Increasing the efficiency of a solar oven

Aumentando la eficiencia de un horno solar

Recibido: julio 11 de 2017 | Revisado: setiembre 16 de 2017 | Aceptado: octubre 14 de 2017

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Abstract

The objective of this experiment was to design, build and evaluate a solar oven that was both economically viable and thermally efficient. In addition to the economic objective, I sought to determine the best reflector angle for the solar cooker, by measuring the following parameters: cooking power, efficiency, and effectiveness. Halogen lamps were used to simulate natural sunlight, as the outdoor condition was too variable in the UK to guarantee continued sunlight for 120 minutes in a controlled fashion. The most effective reflector angle i.e. the reflector angle with the greatest ability to convert the solar insolation into thermal energy is the 60°C. However, the data shows that the 70°C reflector angle produces the highest temperature consistently. Over the series of different methods for evaluating the best reflector and angle, it would seem that a 70°C angle is consistently highest in most of the test. With a reflector angle of 70°C, by 120 minutes, the solar oven was able to heat a pan of water to 78°.

Keywords: solar, energy, oven, box, efficiency, Global Warming

Resumen

El objetivo de esta investigación fue diseñar, construir y evaluar un horno solar que fuera económicamente viable y térmicamente eficiente. Además del objetivo económico, se buscó determinar el mejor ángulo de reflector para la cocina solar, midiendo los siguientes parámetros: potencia de cocción, eficiencia y efectividad. Se utilizaron lámparas de halógeno para simular la luz solar natural, ya que la condición al aire libre era demasiado variable en el Reino Unido para garantizar la continuidad de la luz solar durante 120 minutos de manera controlada. El ángulo del reflector que ofrece mayor capacidad para convertir la insolación solar en energía térmica fue de 60 grados. Sin embargo, los datos muestran que el ángulo del reflector de 70 °C produce una temperatura mayor y, a la vez, constante. Con un ángulo de reflector de 70 grados, por 120 minutos, el horno solar fue capaz de calentar una cacerola con agua a 78°C.

Palabras clave: solar, energía, horno, caja, rendimiento, calentamiento global

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https://doi.org/10.24265/campus.2017.v22n24.01

Introduction

The first recorded design of a solar oven was in 1767 by a Swiss naturalist named Horace de Saussure. Most of his experiments were not concerned with solar ovens directly but with the nature of solar energy (Arenas, 2007), he managed to generate temperatures of approximately 88 °C (Layton, 2017). After this date, there were records from 1894 of the concept used by British soldiers in India on-board boats on long voyages, but these were mainly isolated cases (ibid). It was not until the 1950' s that the concept became formalised.

The inherent instability in oil prices due to the complex and ad-hoc nature of socio-economic and global politics has left many people in developing nations to choose between purchasing fuel and food on a daily basis. This would be less of an issue if it were not for the fact that globally 2.8 billion people live on less than $2 a day (World Bank, 2001). The collection of biomass (typically wood) for fuel is contributing to increased desertification, deforestation, soil erosion and depletion of biodiversity in ecosystems (Bowman, 1985). Moreover, this practise promotes the use of a resource that could otherwise be utilised for building material or fertilizer. In this regard, in relation to deforestation Suharta, Seifert, and Sayigh (2006) commented: Through the 1990s the annual net loss [of forest] was 9 million hectares per year and down to 7.3 million ha/year between 2000 and 2005. This figure in itself is striking, but is also compounded by the fact that forests also act as a carbon sink.

In the case where groups of people are reliant on primary fuels such as refined petrochemicals like propane, petrol etc., it is accelerating global warming and restricting the conservation of primary fuels for alternative uses such as making plastics or other purposes. Taking this into account, the rationale of this paper is that some of the detrimental effects of burning biofuels or refined petrochemicals can be ameliorated by the use of inexpensive solar technology. The use of a solar oven can relieve or contribute to lessening the time and effort needed to collect biomass or other fuel, whilst also diminishing the production of CO and CO_2 thus reducing the impact on the environment.

