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Design, Fabrication and Performance Evaluation of Parabolic and Enhanced Solar Box Cookers in Isimani, Tanzania

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Abstract

Clean cooking energy is a global priority, especially in developing countries where firewood and charcoal remain the primary cooking fuels. Solar cooking is an attractive alternative in these countries since it is eco-friendly and utilises freely available solar radiation. Utilisation of solar cookers however is still very low mainly due to the perceived complexity and lack of confidence in the available solar cooker models. In this work, the enhanced box and parabolic solar cookers were designed, fabricated and tested taking into consideration standard solar cookers and local cooking requirements. The enhanced box solar cooker was designed with booster mirrors making an effective aperture area of 0.68 m^2, a double glass glazing and a glass wool insulator between the double walls of the cooking box. The parabolic cooker was designed with polished aluminium paraboloid with a net aperture area of 1.44 m^2, a parabola depth of 0.47 m and manual solar tracking. In field tests in Isimani Tanzania, the enhanced solar cooker attained a maximum temperature and cooking power of 129.8 °C and 101.9 W, respectively, and was able to boil 2 litres of water in 100 minutes. The parabolic cooker on the other hand registered a maximum cooking power of 513 W at solar noon and was able to boil 2 and 5 litres of water in reasonable times of 30 and 60 minutes, respectively.

Keywords: Clean cooking, parabolic solar cooker, enhanced box solar cooker, polished aluminium, cooking power

Introduction

Access to clean and affordable energy for cooking is an integral part of the United Nations' sustainable development goal (SDG) 7 (affordable and clean energy) and may indirectly contribute to several other SDGs. It is also part of several local policy documents such as Tanzania's National Energy Policy 2015 (MEM 2015a), Tanzania's SE4All Action Agenda (MEM 2015b), and National Clean Cooking Strategy 2024-34 (ME 2024), all of which calls for increased access to clean energy. Despite the significant global, and to some extent, local progress in the access to clean and modern cooking energy (Stoner et al. 2021, Clements and Todd 2022), about 3 billion people worldwide are still using polluting fuels for cooking (Mock et al. 2017, United Nations 2019). In Sub-Saharan Africa, the trend in the use of polluting fuels (e.g. firewood, charcoal, and kerosene) in absolute numbers is increasing due to population growth (Bonjour et al. 2013, Stoner et al. 2021). In Tanzania, 92% of households use firewood or charcoal as the main source of energy for cooking (ME 2023). Use of these polluting fuels and technologies is associated with several social economic problems that include; deforestation, pollution, health, as well as poverty and even death. In pollution, for example, burning solid fuel (firewood, charcoal, coal) accounts for up to 58% of global black carbon emissions (Sharma and Mishra 2022). Considering indoor pollution;

increasing population and changing economic activities, means that the time people spend inside buildings is increasing (Granqvist et al. 2010, Mannan and Al-Ghamdi 2021) and so is their exposure to poor air quality induced by burning polluting fuels. Most of these problems disproportionately affect women and children, particularly those living in rural areas. Clean cooking energy sources, such as natural gas, liquefied petroleum gas (LPG), electricity, and solar have been advocated to mitigate the impacts resulting from the use of polluting energy sources (ME 2024). For rural and poor suburban communities, however, clean cooking solutions such as LPG and electricity are either too expensive or unavailable. For these communities, solar cooking presents a viable alternative solution since the technology exists, is affordable and uses free solar energy. Despite the high solar irradiance in many areas of Tanzania and other sub-Saharan countries, solar cooking adoption is still very low (Kimambo 2007, Kebede and Mitsufuji 2014, Mosses et al. 2023). Barriers to the adoption of solar thermal technologies are many and intertwined. First and foremost, the complexity (or perceived complexity) of the technology which mostly requires technical solutions, in terms of designs suited for each targeted group as well as awareness campaigns. Technically, from simplest and inherently cheapest for rural communities to more complex designs for institutions in rural and suburban settings (Cuce and Cuce 2013). Secondly, low purchasing power coupled with the lack of long-term investment culture in rural communities which can benefit most from solar cooking technologies can be addressed by both device designs as well as the design of attractive purchasing models. Thirdly, lack of awareness about the relative advantages of solar thermal technology over other technologies such as firewood, charcoal, and kerosene stoves. Other barriers include social and cultural practices such as preference for cooking dinner well into the evening and indoors as well as lack of overall confidence in the technology all of which require a multidimensional approach to address (Bielecki and Wingenbach 2014, Larsen and Seim 2015).

