Development and performance testing of solar cookers

C Z M Kimambo
Department of Energy, University of Dar es Salaam

Abstract
The most common type of energy used is firewood. In some Sub Saharan countries, up to 90% of total energy use is from firewood. The consumption of wood fuel is in some countries as high as twice the sustainable yield, something that has led to environmental degradation due to deforestation and scarcity of firewood. The use of fossil fuels such as kerosene and LPG for cooking is expensive. Solar energy is a non-consumptive and non-polluting fuel. It can help alleviate the problem of insecurity of cooking energy, which is the major domestic energy requirement. Several attempts have been made to introduce solar cookers in different countries and have achieved variable successes. There are still critical issues yet to be resolved in order to make that technology acceptable for wider dissemination. They include getting the most appropriate types of solar cookers for specific locations, optimum size/capacity, types of materials to be used, optimal design and affordable cost. In an attempt to resolve these issues, a comprehensive study involving theoretical review, development work, experimental testing and evaluation of solar cookers was conducted for several years on six different types of solar cookers. The cookers are the 'SunStove' box cooker, wooden box cooker, panel cooker, reflector cooker with unpolished aluminium reflectors, reflector cooker with polished aluminium reflectors and reflector cooker with glass mirror reflectors. This paper presents the results of the study. Results obtained indicate that many of the cookers could be used to cook food for households in areas with medium and high insolation, with appropriate selection of the type and specification of the cookers. The specification should be based on the measured insolation data of the location indication of the direct and diffuse components. As a guiding tool, reflector cookers offer best comparative performance in areas with longest durations of clear sky (greatest direct beam), panel and collector cookers under moderate cloudy conditions and box cookers under very cloudy conditions.

Keywords: solar, cooker, test, performance, evaluation, Tanzania

Introduction

The increasing demand for fuel and the scarcity of alternative sources is a major factor leading to deforestation. In Tanzania, for example, urban growth has created a great demand for charcoal resulting in a loss of some 575 000 hectares of forests annually through fuel wood extraction. Fuel wood supply to Dar es Salaam City alone had been depleting forests in the surrounding areas at a rate of 75 000 hectares per annum. Consequently, today charcoal is brought from distances of up to 200 km inland. The gradual disappearance of woodland in circular areas around towns has also been observed in the central region of Dodoma in Tanzania. The major effects of deforestation in Tanzania have been deterioration of ecological systems, with resulting negative impacts on soil fertility, water flows and biological diversity. Soil erosion has become a serious problem in many parts of the country, particularly in the central regions. Sheet and gully erosion are widespread, rendering most of the land unproductive.

Deforestation has also led to acute shortages of fuel wood in many parts of the country. Women in rural areas are forced to walk long distances up to 7 km or more with heavy burdens of wood fuel. Until the late 1970s, women were able to collect firewood within a radius of one to 2 km from their villages. By the 1980s, however, women particularly in semi-arid areas were walking 10 km or more looking for firewood. Regions which are experiencing fuel wood deficits also include Mwanza, Shinyanga, Mbeya, Mara and Arusha. The depletion of forest resources in Tanzania is of great concern for environment and development. It is affecting not only the economy of the country, through negative effects on agriculture, but also the health of the people. It is undermining the potential for sustainable development. In an effort to arrest the situation, the Tanzanian Government (URT, 2006) has issued a Strategy for Urgent Action on Land Degradation and Water Catchments. The strategy outlines measures and actions to control environmental degradation due to felling of trees for firewood and charcoal.

Solar cooking presents an alternative energy source for cooking. It is a simple, safe and convenient way to cook food without consuming fuels, heating up the kitchen and polluting the environment. It is appropriate for hundreds of millions of people around the world with scarce fuel and financial resource to pay for cooking fuel. Solar cookers can also be used for boiling of drinking water, providing access to safe drinking water to millions of people thus preventing waterborne illnesses. Solar cookers have many advantages, on the health, time and income of the users and on the environment. In tropical countries, the solar energy is plenty and therefore it becomes a reliable and sustainable source of energy.

Review of solar cooker application and testing

Principles of operation of solar cookers

The principle of solar cooking is that rays of sun are converted to heat and conducted into the cooking pot. The ability of a solar cooker to collect sunlight is directly related to the projected area of the collector perpendicular to the incident radiation. In this regard, the geometric concentration ratio is defined as

$$CR = \frac{A_t}{Ar_c} \quad (1)$$

where A_t is the total collector area and A_{rc} is the area of the receiver/absorber surface.

In the case of the simple box with no reflectors, the energy entering the aperture can be given simply as:

$$Q_c = A_p \tau_g I \quad (2)$$

where A_a is the area of the surface of glazing material facing the sun (assumed perpendicular), τ_g is the transmissivity of the glazing material, and I is the value of the global solar radiation perpendicular to the collector. Equation (2) assumes that the collector is normal to the incident radiation.

The variation of the apparent area of the collector with the angle of the sun is given by equation (3).

$$A_{ap} = A_p \mathrm{Cos}(\theta) \mathrm{Cos}(\phi) \quad (3)$$

where A_{ap} is the apparent area of the collector; A_p is the area of the collector assuming the solar radiation is perpendicular to the surface; θ is the solar azimuth angle, and ϕ is the difference between the solar elevation angle and the collector tilt angle.

Types of solar cookers

A survey of solar cookers worldwide shows that a wide variety of cookers have been designed. However, the available designs of solar cooker fall into four main categories namely, the solar box cookers or popularly known as solar ovens, panel cookers, collector cookers and concentrating or reflector cookers. The feature common to each design is the shiny reflective surface that directs the sun's rays onto the cooking area and dark inner walls of the cooking area and cooking vessel. Each type of solar cooker has advantages when compared on their cooking ability, ease of construction, and safety of use.