If designed and built correctly, "It is estimated that a solar cooker on average would save 3.7 tonnes a year of CO_2" (Seifert, 1999), that would otherwise be generated by burning biomass. Solar ovens could also contribute to pasteurising and purifying water sources that are contaminated and undrinkable, and so consequently offer additional functionalities than heating.

As such, the use of carbon-based fuel is becoming a large contributing factor to the depletion and strain on global fuel reserves. Solar ovens use no fossil fuel; consequently, it is my contention that they have a role to play in reducing fuel poverty in developing nations and reducing their dependence on inflated and erratically priced foreign fuel imports. As global energy consumption is forecast to in increase by 1.6% by the International Energy Agency per annum until 2030 (Aswathanarayana & Divi, 2009) and that global oil consumption grew by 1.1% in 2007, or 1 million barrels per day (b/d) slightly below the 10-year average (ibid). As such, the near future is that fuel poverty will become a standardised trend, so reducing fossil fuel use and conserving land resources will continue to be an important factor in both developing and developed nations. Due to this, there are a number of schemes run by NGO's trying to promote the use of solar ovens.

Therefore, to work towards improving the efficiency and diversification of these devices, which would give more time and freedom to people in developing nations. Who are becoming increasingly dependent on using fuel that is priced beyond their economic abilities? Additional, the assembly, dissemination and use of solar cookers creates jobs and would be upholding and promoting the spirit of Article 12 of Kyoto Protocol in poverty alleviation which states:

- To assist Non-Annex 1 countries (developing countries) in achieving sustainable development.
- To assist Annex 1 countries in achieving their emission reduction commitments. (Suharta, Seifert, and Sayigh 2006)

The objective here was to design and construct an economically viable solar oven and evaluate the effect of different external reflector angles on the efficiency of the oven.

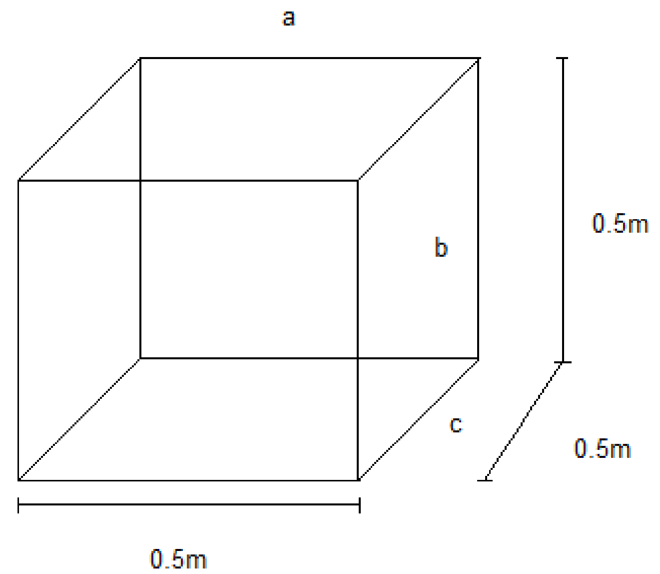
Solar Oven Design

Solar ovens are box-like structures that concentrate natural sunlight using reflectors to heat water. Solar cookers are a useful alternative to carbon fuel use, and its effects on deforestation and climate change. The ethos behind the design of the solar oven is driven by the compromise between economics and efficiency. Thus, to make the design of the product sustainable and applicable for developing nations we must employ Ockham's razor:

'Entities should not be multiplied unnecessarily' (Encyclopædia Britannica 2015)

A truncated pyramid design has been chosen because it minimises the surface area for thermal energy to dissipate, whilst widening the aperture of the glass window making a larger solar interception area. Reducing the net heat loss and increasing efficiency (see Figures below). The solar cooker will have a relatively low height reducing heat loss rising through conduction. The unit will have reflectors to channel the solar energy towards the apex of the truncated pyramid along its zenith angle. As the unit was tested in controlled ambient conditions, the wind load is no object to stability consequently; the reflectors will be made large to channel as much radiant energy as possible. The design of the solar cooker can be found in the scheme below.

