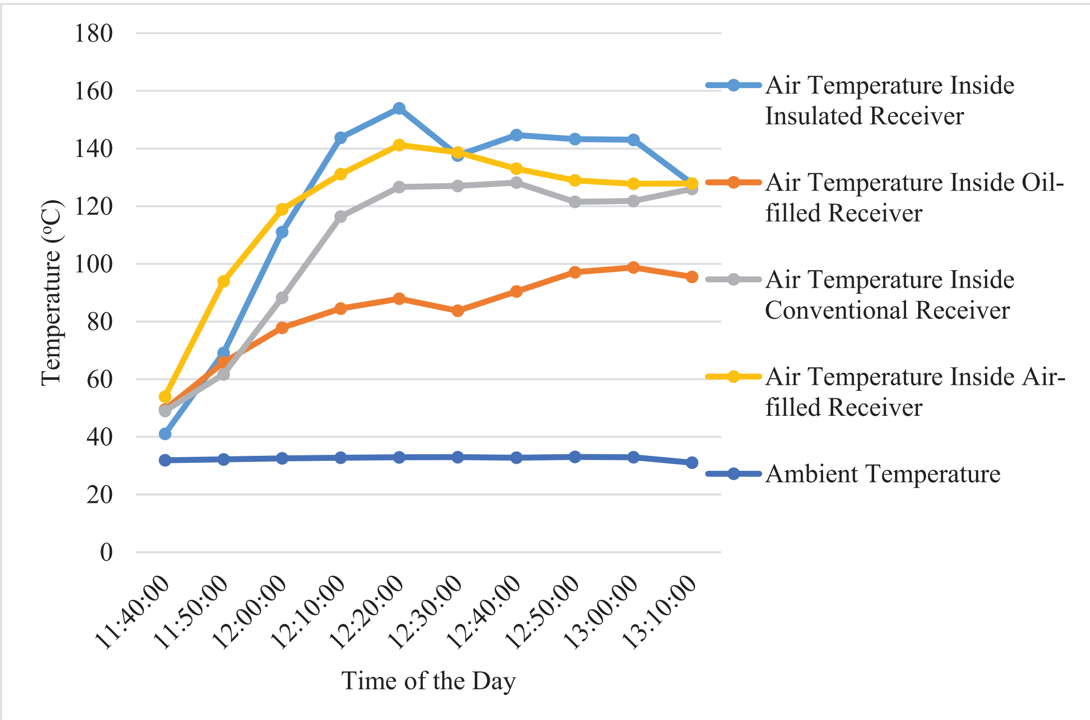

Fig. 7. Stagnation temperature test for solar cooking systems.

IRBCR and AFRBCR were lower than the other two and almost equal to each other. This meant that their heat losses were lower as compared with the OFRBCR and CR.

5.2.1 Second figure of merit

The second figure of merit (F_2), just like first figure of merit, gives an indication of thermal and optical quality of the design of the systems. In this work, this performance indicator was calculated for all systems using equation (3). The calculated values were 0.36 for IRBCR system, 0.15 for OFRBCR system, 0.14 for AFRBCR system and 0.33 for CR system. Higher values indicate good quality of the system since it is an indication that the heat capacity ratio and heat transfer from the receiver to the cooking load are good [38]. It also indicates that there is a good optical transmission from the concentrator to the receiver and that the heat losses are reasonably low [38]. The results