The solar box cooker or solar oven is the most common type of solar cooker made for personal use. It consists largely of a box made of insulating material with one face of the box fitted with a transparent medium, such as glass or plastic. The panel cooker is quite similar in operation to the solar box cooker. The same principles are employed but instead of an insulated box only, the panel cooker typically relies on large (often multi-faceted) reflective panels, which focus the sunlight on a cooking vessel. The collector cooker is made up of two parts that often share a single casing: a collector for gathering heat and a cooking part for exploiting the yield. A typical collector cooker would consist of a flat plate solar collector, side and head mirrors, and the cooker part. The user is not affected by radiation and heat as the cooking part is separate and protected from radiation. Oil is used as the heat transfer medium in order to allow higher temperatures to be reached. The concentrating solar cooker or reflector cooker utilizes the principles of concentrating optics. It concentrates direct solar radiation on the bottom of the cooking pot, heating the pot in a fashion similar to a traditional electric or gas powered stove. The most commonly used shape is that of a parabola hence, the name parabolic cooker. Using mirrors and/or lenses, this cooker can achieve extremely high temperatures. Table 1 summarises the advantages and disadvantages of the four types of solar cookers described above.

Solar cookers application worldwide

The first reported solar cooker user worldwide was by a Swiss, de Nicholus Saussure (1740-1799) who built his black insulated box cooker with several glass covers. Even without reflectors, he reported to have successfully cooked fruits at that time reaching a temperature of 88°C. Over the years, de Saussure and others focused their solar box cooker design work on variations of shape, size, sidings, glazings, insulations, reflectors, and the composition and reflectance of the internal surfaces. In Africa, an Englishman, John Fredrick Herschel, used solar cookers in 1837, at the Cape of Good Hope, South Africa. He used a black box made of hard wood with a double glass window without a reflector and buried it in sand for insulation. The temperature reached was 66°C. In Asia, experiments on solar cookers were carried out by an Englishman, William Adams, in Bombay, India in 1878. He used glass

Table 1: Advantages and disadvantages of different types of solar cookers

Type of cooker	*Advantages*	*Disadvantages*
Solar box cooker (solar oven)	Uses both direct and diffuse radiation Requires little intervention by the user Very easy and safe to use Easy to construct High acceptance angle* High tolerance for tracking error	Widely divergent thermal performance (slow even cooking)
Panel cooker	Better performance than box cooker	Poor performance on cloudy conditions Relies more on reflected radiation
Collector cooker	Uses both diffuse and direct radiation Could used as a multicooker Higher cooking temperatures Simple, safe and convenient to use	Complicated to build Expensive
Concentrating (reflector) cooker	Quite efficient Can achieve extremely high temperatures (suitable for frying) Cooks quicker	Harder to make and use Requires the user's attention Strong reliance on direct beam Suffers from wind Low acceptance angle Relatively high cost Safety problems (burns or eye damage)

** Angle through which the sun's image remains on the absorber.*

planar mirrors arranged in a shape of an inverted eight-sided pyramid that focused light through a cylindrical bell jar into the food container. In America, an American, Samuel Langel, pioneered solar cooking in 1884. He used a box type cooker at Mount Whitney, California, at an altitude over 4 km.

Solar cooking is particularly appropriate in dry and sunny areas. Tropical countries have great potential in using solar cookers because they suffer most from shortages of cooking energy, and sun energy is plentiful in those countries. Numerous factors including access to materials, availability of traditional cooking fuels, climate, food preferences, cultural factors and technical capabilities; affect people's perception of solar cooking.

After the early pioneers described above, there were other solar cooker disseminators and researchers in the 20th century. Many organizations and institutions worldwide are doing research on how to improve the efficiency of solar cookers and make them acceptable to the intended users. Some of these organizations are Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) and Solar Cookers International (Solar Cooker International, 1995) and others in Europe and North America (Kerr, 1991) and (Synopsis, 1994). Despite attempts that have been made to disseminate solar cookers in Africa, only modest results have been achieved and too little attention has been paid to the social context as defined by the needs of potential users (Biermann *et al,* 1999).

The most comprehensive study of solar cooking reported in Africa is that conducted in South Africa. It involved field testing of solar cookers and dissemination of the cookers (GTZ, 1999). A one-year comparative field-test of seven different types of solar cookers, involving 66 families in three study areas in South Africa, was conducted by the South African Department of Minerals and Energy (DME) and the GTZ (Biermann *et al*, 1999). The different types of cookers are four box cookers, one concentrator and two collector-type cookers. All the seven types of cookers proved able to handle the traditional dishes. With regard to acceptance, the solar cookers were shown to be the most frequently used cooking implements along with wood, gas, kerosene, coal and electricity. A commercial pilot dissemination programme of the cookers concludes that unless the technical aspects are accommodated to the people's needs, the solar cooking technology will never be able to gain any real popularity.

Rather contrasting results were obtained in another study in the neighbouring country of Lesotho (Eberhard, 1984) and (Grundy and Grundy, Undated). Using the research results coupled with more recent empirical information on the diffusion of solar cookers among the Basotho of Lesotho, it is concluded that the use of solar cookers and their effective diffusion in Lesotho is rather bleak. Forty-five box cookers were introduced to the people of Thaba Tseka as a gift from the University of Cape Town. The Basotho of Thaba Tseka indicated that since they already used fire to heat their homes, they preferred to cook over their fires rather than use the solar cookers. It is claimed that the reason for this failure of adoption of the solar cookers is that the key characteristic that help to explain the rate of adoption of any innovation i.e. 'relative advantage', as perceived by the users was negative.