All solar cookers work on the principle of concentrating or retaining solar radiation to heat food. There are several designs of solar cookers that can be classified into three groups, namely, box, panel collector and concentrator designs (Kimambo 2007). Box and panel cookers are simple to design, fabricate and handle, however, they generally have low cooking temperatures below 100 ºC (Folaranmi 2013) as they utilise direct solar radiation. The concentrating solar cooker on the other hand converges solar radiation onto a small focal region and is capable of attaining high temperatures above 300 ºC (Farooqui 2017). The cooker can therefore more easily compete with electric, gas, charcoal or wood-fired stoves. One type of the concentrating solar cooker known as the Scheffler cooker, utilises large concentrating paraboloid mirrors and can attain temperatures above 1000 ºC (Farooqui 2017). Over many years, different models of solar cookers have been designed and tested with a wide range of reported cooker performance depending on geographic location, design considerations, and materials used (Ceviz et al. 2024). For the box solar cooker, the most reported design considerations for improved performance include insulation, glazing and booster mirrors (Misra et al. 2023). For the parabolic solar cooker, the important design aspects include geometry, size, focal length, and reflecting material (Ahmed et al. 2020). In all types of solar cookers, some kind of solar tracking and a good absorber surface, which could simply be a blackened surface, but more preferably a selective surface could significantly boost the performance of the cooker (Tibaijuka et al. 2023, Verma et al. 2023).

While several solar cooking technologies exist, few studies have tested models that are both high-performing and accessible for Tanzanian rural and sub-urban communities. This study aims to address these gaps by testing two improved solar cooker designs in local conditions. We therefore report on the design, fabrication and performance evaluation of the parabolic and enhanced box solar cookers with optimal materials and design for improved performance and ease of use. The goal is to remove some of the identified technical barriers to the adoption of solar cookers in the country and the region.

Materials and Methods

Design and Fabrication of the Solar Cookers

In the design of solar cookers, several parameters were considered. These were categorized as design output parameters that include cooking energy requirement, cost and robustness, whereas design input parameters include solar insolation, cooker dimensions, insulation, booster mirrors, cooking time, manual tracking for the parabolic and the enhanced box solar cookers. An enhanced box solar cooker was designed such that it can accommodate a cooking vessel sufficient for up to 10 people, a number twice the average family size in Tanzania (Jamuhuri ya Muungano wa Tanzania, 2024). The aperture area A of the box cooker was calculated using Equation 1 (Bigelow et al. 2024) and found to be 0.49 m^2, where a standardised cooking power of 65 W and ~ 19% efficiency as per American Society of Agricultural and Biological Engineers Standard ASAE S580.1 for testing and reporting solar cooker performance (ASABE 2013) were utilised.

$$A = \frac{P_S}{I_S \eta} \qquad (1)$$

where P_S is the standardised cooking power in W, I_S is the standardised solar insolation at 700 Wm^{-2}, and η is the cooker's efficiency. The dimensions of the inner and outer boxes were $44 \times 44\ \mathrm{cm}^2$ and $60 \times 60\ \mathrm{cm}^2$ on the sides, whereas the depths were, respectively, 42 cm and 51 cm enough to accommodate the cooking vessel and tray (see Figure 1(a)). The inner walls of the cooker were all made of polished aluminium and the space between the inner and outer boxes was filled with highly thermal insulating glass wool. Apart from glass wool, in places where mechanical strength was required, pieces of solid polyester fibre panels were used to thermally separate the inner box from the rest of the cooker. The glazing was made up of double glass (preference should be iron-free clear glass (Ademe and Hameer 2018)) with a space of about 1.5 cm between the glass panes. Clear glass is the material of choice for the glazing because of its high transmittance of incoming solar radiation and low transmittance of the long-wave thermal radiation. The air gap between glass panes ensures extra insulation against both conductive and convective losses, and the outer glass radiates back about half of the little thermal energy that was transmitted by the inner glass. All this ensures good thermal energy retention in the box cooker. The suspended cooking tray was designed in such a way that the cooking vessel will always be upright even as the cooker is manually adjusted to track the Sun. The booster mirrors consisted of four polished aluminium square mirrors and four (isosceles) triangular mirrors, all joining the cooking box at the square glass glazing. The mirrors formed an angle of 30° from the vertical wall, and making an octagonal shape at the top end with a total effective aperture area of $0.68\ \mathrm{m}^2$. The booster mirrors were designed to maximise the solar radiation captured without significantly increasing the size of the cooker. The polished aluminium mirrors reflectivity for both the solar wavelength range at $250\ \mathrm{nm} \leq \lambda \leq 2500\ \mathrm{nm}$ and the infrared range at $2500\ \mathrm{nm} \leq \lambda \leq 15000\ \mathrm{nm}$ was measured by the Perking-Elmer lambda 1050+ UV/VIS/NIR and the Perkin Elmer Spectrum BX FT-IR spectrophotometers, respectively. For the solar wavelength range, a variable angle reflectance accessory was used to vary the angle of incidence from 15° to 75° during reflectance measurements. For the infrared wavelength range, the reflectance took place only at near normal angle of incidence due to system limitations.