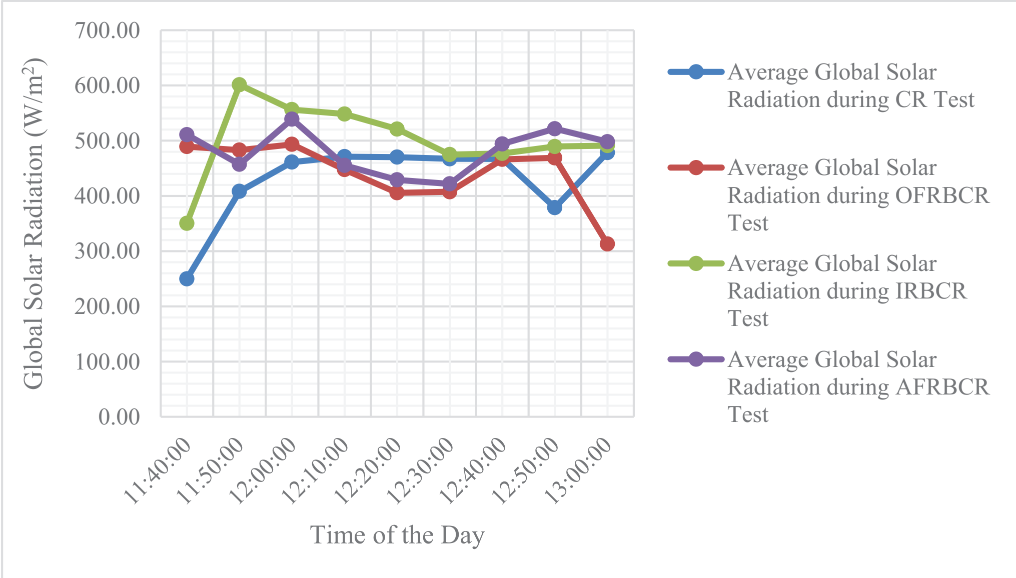

Fig. 8. Variation of global solar radiation with time of the day during stagnation tests.

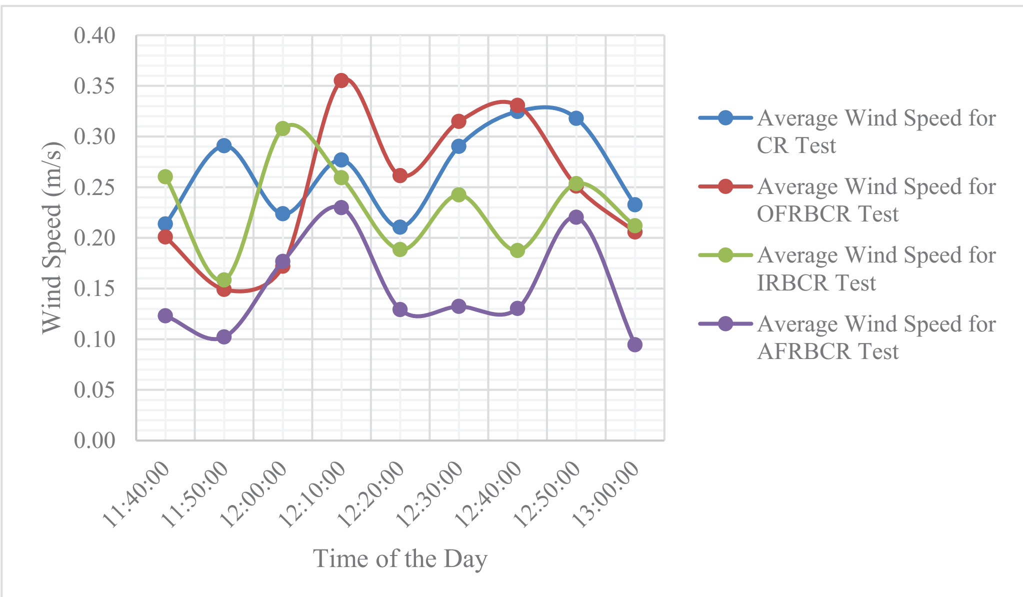

Fig. 9. Variation of wind speed with time of the day during stagnation tests.

therefore show that IRBCR and CR systems were preferable systems with IRBCR system being the best configuration.