Solar Cookers International has recently had a breakthrough in Kenya in using a panel solar cooker. More than 5 000 families are now solar cooking there. Effort has been made also in Tanzania, where several projects have been implemented on solar cookers. These are described in the preceding section.

Solar cookers applications in Tanzania

The practical application of solar energy for cooking purposes in Tanzania has been introduced very recently. Box type solar cookers were the first to be introduced in Tanzania, but their popularisation was not successful. Some of the cookers were imported from abroad, but there are some that have been made locally. Solar cooking has become increasingly popular in Tanzania in the past few years, particularly in the dry central regions, where fuel wood resources in some places are completely exhausted.

A reflector solar cooker with polished aluminium reflectors that was developed in Germany has been promoted in several regions, mainly through the Evangelical Lutheran Church in Tanzania (ELCT) (Mshana and Ischebeck, 1999). The cooker frames are fabricated in Tanzania and assembled with polished aluminium reflectors imported from Germany. Over fifty units of the reflector cooker had been disseminated in Mpwapwa district in the Dodoma region alone, by the end of the last century. The cooker has also been disseminated and is being used in other parts of the country for household and institutional applications. A survey conducted (Kawambwa and Kimambo, 1999) witnessed the reflector cookers being used successfully for cooking and boiling of drinking water at Kibosho Hospital in the Kilimanjaro region and Karatu Lutheran Centre in the Manyara region. Both these locations are in the Northern highlands of Tanzania, with altitudes of above 3 000m above sea level.

In an attempt to cut down the cost of the reflector cooker, alternative locally available aluminium (unpolished) was used as a reflector. Performance is rather poor compared to the imported plates from Germany. A better performing reflector cooker using glass mirrors as reflectors was developed as a joint project of the four research and development organisations namely, the Centre for Agriculture Mechanisation and Rural Technology (CAMERTEC), Tanzania Engineering and Manufacturing Design Organization (TEMDO), Tanzania Industrial Research and Development Organisation (TIRDO) and the former Institute of Production Innovation (IPI) of the University of Dar es Salaam in the early 1990s. This cooker is now being disseminated by CAMARTEC and seems to be more acceptable. Institutions that have been involved in the development and dissemination of solar cookers in Tanzania include the University of Dar es Salaam, TIRDO, CAMERTEC, Tanzania Traditional Energy Development Organization (TaTEDO), Enviro Care, CAMARTEC and some religious organisations.

A collector cooker with side reflectors 'Sunfire' made by Sensol of Germany is being used for cooking and boiling of drinking water at the Lutheran Centre, Karatu in the Manyara region of Tanzania. The cooker was installed in October 1998. Whenever there is sufficient sun, the cooker is used for cooking all kinds of dishes. It has proved to be acceptable by the users and it is very reliable. The cooking time is also acceptable – it takes two and a half hours to cook the most difficult food to cook, which is a mixture of dried maize and beans. When it is not used for meals, it is used for heating or boiling water. The cooker is made by a German company, SESOL. The main barrier to widespread dissemination of the cooker in Tanzania is its exorbitant cost.

Solar Cooking Zanzibar, a project of a German NGO, Green Ocean, and another German NGO, Deutsch-Tansanische Partnersschaft e.V. (DTP), report that they currently assist rural women in Zanzibar who produce and use solar cookers. Of recent, there have been new designs of solar cookers for household applications introduced to the Tanzanian market. Two notable ones are reflector cookers imported from China that are being supplied by a local company by the name of Sunshine Solar Technology Limited, and a panel box cooker being promoted by an American NGO by the name of Solar Circle, in Southern Tanzania. The NGO is working in collaboration with the Ndanda Catholic Mission, Masasi Catholic Mission and the Anglican Diocese in Masasi. The latter cookers are being made at Ndanda Catholic Mission in Mtwara and are sold at a subsidized price of approximately US$40. The former cookers are available in two sizes costing US$115 and US$138 respectively. The Chinese reflector cookers have the advantage of light weight due to the fibre glass parabolic dish that has been used. They are also on wheels, which makes it convenient to move in and out. The reflector is an aluminium foil, which is stuck onto the glass fibre dish. The panel cooker consists of a wooden box with a single glass cover and foldable aluminium reflector panels. It is fitted with a temperature gauge.

The current work

The work being reported in this paper started in 1999 and is being conducted at the College of Engineering and Technology, University of Dar es Salaam, Tanzania. The study has involved a total of five student projects (Lissu, 2000), (Raphael, 2002), (Kikoti, 2004), (Kilangi, 2005) and (Mwangomba, 2006). Various types of solar cookers that are being promoted in Tanzania and those that were developed as part of this project have been investigated.

The work has been based on conducting experimental testing of performance of solar cookers and improving their performance hence, their potential for successful dissemination as an alternative cooking technology.

Two types of solar cookers tested and evaluated are box cookers, panel cooker and parabolic reflector cookers. Among the box cookers, there is one developed in South Africa, the SunStove. A new improved solar cooker of the panel type was developed and tested (Kilangi, 2005). The reflector cookers are of the two basic designs namely, the one developed in Germany, with aluminium reflectors and the CAMARTEC-IPI-TEMDO-TIRDO design using glass mirrors as reflector.