The completed solar cooker was pivoted to the supporting wheeled base for smooth manual tracking of the Sun (Figure 1(b)). Even though a box cooker can work even without tracking the Sun, east-west Sun tracking will increase solar radiation intensity received by the cooker and hence improve–performance (Khatib et al. 2004).

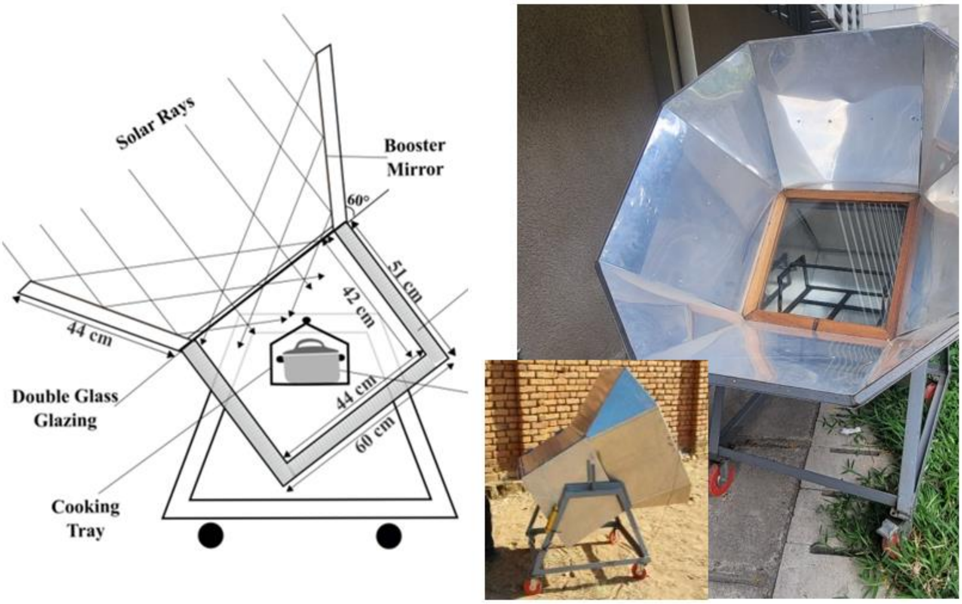

Figure 1: (a) Cross section with dimensions and (b) picture of the fabricated enhanced solar box cooker (Inset: side view of the cooker).

Similar cooking requirements of about 10 people were considered in the design of the parabolic solar cooker. Standardised cooking power of 198 W and cooker efficiency of 35.2% (can flexibly vary between 30% and 50% (Ahmed et al. 2020)) for the parabolic solar cooker as per ASAE S580.1 standard for testing and reporting solar cooker performance and Bigelow et al. (2024), respectively, were utilised in the design. Using the standardised solar radiation of 700 Wm^{-2} as was done for the box cooker, the aperture area, A of the parabolic solar cooker was calculated using Equation 1 and found to be 0.8 m^2. Alternatively, cooking power can also be calculated from the energy and time required to cook local foods. Taking the weight of rice, $m_r = 2\ \text{kg}$ (enough for 10 people) and that of water, $m_w = 1.5$ kg with specific heat capacities of rice and water being, $c_r = 1.76\ \text{kJ/kg °C}$ and $c_w = 4.18\ \text{kJ/kg °C}$, respectively, and cooking time $t = 1\ \text{hr}\ (3600\ \text{s})$, cooking power may be calculated using Equation 2 (Funk 2000). The cooking power was then used to determine the aperture area as 1.16 m^2. This value is only slightly larger than that determined from standardised cooking power. In our case we chose the aperture area of 1.44 m^2 for the parabolic solar cooker, slightly larger than the calculated value from standardised power as well as actual cooking power requirements to compensate for any unforeseen power loses.