In equation (3), 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 °C, T_{wi} was the initial temperature of water in the cooking vessel in °C, T_{wf} was the final temperature of water in the cooking vessel in °C and t was the time interval taken as 10 min (600 s) for interval calculations and sensible heating time for overall calculations, A_a was the aperture area of the solar cooker (m^2), F_1 was the first figure of merit obtained from equation (2), while T_a and I_b were as defined in previous sections.

$$F_2 = \frac{F_1 M_w C_w}{A_a t} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{wi}-T_a}{I_b}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{wf}-T_a}{I_b}\right)} \right]. \qquad (3)$$

5.2.2 Heat loss factor and optical efficiency factor

The results of sensible heating and cooling tests as depicted in Table 4 and Figures 5–8, were used to determine heat loss factor ($F'U_L$) and optical efficiency factor ($F'\eta_o$) using

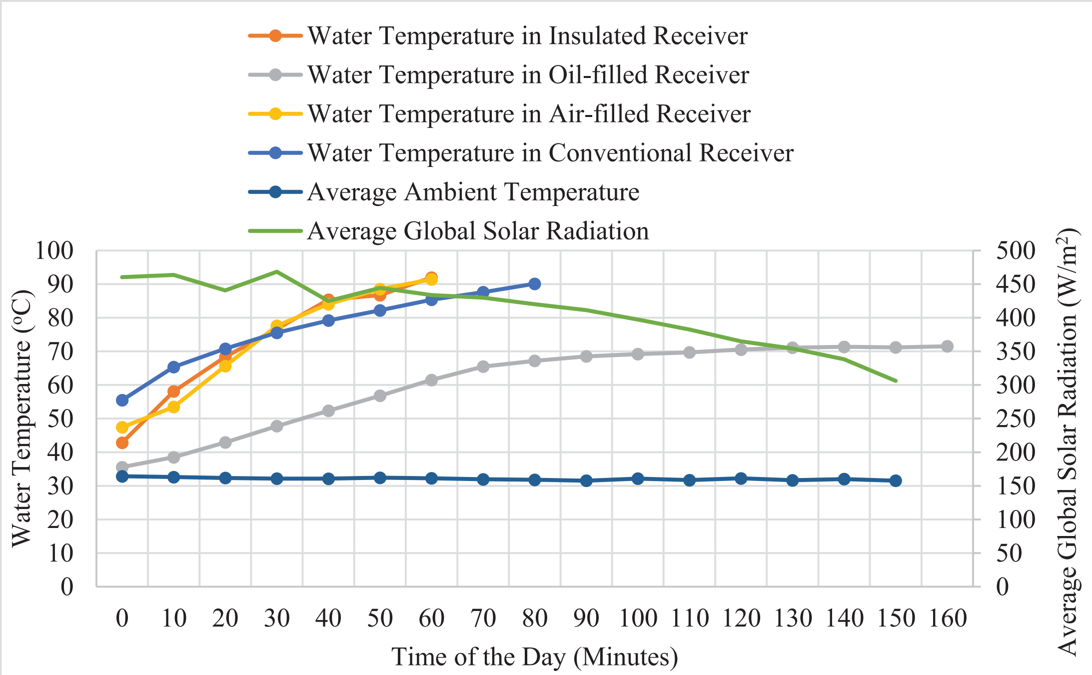

Fig. 10. Water heating tests of solar cooking systems for different receivers.

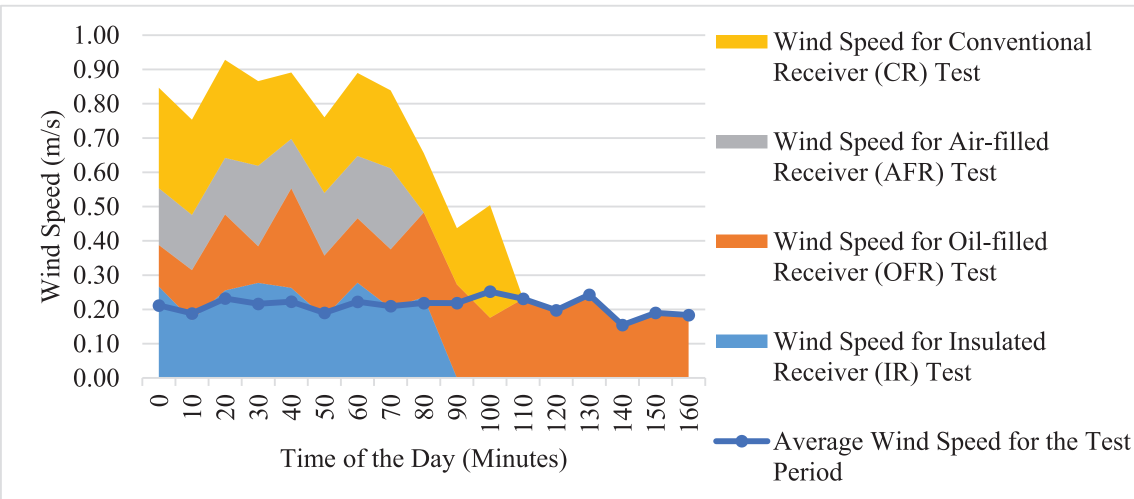

Fig. 11. Variation of wind speed with time of the day during water heating tests.