Experimental testing of solar cookers

Review of solar cooker testing procedures

A procedure for testing the solar cookers was developed based on existing international testing standards. A review of some commonly used international standards was made. They include three major testing standards for solar cookers that are commonly employed in different parts of the world. These are the American Society of Agricultural Engineers Standard (ASAE S58, 2003), Bureau of Indian Standards Testing Method and European Committee on Solar Cooking Research Testing Standard and others (Funk and Larson, 1998).

The American Society of Agricultural Engineers Standard ASAE S580 monitors the average temperature inside a pot of water while the cooker is operated under a set of guidelines given in the standard for tracking procedure, thermal loading, etc. Ambient temperature and normal irradiance (solar energy flux per area) are also measured and recorded, at least as often as load temperature. Under conditions of high wind, low insolation, or low ambient temperature, tests are not conducted. The primary figure of merit used is the cooking power.

The Bureau of Indian Standards Testing Method is based on thermal test procedures for box-type solar cookers (Mullick *et al*, 1987). A characteristic curve can be developed that describes, for a given set of conditions, how long the cooker will take to reach the reference temperature.

In the European Committee on Solar Cooking Research (ECSCR) Testing Standard, the evaluation process is driven by several detailed data sheets, which are filled out by the tester. Additional data that is provided by the manufacturer is also included. Data is collected under a set of conditions for what is known as the 'Basic Test'. The general conditions for conducting the tests using this standard are also stipulated. The standards differ widely in their scope, complexity, and deliverables. Table 2 summarises the advantages and disadvantages of the three standards for solar cooker testing described above.

Adopted test procedure and experiments carried out

The necessary conditions that must be fulfilled prior to and during testing are environmental factors, controlled factors and measurement standards. With regard to environmental factors, the testing of solar cookers must rely, to some degree, upon the weather and climate of the testing site. In order for results to be consistent, the factors described below should be monitored and accounted for when calculating figures of merit from the collected data. The factors that were considered for the tests are wind speed, ambient temperature, insolation and precipitation. Controlled factors represent the portions of the test that are controlled by the tester. These factors can have a significant impact on the obtained results. Controlled factors that were considered are cooking vessels, tracking, time, thermal loading and data collection and recording. With regard to measurement standards, these should be considered as

Table 2: Advantages and disadvantages of different solar cooker testing standards

Test standard	*Advantages*	*Disadvantages*
American Society of Agricultural Engineers Standard (Funk, 2000)	Simple Applicable in less developed areas	Analysis of performance of a cooker, rather than simply comparison is very difficult Does not address qualitative factors e.g. ease of use, safety, or financial issues
Bureau of Indian Standards Testing Method (Mullick et al, 1987)	Presented in a more technical framework than ASAE S580 Independent of weather conditions (such as wind speed, insolation, etc.)	Does not address qualitative factors e.g. ease of use, safety, or financial issues
European Committee on Solar Cooking Research (ECSCR) Testing Standard	Includes an exhaustive thermal testing regime Cheaper and easier to run – tracking pyranometer not required Explores qualitative factors e.g. safety, ease of cooking, pot access, durability etc. Useful for comparison of any cookers	Relies on measurements of time taken for certain conditions to occur Not well suited to multiple testing – procedure is quite comprehensive Requires long time – time taken for the basic test alone is 3 clear days

guidelines and any measurement error outside the given ranges should be reported and emphasized in the results.

Aims and procedures for the experiments carried out are described in detail (Lissu, 2000), (Raphael, 2002), (Kikoti, 2004), (Kilangi, 2005) and (Mwangomba, 2006). The experiments that were carried out were the following:

a. Determination of heating/cooking rates
b. Determination of the maximum attainable temperature
c. Determination of effect of cloud covers
d. Water – boiling tests
e. Controlled cooking tests

The measured variables are global radiation, ambient temperature and the temperature of the water in cooking pots. Experiments were performed to find performance of each solar cooker and also for comparison purposes. The cookers that were tested are box cookers, a panel cooker, reflector cooker with glass reflectors, reflector cooker with polished aluminium, and a reflector cooker with unpolished aluminium. The following measuring instruments were used in carrying out the experiments:

(i) Pyranometer: The type of pyranometer used is a portable digital pyranometer using solar photovoltaic cells as the sensor. The make of the instrument is MacSolar made by a German company, Solarc. The instrument measure global radiation and its accuracy of the measurement is within 10 W/m^2.
(ii) Anemometer: Wind speed was measured at the testing site by an anemometer with resolution of at least 0.5 m/s. The type of anemometer used is GGA – 65P.
(iii) Thermocouple: All temperature measurements were made with thermocouples of a type appropriate to the expected temperature range of the cooker(s) being tested.

Test results

Test conditions

The solar cookers were tested outdoor under laboratory conditions in Dar es Salaam, mostly during the months of April and May, when solar radiation energy is at lowest levels. Also, Dar es Salaam has moderate solar radiation compared to other parts of Tanzania (TMA, 1994 – 2004).

Cooker specifications

Specifications of the cookers tested and appliances used are presented in Table 3. These are the specifications that are recommended by the cookers' suppliers to the users.

Water temperature variations

Quantitative performance evaluation of the cookers was conducted based on the procedure outline in this paper. For ease of comparison of various cookers, where possible, the experiments were conducted simultaneously. In case where this was not possible, insolation data for each test was recorded for the entire test duration. The location of the tests was at the University of Dar es Salaam main campus. Water temperature variations for different cookers were investigated on a clear day and on a cloudy day in water boiling tests. The amount of water used in the cookers was as shown in Table 3. The results are presented in Figures 1 and 2 for the clear and cloudy days respectively.