Cubic Frame



$$V_{cube} = \Pi a \times b \times c$$

a = 0.5m

b =0.5 m

c = 0.5m

$$V_{cube} = 0.5 \times 0.5 \times 0.5$$

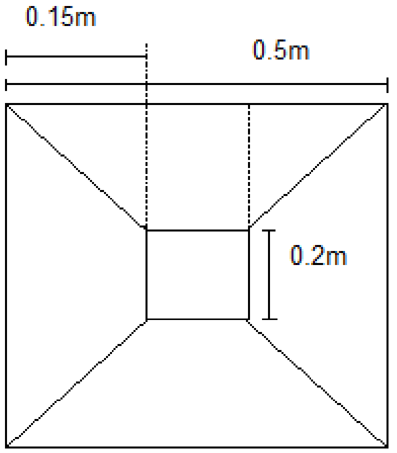
$$V_{cube} = 0.125m^3$$

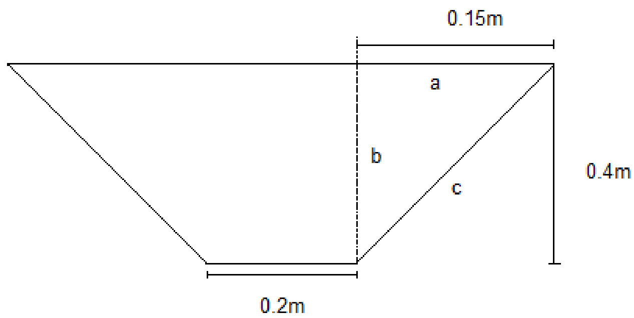
m = meters

Volume of a cube

Truncated pyramid Bird's Eye View

Volume of a Truncated Pyramid





Where h = height of pyramid (0.4m)

a = top width of pyramid (0.2m)

b = bottom width of pyramid (0.5m)

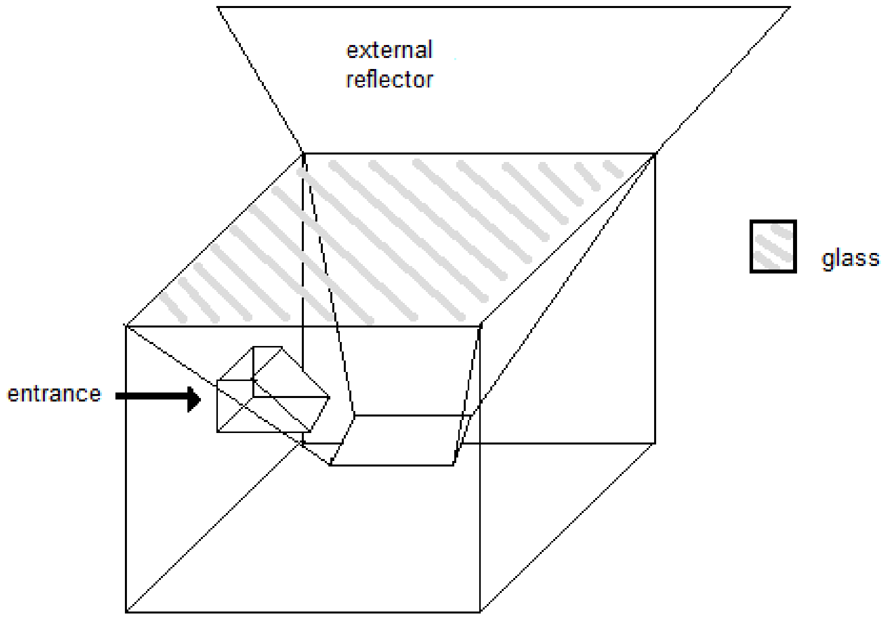
$$v = \frac{1}{3} h(a^2 + a \times b + b^2)$$