equations (4) and (5). Also determined, were heat transfer coefficient (F'), optical efficiency (η_o) and cooker opto-thermal ratio (COR) for each of the systems. These solar cooker parameters are presented in Table 6.

(i) Heat loss factor ($F'U_L$)

The heat loss factor was computed with equation (4) [35,39], in which M_r represent the mass of receiver, C_r represent specific heat capacity of receiver, A_{tr} represent total surface area of receiver and τ_o represent time constant obtained from the semi log plot of standardised linear regression curve.

$$F'U_L = \frac{M_w C_w + M_r C_r}{A_{tr}\tau_o}. \tag{4}$$

(ii) Optical efficiency factor ($F'\eta_o$)

The optical efficiency factor was determined using equation (5) [35,39], in which, C was the ratio of solar cooker aperture area to receiver surface area, t was sensible heating time within which water temperature was raised to

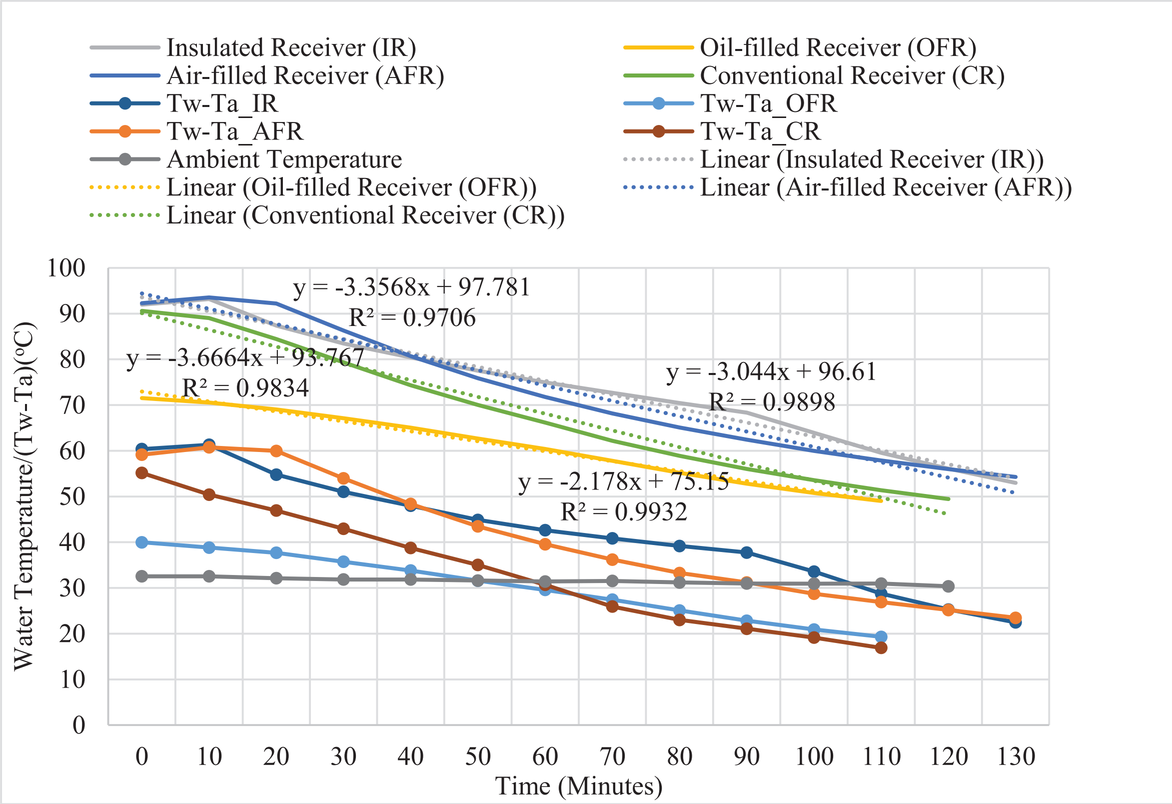

Fig. 12. Water cooling test for receivers.