Determination of the maximum attainable water temperature

The maximum attainable water temperatures during water boiling tests conducted under the same test conditions as above are presented in Figure 3. These temperatures are not the highest attainable temperatures for the cookers, but provide a comparison of the cookers tested under the same conditions of solar insolation and time. In this comparison, the cookers were tested simultaneously.

Controlled cooking tests

Controlled cooking tests were performed for two types of solar cookers namely, the 'Sunstove' box cooker and the reflector cooker with glass mirror reflectors. The tests were performed on a good solar day, with few clouds and light winds. The type of

Table 3: Specifications of cookers tested

Type of cooker	*Glazing*	*Reflector*	*No. of pots*	*Nominal vol. (l)*	*Aperture area (m^2)*	*Collector area (m^2)*
'Sunstove' box cooker	Single PVC	Aluminium	1	2	0.34	0.34
Wooden box cooker	Double glass	None	1	2	0.24	0.24
Panel cooker	Single glass	Glass mirror	1	2	0.56	0.14
Reflector cooker – unpolished aluminium	–	Unpolished aluminium	1	4	1.61	1.61
Reflector cooker – polished aluminium	–	Polished aluminium1	1	4	1.61	1.6
Reflector cooker – glass mirror	–	Glass mirror	1	4	2.15	2.15

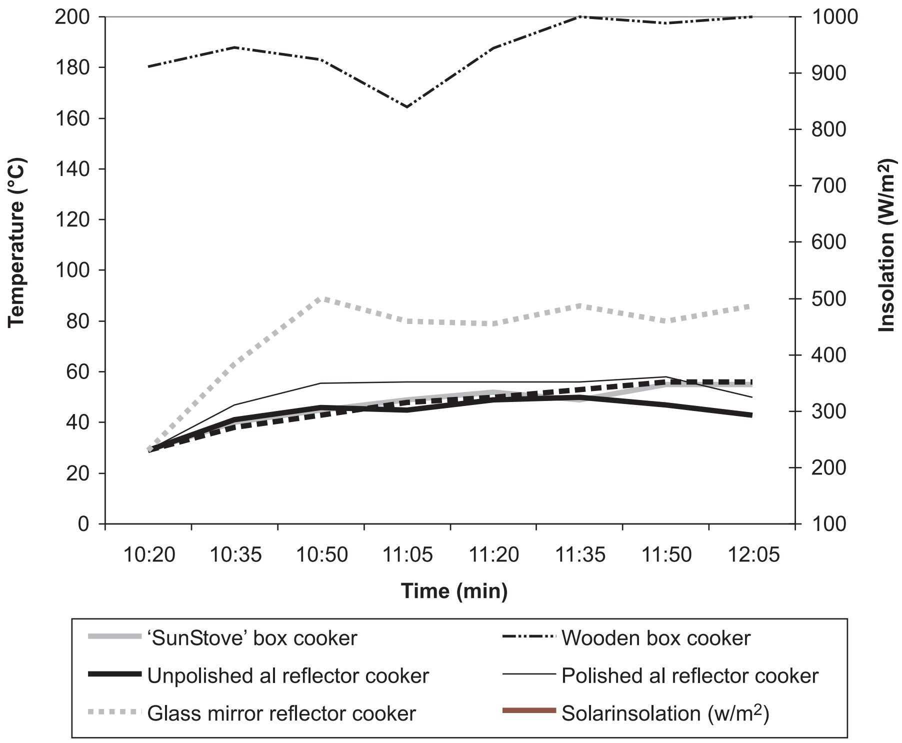

Figure 1: Water temperature variations and insolation against time on a sunny day

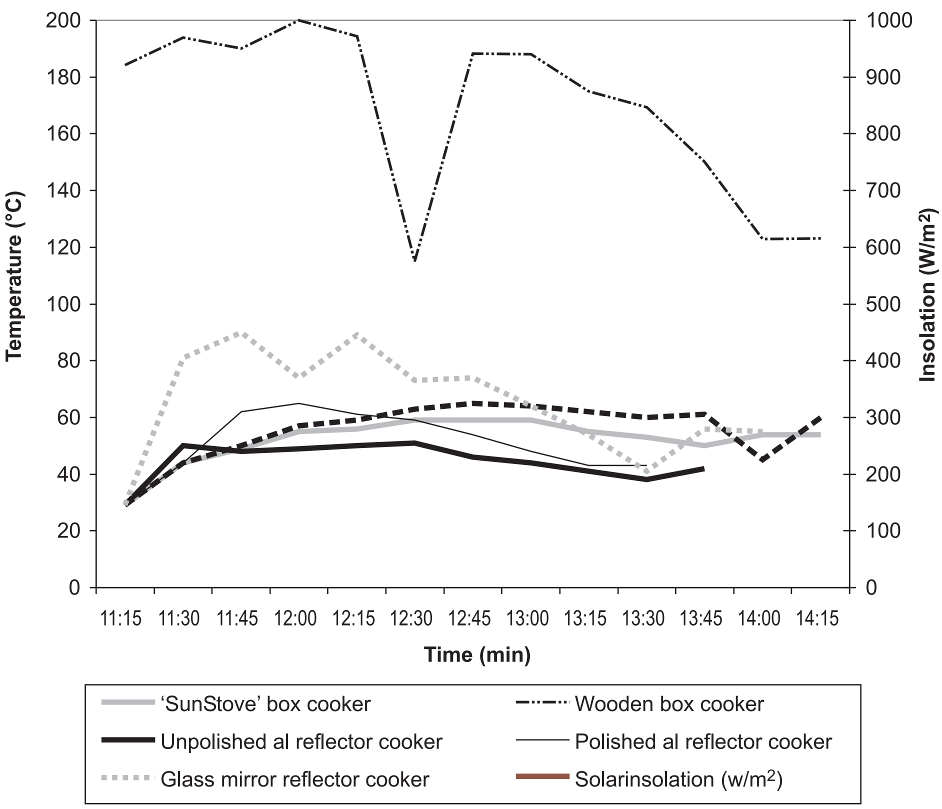

Figure 2: Water temperature variations and insolation against time on a cloudy day

Table 4: Controlled cooking test results

Cooker type	Quantity (kg) Food	Water	Average insolation (W/m^2)	Cooking time (min)	Comment on the food
'Sunstove'	1.5	3.0	1000	180	Uncooked
Reflector – with glass mirror	1.5	3.0	1000	100	Cooked

food cooked was rice. The test conditions and results obtained are presented in Table 4.