$$v = \frac{1}{3} \times 0.4 \times (0.2^2 + 0.2 \times 0.5 + 0.5^2)$$

Inter volumetric space between cube and pyramid = $v_{cube} - v_{pyram}$

$$v_{inter} = 0.25m^3$$

Full Design



Choice of Materials for Unit

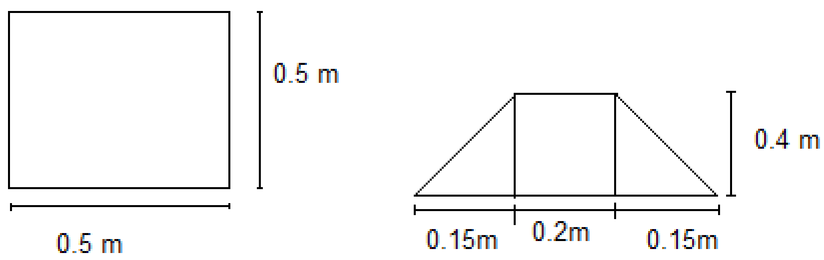
The materials used should be cost-effective but also available in developing nations and hence replaceable, non-toxic and economically viable. They should be easy to repair and maintain. This is because the persons who would be the recipients of the unit would typically have low per capita income and less facilities and infrastructure than developed nations. One of the contradictions of solar ovens is that the people designed to help cannot afford them. I have attempted to overcome this, once more by applying Ockham's Razor.

Equipment list

- Wood panel 2.6m^2 jigsaw, wood glue, door knobs
- 6 non-flush hinges, power drill, glass, wood and glass sealant
- Wood screws, baking foil, insulation, hand saw, pan

Mass of water to be used in the Solar Oven

In the paper *Testing and Reporting Solar Cooker Performance* by the *American Society for Agricultural Engineers*, based on the test standards set at the *Third World Conference on Solar Cooking* it states in section 6.1 Loading, that: "Cookers shall have 7,000 grams potable water per square meter intercept area distributed evenly between the cooking vessels supplied with the cooker." (ASAE, 2003, p. 3). This will serve as the basis for calculations of the mass of water required in testing the unit. The diagram below illustrates the intercept area dimensions of the unit and of an internal reflector.



Area of square intercept	=	0.5m x 0.5m = 0.25m^2
Area of internal reflector	=	(area of right angle triangle) x 2 + Area of rectangle
Area of Right angle triangle	=	0.5 x (length x width) = 0.03 m^2
Multiplied by 2	=	0.06 m^2
Area of rectangle	=	0.20 x 0.40 = 0.08 m^2
Reflector area	=	0.14m^2

Intercept area = square intercept area – internal reflector area

Intercept area	=	0.11m^2

Calculation of Mass of Water

Mass of water	=	0.77 kg/m^2

The area of the internal reflector and square intercept has been taken into account because the standardised method is based on the use of a square box cooker without an internal reflector. The exact definition in the research literature of the intercept area is "The sum of the [external] reflector and aperture areas projected onto the plane perpendicular to direct beam radiation" (ASAE, 2003, p. 2). However, in the experiment the parameter being varied is that external reflector angle, which consequently changes the area of the intercept area meaning that the mass of water would have to vary with each replicate. This would make the results of each replicate incompatible with each other when trying to analyse them, as the load of water would change for each one. So instead of taking into account the external reflector, the internal reflector, which is stationary has been considered instead. However, the internal reflector reduces intercept area so instead of summing the two values of the square aperture and internal reflector have been deducted in calculating the mass of water required.

Unit Assembly Method

The wood for the exterior cubic frame and truncated pyramid was purchased based on the design plan area, which was 1.5 m^2. The wood intended is an area of 2.6 m^2 allowing for errors in the woods cutting if needed. Five squares of dimension 0.5X0.5 m^2 were cut for the cubic frame; the dimensions were pre-marked out on the wood surface and cut with a jigsaw. Followed by 4 truncated triangles to the specification shown in the design and a 0.20X0.20 cm square for the truncated pyramid top, all cut with a jigsaw and shaved to specification if cutting was inaccurate. Following the cutting four small non-flush hinges and wood screws were used to construct the truncated pyramid, hinging together the four truncated triangles cut to their base. Their sides were cut at a 45° angle so as to ensure they form a square at their top when raised together. After this, the five panels of the cubic frame were screwed together using blocks joining two panels together, a picture showing the blocks in the unit is shown in Figure 2.