$$P = \frac{m_\text{w} \times c_w \times (T_\text{f} - T_\text{i}) + m_\text{r} \times c_\text{r} \times (T_\text{f} - T_\text{i})}{t} \qquad (2)$$

A parabola depth h of 0.47 m was chosen to ensure that the focal point is at an appropriate position for a stable cooking pot support that allows for easy manual tracking of solar radiation (Figure 2(a)). The focal length of the cooker was 0.25 m as calculated from Equation 3, where the aperture diameter, D of 1.36 m was utilised.

$$f = \frac{D^2}{16h} \qquad (3)$$

Triangular polished aluminium reflectors, 0.6 mm in thickness, were assembled following the parabolic curvature and were supported by their strength and a nearly circular rim made of mild steel. The rim was flexibly attached to a horizontal steel pipe whose ends are bolted to the wheeled mild steel frame and contains the cooking pot tray at the vicinity of the focal point of the parabolic reflector (Figure 2(b)). The horizontal pipe also supports rotation of the parabolic reflector, which combined with the possibility for rotating the wheeled cooker frame about the vertical axis, easy manual solar tracking can be achieved.

A simple guiding element made up of two small metal plates a short distance apart, one with a small hole and the other with a small groove arranged along the direction of the optical axis of the parabolic reflector was attached to the rim of the reflector. To sufficiently track the sun, one only needs to ensure that the sun's light passing through the small hole of the guiding element falls directly at the groove. Similar manual tracking approach has been reported by other authors (Devan et al. 2020). The cooking pots for both the parabolic and the enhanced box solar cookers were commercial ports with black painted coats for optimum solar radiation absorption preferably with transparent glass lid to allow for the solar radiation intercepted by the pot to pass into the food being cooked.

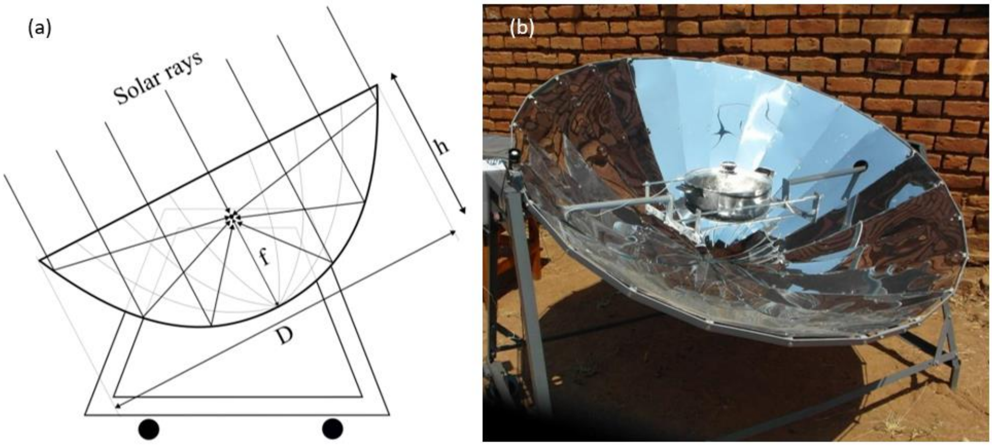

Figure 2: (a) Cross-section schematic and (b) picture of the designed parabolic solar cooker.

Testing of the Solar Cookers in Isimani - Tanzania.