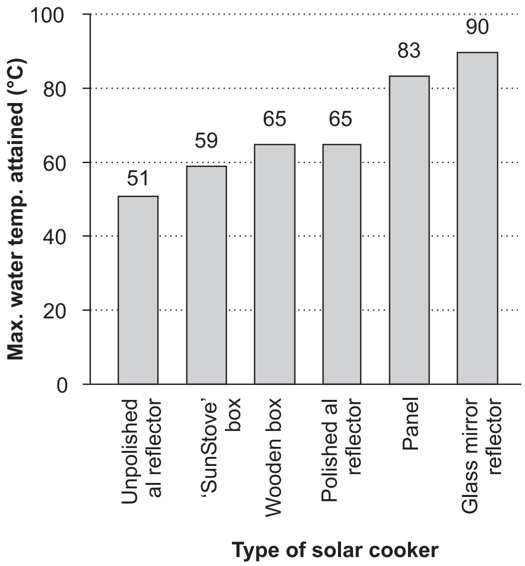

Figure 3: Maximum water temperature attained

Discussion and evaluation

Test conditions

Experimental results in determining the best cooking time revealed that the morning and evening hours when the sun angles are low, have low solar radiation intensity and hence, unsuitable for solar cooking. Between about 9.00 a.m. to 4.00 p.m., the solar intensity is high, ranging from about 700 to 1000 W/m^2, representing a suitable range for solar cooking.

As the solar radiation varies from place to place and with time of the year, the best cooking time may deviate because of the effect of cloud cover. Dar es Salaam is a typical location where cloud cover affects solar cooking. As expected, the effect of cloud cover was more pronounced for reflector cookers. Even though in some cases the solar insolation measured is highest expected (1000 W/m^2), the measured value is the global radiation. This means that there is a significant contribution of the diffuse component to the global figure, since the tests were conducted during the cloudy season of the year. In the case of reflector cookers, therefore, the measured performance does not represent the best performance of the cookers. The direct and diffuse components could not be distinguished because appropriate measuring instruments were not available.

The adopted procedure states that wind speed should not exceed 2.5 m/s for more than 10 minutes during any given test. However, given the fact that Dar es Salaam is a windy area (at the coast) and the tests were conducted on the top of a two storey building, the wind speed did exceed the recommended limit of 2.5 m/s in some occasions, but for shorter durations than 10 minutes. This was the case in all the tests unless otherwise stated and therefore it did not have a very serious effect on the performance of the cookers tested.

Technical performance of the cookers

The results show the maximum temperature reached under the pertaining test conditions for all the solar cookers is around 96°C, which was in a reflector cooker using glass mirrors. The reflector cooker with glass reflectors managed to attain a water temperature rise to 80°C from 42°C in 70 minutes. The average insolation was about 1000 W/m^2 and the maximum temperature was 96°C in 90 minutes. The parabolic cooker with polished aluminium reflectors attained a maximum temperature of 93°C in 150 minutes from 43°C at average insolation of 1000 W/m^2. The wind speed in both cases was around 2.6 m/s. The performance of the latter cooker is low compared to that with that of the former. With unpolished aluminium reflectors, the maximum temperature reached was 79°C in 180 minutes from 40°C at average insolation of 1000 W/m^2 and wind speed of 2.7 m/s. The performance of this cooker is the lowest compared to the other two types.

In the group of box cookers, both the 'SunStove' cooker and the wooden double glazed box cooker attained the highest temperature of around 75°C. The efficiency of the 'SunStove' box cooker in converting the incident radiation has useful energy ranges from 7% to 43%. On average, the efficiency is 19%. Also the maximum temperature attained is 78°C at average radiation and wind speed of 1000 W/m^2 and 2.54 m/s respectively. The panel solar cooker attained the highest temperature of 83°C.

These results indicate that the two solar box cookers have comparable performance whereas the panel solar cooker performs better than the two. It should be noted here (refer Table 3) that the 'SunStove' cooker has a larger collector area that the wooden box cooker, and the latter is double glazed, while the former cooker has a single PVC cover. These two comparative advantages tend to offset each other in technical performance of the cookers. The Maximum Attained Temperature Test (Figure 3) provides an indication of ability and speed of the cookers to cook. It is notable that the reflector cooker with glass mirror reflectors reached the highest maximum temperature of 90°C, followed by the panel cookers that was developed in this study (Kilangi, 2005), reaching a temperature of 83°C.

Variation of water temperature and insolation against time for the stove on a sunny day (Figure 1) also confirm the results presented above – that is the best performing cooker is by far the reflector cooker with glass reflectors, with the box cookers and the reflector cooker with polished aluminium reflectors having almost the same performance on a sunny day and the reflector cooker with unpolished aluminium reflectors having the least performance. The box cooker was not included in these tests, but it is expected to be number two in performance. Variation of water temperature and insolation against time for the stove on a cloudy day (Figure 2) demonstrates the susceptibility of reflector cookers to poor performance on cloudy conditions. All reflector cookers, including the one with glass reflectors that performed best on a sunny day had lower performance than the box cookers.