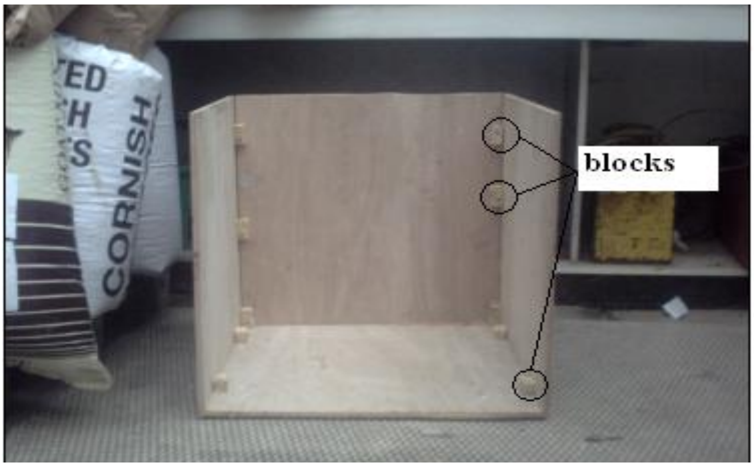


Figure 2. Joining blocks linking wood panels in the solar cooker

On the last panel to be assembled in the cubic frame, a door was made for an entry hatch to introduce the pan of water, which was boiled. The size of the hatch is determined from the width and height of the pan, making it possible to be taken in and out with ease but not so large as to create unnecessary heat loss in the unit. After all the five panels in the cubic frame were assembled, they were sealed using a caulk sealant to reduce heat loss in the unit. The door in the truncated pyramid to introduce the pan was cut next. Once the door was cut and assembled the truncated pyramid was fitted inside the cube frame as shown in Figure 3.

Figure 3. Truncated pyramid inserted into main solar oven cube

The edges of the truncated pyramid were cut and trimmed to the correct size to fit inside the cube frame using a handsaw and plane for minor adjustments, leaving a gap at the top for the pane of glass. The four faces of the truncated pyramid were coated in PVA glue and baking foil attached to them acting as a reflective surface concentrating the solar radiation onto the central cooking pot. The insulation was tightly packed into the 0.25m^3 inter-space gap between the pyramid and the cubic frame. This was to increase the heat retention of the unit and secure the position of the inverted truncated pyramid placed upon the insulation. With this in place the glass was sized, cut and fitted into the top of the unit and sealed in place with glass sealant to reduce heat loss through the top of unit. Next, the external reflectors were made from cardboard, PVA glue and more baking foil in the same manner as the internal reflectors.

External Reflector Design

From the research literature on the international conventions for solar cookers, found in Funk (2000) there are no specifications for the design of the external reflectors as such their dimensions were based on a design made by myself. The design of the external reflectors for the unit will mirror the proportions of the internal reflectors in terms of height and smallest width. The hypotenuse and largest width will vary between replicates as reflector angle varies (Figure 4).

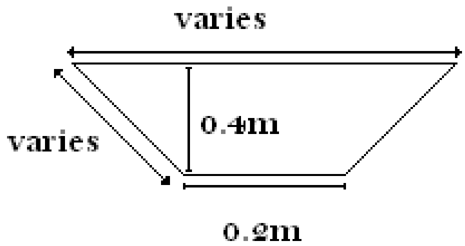


Figure 4. The dimensions of an individual truncated pyramid

The external reflectors were made from cardboard and with baking foil glued to them to create a reflective surface. Each replicate (i.e. per reflector angle) had to have a different set of cardboards cut as the angle varies. The external reflector will be the sum of four individual truncated triangles that will be attached to together with duct tape to keep the specific angle required (φ) in place.