The parabolic and enhanced solar box cookers were tested in Isimani Iringa which is one of the areas receiving high solar radiation in Tanzania at about $6.1\,\mathrm{kWh/m^2}$ per day (Global Solar Atlas 2024). During testing, the guiding elements were used to manually orient the cooker axis in the direction of the Sun (Sun tracking) for optimum solar energy reception. The parabolic and the enhanced box solar cookers were re-oriented every 5 and 10 minutes, respectively. Thermal performance testing of the cookers followed the ASAE S580.1 standard for testing and reporting solar cooker performance (ASABE 2013). The ambient temperature and solar insolation during tests were in the range acceptable for the cookers test, at 22 °C to 30 °C and 450 $\mathrm{w/m^2}$ to 840 $\mathrm{w/m^2}$, respectively as reported by Funk 2000. Tests took place in September 2021, at Isimani in Iringa, Tanzania, during a dry season with generally very low humidity, clear sky, and moderate wind speed, all conducive for solar cooking. Different loads at 1 to 5 kgs were utilised for water heating tests, and a thermocouple-based MT 645 multichannel digital thermometer was used to record outside ambient temperature, water temperature, and air temperature inside of the box cooker. For water temperature measurements, the thermocouple probe was immersed in the water, 10 mm above the bottom at the centre of the cooking pot as per the standard (ASABE 2013).

Results and Discussion

Spectral reflectance of polished aluminium mirrors

The polished aluminium mirrors used as reflecting surface in both the parabolic and the enhanced box solar cookers were highly reflecting, well above 90% for both the solar wavelength range at $250\ \mathrm{nm} \leq \lambda \leq$

2500 nm (Figure 3) and the infrared range at $2500\ \text{nm} \le \lambda \le 15000\ \text{nm}$ (insert in Figure 3). The high reflectance was realised for small angles of incidence, only slightly decreasing with increase in incidence angel, down to about 80% for 75° angle of incidence. These reflectance values imply good convergence of radiant energy both in the solar spectral range and infrared range and hence their adequacy for use in solar cookers.

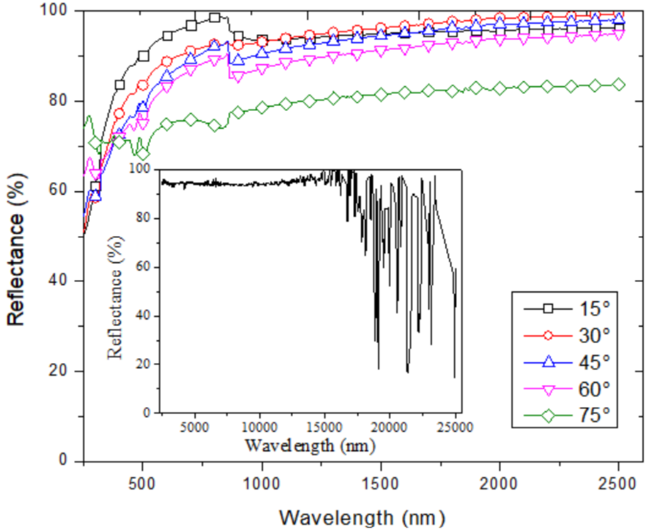

Figure 3: Spectral reflectance of the polished aluminium sheets used in this work in the solar wavelength range at different incident angles. Inset: Spectral reflectance in the infrared wavelength range.

Thermal test results for the enhanced box solar cooker

Thermal testing of the enhanced box solar cooker started at 8:54 and continued to 17:04 solar time as converted from local time using online resources (powerfromthesun 2024) and measurements were repeated every five minutes.

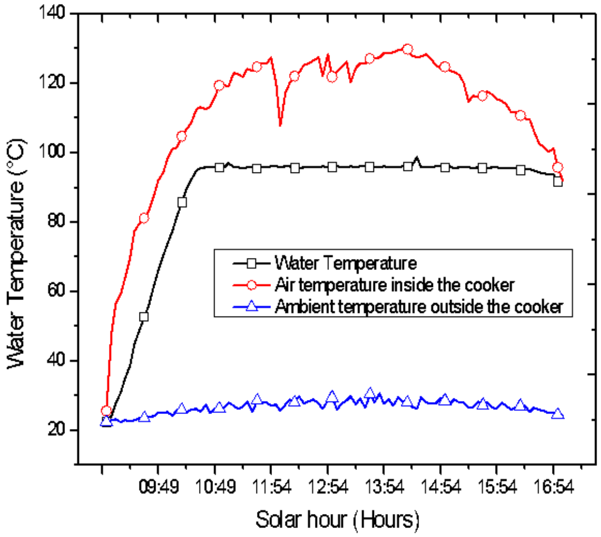

Figure 4: Water and air temperature profile inside the enhanced box solar cooker. Ambient temperature was included for comparison.