The controlled cooking test results (Table 4) indicate the comparative cooking ability of the box and reflector cookers qualitatively. The results indicate that the reflector cooker with glass reflectors can cook food effectively for medium sized families with cooking time that is comparable to currently used wood and charcoal stoves under persistent sunny conditions.

The different types of solar cookers tested have varying surface areas i.e. collector area, aperture area and total area of the collector (refer to Table 3). In the group of box solar cookers where it is generally considered that the aperture area equals the collector area, the locally made wooden box cooker has a smaller area than the 'SunStove' cooker, although the former has a higher thermal performance. The higher thermal performance is attributed to the double glazing, type of glazing material, better insulation of the thick wooden wall and good sealing of the window. The panel cooker has a smaller collector area than the box cookers but its aperture and total areas are much bigger than those of the box cookers. However, it has a better thermal performance than the box cookers. In the group of reflector cookers where the aperture and collector areas are the same, the cookers with an aluminium reflector have a smaller aperture/collector area compared to the reflector cooker with glass mirrors. However, the reflector cookers with aluminium reflectors have a large total collector area compared to the reflector cooker with glass mirror reflectors. This is because of the deep parabola in the case of the former. This together with the exhibited lower thermal performance makes the aluminium cookers less cost effective.

Double glazing has been used in only one of the box cookers, and seems to have improved thermal performance significantly. Given the relatively small collector area of box and panel cookers, it seems cost effective to use double glazing. Also if the conditions where the cookers are to be used is not too rough, a glass cover is recommended, rather than the transparent PVC cover, which has lower optical performance and is difficult to achieve good sealing of the window.

The shape of the parabola is determined so as to ensure optimal focusing of the incident radiation to the cooking pot. As it has been exhibited in the two designs of reflector cookers tested, both could achieve this objective with appropriate tracking within the same time intervals. However, the glass mirror reflector cooker with a shallow parabola, hence lower total area and less construction materials has exhibited a better performance than the deep parabola design.

Challenges in disseminating solar cookers

The results and subsequent discussions of solar cooker tests presented in this paper help to highlight the challenges in getting a solar cooker that would be able to meet the expectations of intended users and different weather conditions. It also highlights the operational requirements that the user of the solar cooker must fulfil in order to achieve optimum performance of the cooker and ensure safety of the user. Another big challenge in dissemination of solar cookers (not investigated in this study) is with regard to social acceptability of cookers by the intended users.

In the case of reflector cookers, depending on its focal length, the cooker must be realigned with the sun every 15 minutes or so. Only direct insolation is exploited, i.e. diffuse radiation goes unused. Even scattered clouds can cause high heat losses. The handling and operation of such cookers is not easy; it requires practice and a good understanding of the working principle. The reflected radiation is blinding, and there is danger of injury by burning when manipulating the pot in the cooker's focal spot. Cooking is restricted to the daylight hours. The cook must stand out in the hot sun except for the fixed-focus cookers. The efficiency is heavily dependent on the momentary wind conditions. The presence of cloud or sometimes even rain affects very much the total performance of the cookers. The results of tests conducted on cloudy days, clearly show that the performance cookers are very low. The highest water temperature is reached and gradually starts to decrease due to the presence of the cloud that reduced the required insolation to reach in the maximum temperature.

In the case of solar box cookers, the glazing window should be designed to provide a complete sealing of the cooker so that air can neither escape nor enter into the cooker when in use. The wooden box cooker is designed and made with high precision such that the sealing is very tight between the wooden frames even without a sealing material. It is recommended that the 'SunStove' is provided with a lock between the box and the cover, which will keep the cooker closed all the time of cooking, and prevent the heat flowing out.

Reflector cookers have low thermal efficiency because the cooking pot is completely exposed to the cooling effects of the surrounding atmosphere. In areas with high wind speeds such as those experienced in this study, this can be a major cause of low performance of the cooker. As much as possible, reflector cookers should be used in areas with low wind speeds. Alternatively, protection against higher winds should be provided where the reflector cooker is used on a windy site.

It has been shown in this paper that attempts have been made in various parts of Africa to disseminate solar cookers, but with very limited success. Also some explanation has been given for the failure to disseminate solar cookers. Results presented in this paper, which are mainly based on technical performance evaluation, help to illustrate the reasons as to why, as attractive as they are, solar cookers do not receive wider and sustainable acceptability by the intended user, many of whom are obviously in dire energy needs for cooking.

Conclusion and recommendations

Results obtained from this study show that under various conditions of insolation and wind, different types of solar cookers are superior to others. However, under best respective operating conditions, box solar cookers have lower performance compared to the reflector cookers. The reflector cooker with glass reflector achieved highest temperatures and accordingly shortest cooking times than any other cookers tested under sunny days with no cloud cover. It is recommended as being the most suitable type of cooker in areas with long durations of strong solar radiation with no cloud cover and low wind interference.

However, special attention should be paid to protect the users from possible burns or eye damage that may occur due to the reflected radiation of the cooker. The reflector cooker with polished aluminium reflectors has significantly lower performance than that of the reflector cooker glass mirror reflectors, under clear sky conditions. The reflector cooker with unpolished aluminium reflectors has the poorest performance of all the solar cookers even the box solar cookers under clear sky conditions. The ordinary unpolished aluminium should therefore never be used as reflector for solar cookers. Dissemination of such cookers would definitely end up in failure as the cookers would not be able to meet the cooking expectations of the intended users. The 'SunStove' box cooker was able to cook 2 kg of rice, which is sufficient for a moderate family in Tanzania. Both the 'SunStove' and the wooden box cooker can be used for cooking where the global insolation is high and wind effects are not pronounced.