a temperature of around 90 °C and other parameters have the same meaning as defined in previous equations.

$$F'\eta_o = \left(\frac{F'U_L}{C}\right)\left[\frac{\left(\frac{T_{wf}-T_a}{I_b}\right) - \left(\frac{T_{wi}-T_a}{I_b}\right)e^{-\left(\frac{t}{\tau_o}\right)}}{\left(1-e^{-\left(\frac{t}{\tau_o}\right)}\right)}\right]. \quad (5)$$

As it can be seen in Table 6, the overall heat loss factor, heat exchange factor and optical efficiency factor of the systems were found to be 59.7 W/m^2 K, 0.18, 28% for IRBCR system; 28.6 W/m^2 K, 0.75, 4% for OFRBCR system; 20.49 W/m^2 K, 0.69, 4% for AFRBCR system; and 73.4 W/m^2 K, 0.23, 17% for CR system. These parameters were determined by firstly, obtaining the overall heat transfer coefficient (U_L) by dividing the slope of standardised cooking power regression line with surface area of respective receivers. It was observed that IRBCR system had the lowest heat loss factor of 0.16 per concentration ratio, and higher values of optical efficiency factor and cooker opto-thermal ratio; indicating that the design provided best optical as well as heat transfer characteristics than other systems.

5.3 Comparison of findings of present work with similar studies

A review of previous studies on performance analysis of parabolic solar cookers indicated in Table 1 showed that many of the studies used protocols provided by American Standard for Agriculture Engineers (ASAE). Some studies used protocols provided by the Bureau of Indian Standards (BIS) but the results did not provide the full scope of performance parameters required for a comprehensive comparison with the current findings.

As can be observed, Mekonnen et al. [24–26] found the overall heat loss factors of 62 W/m^2 K, 109 W/m^2 K, 41.8 W/m^2 K, respectively which were higher than IR system of present study which was found to be 59.65 W/m^2 K. For COR, present study performed well with 0.29 compared to Mekonnen et al. [24] who found 0.16. In terms of the first figure of merit, the AFR system for the present study performed well comparing with the IR system, system studied by Mekonnen et al. [24] and systems studied by Chandak et al. [33]. However, on second figure of merit, heat exchange factor and optical efficiency, systems studied by Chandak et al. [33] performed better than Mekonnen et al. [24] and this study.

6 Source of errors for experimental tests

6.1 Instrumentation errors

The pyranometer and wind sensor that were used in measuring site specific insolation and wind speed data had not been calibrated for over a decade. This might have not reflected the accurate readings from data loggers. Data from nearby sites were not available to compare with data collected with these instruments during trial tests.