Figure 4 shows the variations of temperature with solar time for the 2 L water in a blackened pot, air inside the cooker enclosure and ambient temperature outside the cooker. The 2 L water was able to reach boiling point at 95.6 °C from 22.5 °C initial temperature, in 1 hr 40 minutes and boiling was maintained until 16:19 solar hour. The air temperature inside the cooker with the cooking pot in place attained a maximum value of 129.8 °C at 14:14 solar hour. The temperature of the cooker surface on the outside was nearly the same as that of ambient air at 24 °C, despite the high temperature inside the cooker, signifying the efficiency of the insulating material (glass wool) between the inner and outer walls of the enhanced box solar cooker. The air temperature inside the cooker is sufficient to cook many types of local dishes. The cooking power of the enhanced box cooker was calculated from a sensible heating test utilising Equation 2. The initial and boiling temperatures of 2 L of water at 22.5 °C and 95.6 °C, respectively, time taken of 1 hr 40 minutes, and c_w = 4.18 kJ/kg °C were used. The resulting cooking power was 101.9 W, a value that is within the range of several reported values for similar cookers (Ahmed et al. 2020, Verma et al. 2023). The cooking power is significantly larger than the design power because of the larger aperture area of the fabricated cooker and higher solar insolation compared to the design values.

Thermal Test Results for the Parabolic Solar Cooker

Different loads of water at 1 to 5 L were used for load tests of the parabolic solar cooker to establish the cooker capacity for different loads. Figure 5 shows water temperature variations with heating time for different volumes of water. The measurements started at 9:05 to 13:34 solar hours and 1 L of water came to the boil in 10 minutes, the time that gradually increased with larger volumes of water to 60 minutes for 5 L of water. On the other hand, the parabolic reflector surface temperature was maximum at solar noon at 35.5 °C, only 6 degrees higher than the surrounding ambient temperature at 29.5 °C indicating good reflectivity or minimum solar absorption by the reflector as depicted by high spectral reflectance of the parabolic reflector at different angles of incidence (Figure 3).

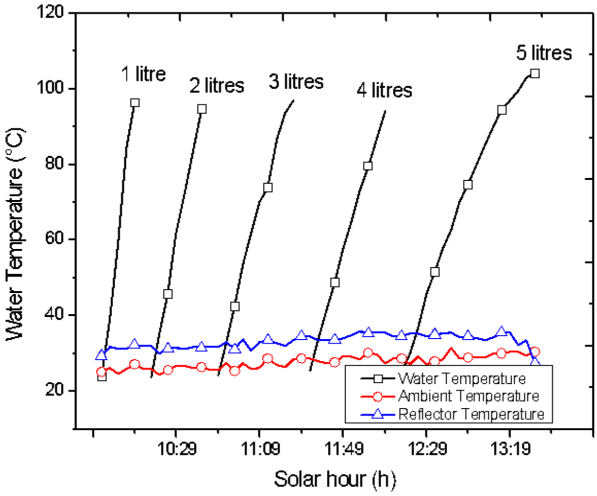

Figure 5: Temperature variations with time for different water loads in the parabolic solar cooker.

Cooking power calculations performed as per Equation 2, with only water load for the parabolic solar cooker revealed variations of the cooker power with interval temperature differences and water loads. The 10 minutes interval heating of 1L of water registered a cooking power value of 314 W, whereas that of 2 L, 3 L, 4 L and 5 L water loads registered cooking powers in the ranges of 343 W to 431 W, 353 W to 431 W, 416 W to 444 W and 373 W to 513 W, respectively (Figure 6). The highest cooking power was registered close to solar noon at 513 W for the 5-litre water heating.