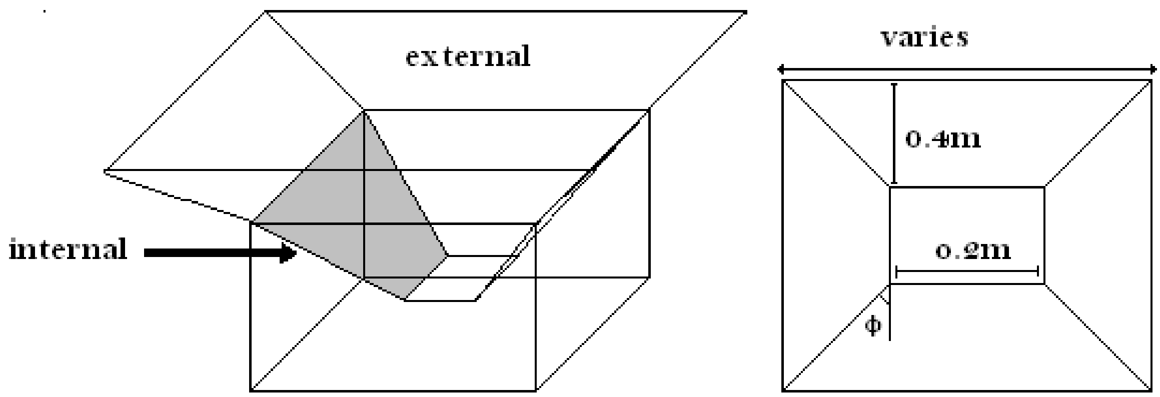


Figure 5. Schematic of external reflector dimensions and angles mounted on the unit

The reflectors will also be held in place with string attached to alternate sides of the cardboard frame, which can be adjusted if needed to alter the angles (Figure 5). The string will cause small amounts of shading from the light source in the experiment but because the string is so thin, its effects will be minimal.

Project Limitations to *en mass* Dissemination and Use

There is an inherent lack of versatility in the design that I have produced because it can only cook for a small number of people. Communal cooking and larger families are more common in developing nations. So building a more culturally relevant design is required. The design is only suitable for slow cooking due to its thermodynamic inefficiencies and cannot compete with the convenience of fast burning primary fuels. It can only be used efficiently in direct sunlight, and requires continual realignment with the sun's declination and ascension in the sky. The reflectors on the unit are easily scratched which reduces the reflectivity and effectiveness. The mass and dimensions of the design may be a deterrent to its use as it is not easily mobile. There is an additional economic problem of replacing the reflectors and other materials that break, which needs to be considered. This comes with the limitation that in remote places the materials may not be able to be obtained; even if this is possible, there may not be a person available with the skills or knowledge to repair the unit. These additional costs could drive up the price of the unit to comparable levels of purchasing fossil fuels making the whole project redundant. Culturally there has been some documented resistance to solar cookers, as they may be at odds with religious or cultural beliefs, and also involve a change from traditional methods of cooking by the people using the unit (Coyle, 2006). There is an onus to produce ovens that are socially acceptable; this in itself is troublesome due to variations in cultural preferences.

Data Analysis - Exergy and Energy

I have tried to make my data analysis transparent so that it can be compared with other projects. Consequently, I have attempted to use analysis methods in concordance with the standardised testing procedures set out in the paper by *Ashok Kundapur* et al of the *International Alternate Energy Trust*, and Kalashree in his paper, *proposal for new world standard for testing solar cookers,* see Kundapur and Sudhir (2009) which contains the standardised nomenclature, analysis and methodology for evaluating solar oven efficiency. Which in turn is a ratification of the paper *Evaluating the international standard procedure for testing solar cookers and reporting performance* by Funk (2000) which sets out the ground work for the need for an international standardization of the methodologies of solar oven efficiency analysis. The data analysis methodology includes both exergy and energy analysis, this is because measuring these quantities gives results that are thermodynamically and economically rational, meaningful and practical (Öztürk, Öztekin & Başçetinçelik, 2004, p. 1). In addition, it gives an insight into the quality of the thermal energy produced, whilst also fitting the ethos of this paper: economic viability, and thermal efficiency.