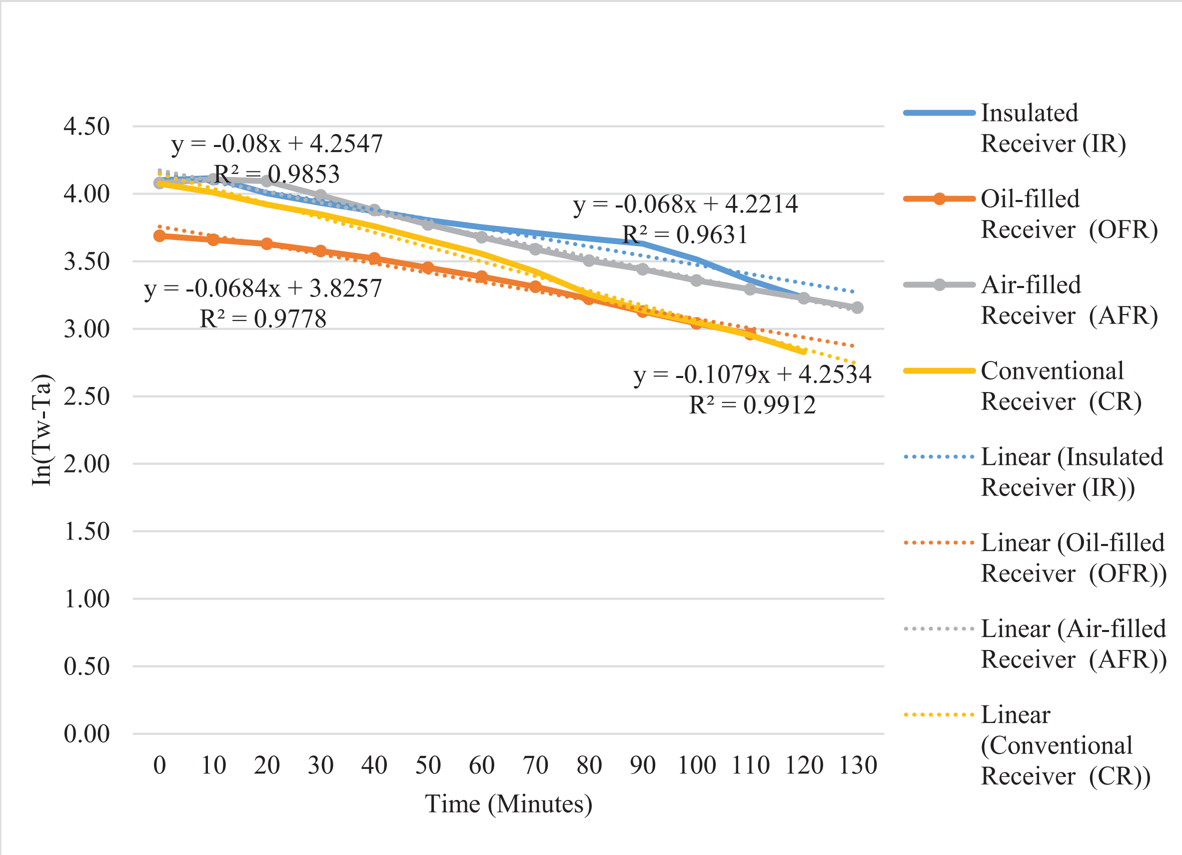

Fig. 13. Comparison of cooling curves for receivers.

Table 6. Solar cooking system performance parameters.

System parameter	Solar cooking system			
	Insulated (IRBCR)	Oil-filled (OFRBCR)	Air-filled (AFRBCR)	Conventional (CR)
$F'U_L$ (W/m^2K)	10.84	21.47	14.14	16.92
$F'U_L/C$(W/m^2K)	0.16	0.34	0.22	0.20
$F'\eta_o$	0.05	0.03	0.03	0.04
COR	0.29	0.08	0.13	0.20
U_L (W/m^2K)	59.65	28.58	20.49	73.39
F'	0.18	0.75	0.69	0.23
η_o (%)	28	4	4	17

6.2 Sun tracking errors

The solar cooking system was manually tracked. It was hard and subjective to make the concentrator follow the direction of the sun and get it inclined according to the sun's position and elevation all the times. The concentrator did not have a device to direct when and how to orient it towards the sun. It was therefore not possible to ensure that the sun's image was focussed at the bottom of the receivers throughout the testing times. This might have led to inaccurate results.

6.3 System components fabrication errors

It was observed that the solar concentrator had some glass mirrors smeared with glue and that some pieces were broken. This interfered with the reflectivity of the surface and also led to scattering reflections outside the focal point or missing part of the incoming radiation. Poor workmanship for fabrication of receivers was also the cause that might have led to results that do not tally with the conceptualisation principles for this work.

7 Conclusion

The work found that standard stagnation temperature and first figure of merit from the no load tests were 159 °C, 100 °C, 154 °C and 109 °C; and 0.26 W/m^2 K, 0.15 W/m^2 K, 0.54 W/m^2 K and 0.17 W/m^2 K for systems with IRBCR, OFRBCR, AFRBCR and CR respectively.