The current work has shed some light on the status of solar cooking worldwide and provided a detailed account of activities taking place in Tanzania, in relation to solar cooking. Existing and new designs of solar cookers have been described and a comprehensive testing performed on some of the solar cookers that are available in the Tanzanian market.

Results obtained indicate that many of the cookers could be used to cook food for households in areas with medium and high insolation with appropriate selection of the type and specification of the cookers. The specification should be based on the measured insolation data of the location indicating the direct and diffuse components. This should go hand in hand with proper instruction and training of the users for successful dissemination. As a guiding tool, reflector cookers offer best comparative performance in areas with longest durations of clear sky (greatest direct beam), panel and collector cookers under moderate cloudy conditions and box cookers under very cloudy conditions. It should be noted here that all types of cookers offer best performance under clear sky conditions. It is envisaged that future work will be based in the field in order to incorporate the other aspects such as social, economic and environmental aspects that could not be assessed in this study. Parallel to the field test, improvements will be performed on the existing cooker designs in order to make them perform better technically, more convenient to use and less costly.

Nomenclature

A Area (m^2)
C_p Specific heat capacity (J/kg K)
CR Geometric concentration ratio
E Energy supplied (J)
h Heat transfer coefficient (W/m^2K)
I Global solar irradiance perpendicular to col-

lector (W/m^2)

L Mean length of glazing window (m)

LPG Liquefied Petroleum Gas

m Mass (kg)

P Power (W)

Q Heat Flux (W/m^2)

T Temperature (°C)

t Time (s)

σ Boltzman constant

ϕ Difference between the solar elevation and collector tilt angle (°)

ε Emissivity

θ Solar azimuth angle (°)

τ Transmissivity

η Efficiency

Subscripts

1 Initial

2 Final

a Aperture (area)/ambient (temperature)

ap Apparent

c cooker

cv Convection

g Glass

p Perpendicular

r Radiation

rc Receiver

s Stagnation

t Total

w Water

wd Window

References

ASAE, 2003, *ASAE S580:* Testing and Reporting of Solar Cooker Performance.

Biermann, E., Grupp, M. & Palmer, R. 1999, Solar Cooker Acceptance in South Africa: Results of a Comparative Field-Test, Solar Energy, Elsevier, Oxford, Vol. 66, No. 6, pp. 401-407.

Eberhard, A. A. 1984, Dissemination of Solar Ovens in Lesotho: Problems and Lessons. Proceedings of the Eighth Biennial Congress of the International Solar Energy Society. New York: Pergamon Press.

Funk and Larson, 1998, Parametric Model of Solar Cooker Performance, Solar Energy Vol. 62, No. 1, pp. 63-68.

Funk, (2000) Evaluating the International Standard Procedure for Testing Solar Cookers and Reporting Performance.

German Technical Cooperation (GTZ), 1999, Moving Ahead with Solar Cooker – Acceptance and Introduction to the Market.

Grundy, R. R. & Grundy, W. N. Undated, Diffusion of Innovation: Solar Oven Use in Lesotho, Business Department, College of DuPage, USA.

Kawambwa, S. J. M. & Kimambo, C. Z. M. 1999, A Compendium of Sample Solar Energy Applications in Tanzania, Research Report Submitted to Sida/SAREC, Institute of Production Innovation, University of Dar es Salaam.

Kerr, B. P. 1991, The Expanding World of Solar Box Cookers, Kerr-Cole, California.

Kikoti, V. E. 2005, Comparative Testing of Domestic Solar Cookers, Final Year Project Report (Project No: 15-03-04), Department of Energy Engineering, University of Dar es Salaam.

Kilangi, J. 2004, Design and Manufacturing of Solar Cooker, Final Year Project Report (Project No: 13-04-04), Department of Energy Engineering, University of Dar es Salaam.

Lissu, M. 2000, Solar Cooker: Is it Suitable for Large Amount of Food Typical of Tanzanian Family? Final Year Project Report (Project No. 17-99), Department of Chemical and Process Engineering, University of Dar es Salaam.

Mshana, R. R. & Ischebeck, O. (eds) 1999, Sustainable Development through Renewable Energies in Tanzania', Akademischer Verlag Muenchen.

Mullick et al. 1987, Thermal Test Procedure for Box-Type Solar Cookers, Solar Energy Vol. 39, No. 4, pp. 353-360.

Mwangomba, M. 2006, Testing and Evaluation of Domestic Solar Cookers, Final Year Project Report (Project No: 14-04-05), Department of Energy Engineering, University of Dar es Salaam.

Raphael, A. D. 2002, Comparative Testing of Domestic Solar Cookers, Final Year Project Report (Project No. 01-01-3), Department of Energy Engineering, University of Dar es Salaam.

Solar Cooker International, 1995, Solar Cookers: How to Make, Use and Understand, 8th Edition.

Synopsis, 1994, Evaluation of Solar Cooking Program, Annual Report, Lodive France.

United Republic of Tanzania (URT), 2006, Strategy for Urgent Action on Land Degradation and Water Catchments, Vice President's Office.

Tanzania Meteorological Agency (TMA), 1994 – 2004, Mean Insolation for Dar es Salaam and other Regions in Tanzania.

Received 20 December 2006; revised 23 July 2007