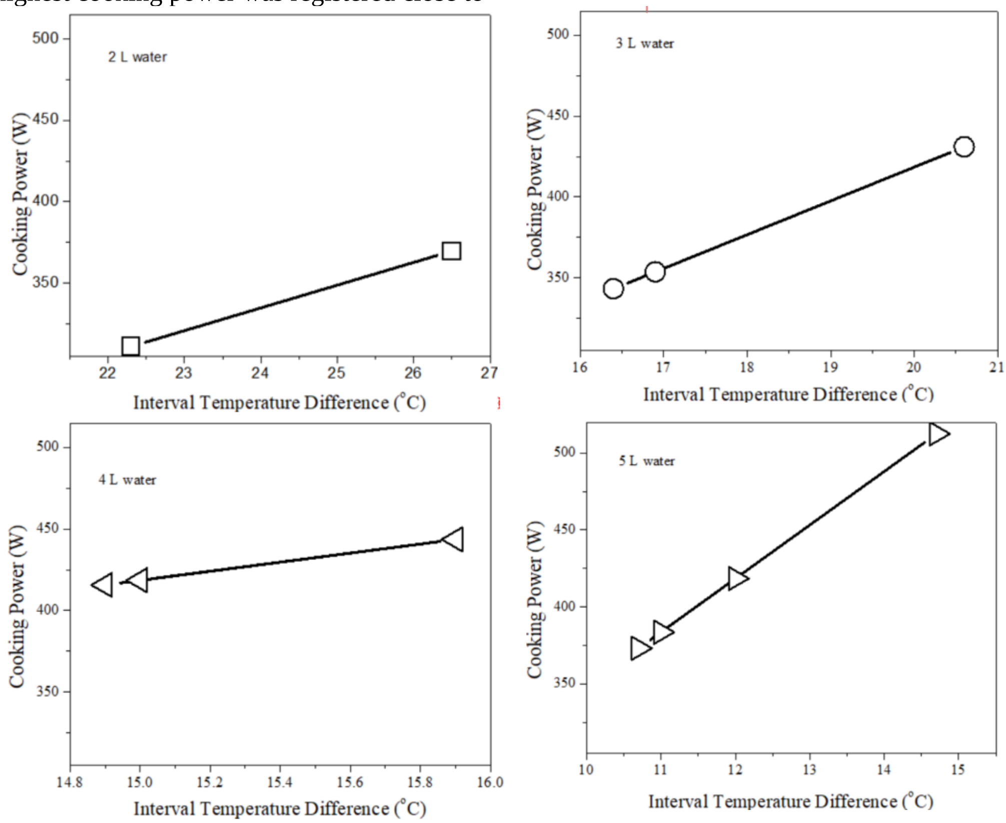

Figure 6: Cooking power calculated from water heating at 10-minute time intervals for various water loads

Around boiling point, the cooker registered only 373 W during 5 L water heating with nearly the same solar insolation conditions, with the lowered cooking power value being a result of increased thermal losses at higher water temperatures. Generally, the cooker power increased with solar time climaxing at noon as expected if the sky was clear all day long. The cooking power of the parabolic solar cooker was high enough to cook local foods even in very early solar hours as long as tracking of the Sun was done.

Conclusions

In this study, family-size parabolic and enhanced box solar cookers were designed, fabricated and tested at Isimani, Tanzania. The enhanced box solar cooker was designed with a 44 × 44 cm^2 double-walled cooking box, between which thermal insulating glass wool was placed, with the walls being held together using solid polyester fibre panels. The cooking box was covered by a double glass glazing and was attached with eight pieces of booster mirrors, forming an octagonal shape on the top end making an effective aperture area of 0.68 m^2. The suspended cooking tray ensured that the food was not spilt even when the cooker was manually adjusted to track the sun. Thermal tests of the cooker revealed a maximum air temperature inside the cooker at

130 °C achieved around solar noon and calculated cooking power of 102 W, a value that is higher than many reported for box solar cookers, attributed to the booster mirrors and good thermal insulation. The parabolic solar cooker was designed with an aperture area of 1.44 m^2, focal length of 0.25 m and a parabola depth h of 0.47 m. Polished aluminium reflectors were assembled following the parabolic curvature supported by a circular rim flexibly attached to a horizontal steel pipe containing the cooking pot tray. A simple guiding element was utilised to manually track the Sun. Thermal testing of the cooker revealed a maximum interval cooking power of 513 W around solar noon with 1 and 5 L of water coming to the boil in 10 and 60 minutes, respectively. Test results of both the parabolic and the enhanced box solar cooker designs have indicated great potential in terms of cooking powers for the use of the cookers as a clean alternative to firewood and charcoal stoves in Tanzania and other places with abundant sunshine. More work however is needed to ascertain the functioning of these devices in different weather conditions, such as cloudy seasons, and high winds, to ensure consistent performance. Durability tests under long-term outdoor exposure would also provide insight into the sustainability of these designs.

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