Calculated values of second figure of merit were found to be 0.36 W/m^2 K for IRBCR system, 0.15 W/m^2 K for OFRBCR system, 0.14 W/m^2 K for AFRBCR and 0.33 W/m^2 K for CR system.

The water cooling tests revealed that overall heat loss factors were 10.84 W/m^2 K for IRBCR system, 28.47 W/m^2 K for OFRBCR system, 14.14 W/m^2 K for AFRBCR system and 16.92 W/m^2 K for CR system. The optical efficiency factors were 0.05 for IRBCR system, 0.03 for OFRBCR system, 0.03 for AFRBCR system and 0.04 for CR system. The cooker opto-thermal ratio of 0.29 for IRBCR system, 0.08 for OFRBCR system, 0.13 for AFRBCR system and 0.20 for CR system.

The study further established that sensible heating time for the systems were 61, 54, 97 and 85 min for the CR, IRBCR, AFRBCR and OFRBCR; and time constants were found to be 120, 130, 130 and 110 min respectively. These findings indicate that IRBCR and AFRBCR performed well and would be preferable than CR and OFRBCR.

The overall analysis of the findings led to the conclusion that IRBCR system performed well than other systems and was established as the best system. However, more work would be required to ensure that other performance parameters are also enhanced for the system to outweigh results of existing studies.

8 Recommendations

The study used fibreglass wool for thermal insulation of insulated and oil-filled receiver systems because it was readily available. It is therefore recommended that for the actual trial of the prototype, low-cost thermal insulation materials should be used in order to reduce the cost and make the receivers affordable.

In experiments for alternative receivers, the cooking vessel was not fully inserted and covered inside the receiver shell for ease of handling and attaching temperature measuring instruments. The study recommends that, in the actual trial of the prototype, the cooking vessel should be fully inserted and covered inside the receiver as this would lead to further increase in performance of the system.

This work was undertaken in summer period in the month of December. As such, the outcome of the findings may not be applicable to other weather conditions such as winter period. A similar study could be undertaken to ascertain the findings for other weather conditions.

The study was supposed to investigate the possibility of further system improvements by using a vacuum receiver and a heat transfer fluid filled receiver with the internal surface of the base circular ring made of refractive material as part of improved receivers. These were not done due to financial constraints as the materials and equipment were expensive. A similar study using these as prospective improved receivers should therefore be conducted.

The Oil-filled receiver system for this study used synthetic oil which performed poorly. A similar study using Heat Transfer Fluid in this system could be undertaken to check the performance of the system.

Implications and influences

This work involved conducting experiments to evaluate solar cooking system incorporating the developed prospective improved receiver prototypes by using the Bureau of Indian Standards (BIS) under the climatic conditions of Dar es Salam in Tanzania. It is expected that the results of this study will help in effectively promoting and disseminating solar cookers due to improved performance. The findings of the study will also provide information to other stakeholders who would want to conduct further research on improving the system and in other areas related to this work.

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Symbols, nomenclature and units

Symbol	Nomenclature
A_a	Aperture area of the solar cooker (m^2)
A_{tr}	Total surface area of receiver (m^2)
C	Ratio of solar cooker aperture area to receiver surface area Unitless
C_r	Specific heat capacity of receiver (J/kg °C)
C_w	Specific heat capacity of water (J/kg °C)
F_1	First figure of merit ($W/m^2 K$)
F_2	Second figure of merit ($W/m^2 K$)
$F' U_L$	Heat loss factor ($W/m^2 K$)
$F' \eta_o$	Optical efficiency factor ($W/m^2 K$)
H_s	Horizontal insolation at stagnation (W/m^2)
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)
SST	Standard stagnation temperature (°C)
t	Time interval (s)
T_a	Ambient temperature (°C)
$T_{\max}$	Maximum temperature (°C)
T_p	Maximum absorber plate temperature during stagnation test (°C)
T_s	Maximum air temperature during stagnation test (°C)
T_{wi}	Initial temperature of water (°C)
T_{wf}	Final temperature of water (°C)
τ_o	Time constant (min)
e	Euler's Number

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