Experimental conditions in accordance with Test Standards Committee at the *Third World Conference on Solar Cooking* (Coimbatore, Tamil Nadu, India, 9 January 1997, see ASAE (1997))

Number of observations

For the purposes of plotting a linear regression, there needs to be an adequate number of observations, also to allow the unit's performance at difference levels to be calculated. In the ASAE paper S580 *Testing and Reporting Solar Cooker*

Performance it stipulates that there is to be a minimum of 30 observations (ASAE, 2003). The graphics here are based on 105 observations and for ease of calculations so will the measurements of the solar oven be.

Ambient Temperature

The ambient temperature in which the oven is tested needs to be below 35°C and not fluctuate over a range of 15°C (Funk, 2000, p. 2).

Insolation

The insolation levels required to validate the data obtained are to be between the range of 450 to 1100 w/m^2 and should not vary more than 100 w/m^2 in a 10 minute interval (Funk, 2000). The insolation will be measured with a pyranometer.

Temperature Measurement

The measurement of the water load and ambient temperature is to be conducted with a LOGIT thermocouple (Funk, 2000).

Data analysis methodology Cooking Power

This value is an indicator of the level of performance of the cooker, but is not an absolute guarantee (Funk, 2000). It corresponds to the ability of the oven to raise the temperature of a given mass of water within a 10 minute time interval (Funk 2000). The equation below is used to calculate the Cooking Power in Watts, once more taken from ASAE (2003):

$$P_i = \frac{(T_2 - T_1)MC_v}{600}$$

Nomenclature

Where

P_i - cooking power in Watts

T_2 - Final water temperature °c

T_1 - Initial water temperature °c

M - Mass of water in Kg

Standardised Cooking Power

This parameter is used as a method of standardisation for the sake of comparing data of other tests conducted in different latitudes and times (ibid). The values of the insolation is normalised by multiplying the cooking power (P_i) by 700 w/m^2 and dividing by the average insolation over the given interval of 600 seconds (10 minutes), hence it represents the cooking power per second (Kundapur & Sudhir, 2009).

$P_s = P_i\,(700 / I_i)$ (ASAE, 2003)

Nomenclature

P_s - Standardized Cooking Power in Watts

P_i - Cooking Power over the 600 second interval in watts

I_i - Average Insolation value over the 600 seconds interval in watts

Energy Input of the Cooker

This figure is simply a product of the average solar insolation and the aperture area of the solar cooker. Moreover, it is used in calculating the efficiency of the solar oven $E_i = I_{aw} A_{sc}$ (Kundapur & Sudhir, 2009)

Efficiency

The efficiency calculation is a function of the oven's power in terms of the energy input into the oven. It is a dimensionless measurement expressed in percentage the equation (Kundapur & Sudhir, 2009), where:

$$\eta = \frac{m_w C_{pw}(T_2 - T_1)}{A_{sc}\int_0^t I_{aw}\Delta t}$$

Nomenclature

η - Efficiency in %

m_w - Mass of water in Kg

C_{pw} - Specific heat capacity of water (4186 J/[kg·K])

T_2 - Final water temperature in °c

T_1 -Initial water temperature in °c

A_{sc} - Aperture area of the solar cooker in m^2

$\int_0^t I_{aw}$ - Integral of Average insolation over time-period

Δt - Difference in temperature ambient and water temperature in °c

t- Time between each interval

Exergy

The concept of exergy is roughly equated with the term *available work* (Coatanéa, Kuuva, Makkonen, Saarelainen & Castillòn-Solano, 2006, p. 83) it represents quantitatively the useful energy or the ability to do work-the work content of a great variety of streams (mass, heat, work) that flow through the system (Dincer & Cengel, 2001, p. 130). The term is difficult to define because it is dependent upon the environment in which it is used (Demirel, 2002, p. 111). It suffices to say it is a method for analysing the efficiency of energy resources use in a system. The form of the equations used to determine exergy are based on using the exergy factor denoted here as r. The exergy factor is used when determining exergy content due to the transfer of thermal energy between two thermal reservoirs (Kundapur & Sudhir, 2009). It is effectively the ratio between the exergy and enthalpy of the resource. See below:

$$r = \frac{m_w C_{pw}\left[\left(T_{w1} + \Delta T_w - T_{w1}\right) - T_0 \ln \frac{T_{w1} + \Delta T_w}{T_{w1}}\right]}{m_w C_{pw}\left(T_{w1} + \Delta T_w - T_{w1}\right)}$$

Simplifying to:

$$r = 1 - \frac{T_o}{\Delta T_w}\ln\left(1 + \frac{\Delta T_w}{T_{w1}}\right)$$

(Kundapur & Sudhir, 2009)

Nomenclature

r - Exergy Factor dimensionless coefficient

T_0 - Ambient temperature in °c

ΔT_w - Change in water temperature over 600 second time interval in °c

T_{w1} - Initial water temperature of 600 seconds interval in °c

Effectiveness

The effectiveness of the cooker is in this case meant to illustrate the ability of the unit to convert the solar insolation entering it into thermal energy (Kundapur & Sudhir, 2009). This value is expressed as a percentage, and as before with the efficiency value it is normalised to a standard insolation value to give it more meaningful application.

$$\varepsilon = \left[\frac{I_{aw} - I_r}{I_0}\right] \text{(ibid)}$$

Where

$$I_r = rI_{aw}$$

Nomenclature

ε - Effectiveness in Percent

I_{aw} -Average Insolation value in w/m^2

I_0 - Average theoretical insolation 700 w/m^2

Total Costing of the Solar Oven

The costs for all the raw materials of the solar were documented. These values have been summed to give a total cost for building the unit. For example, the total cost of wood for the unit is £ 23.21including taxes. It was estimated that the area of wood used divided by the area wood purchased, that 80 % of the original piece costing £23.21 had been utilised. Multiplying £23.21 by 0.80% gives a value of £ 18.57, the same approach was taken to the other materials, all results can be found in the table below.

Table 1
Total cost of the unit's construction

Material	Base Cost £	Final Cost £
Wood	23.21	18.57
Screws	1	1
Handles	1.25	1.25
Foil	1	1
Glue	2.2	2.2
caulk	1	1
Glass	25	6.25
TOTAL £		£31.27

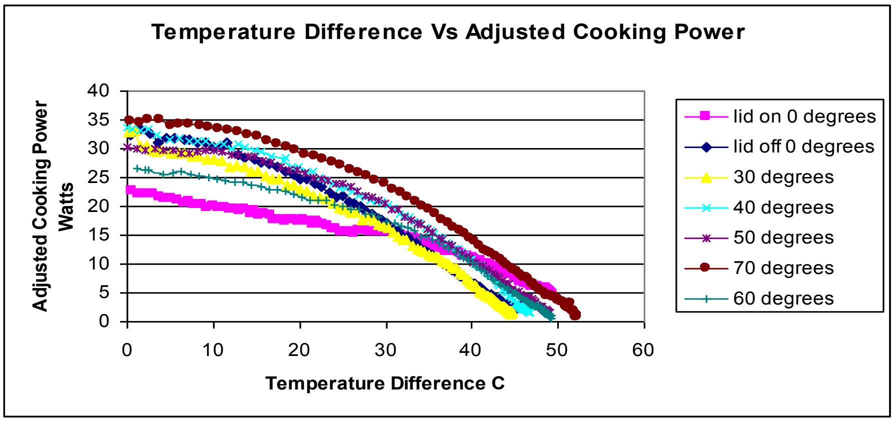
The total cost of the unit is £31.27, in terms of the wages of a person in a developing country this a still a very large sum of money. However, solar ovens tend to be purchased and distributed by NGO's more often than by individuals. The cost of the oven is evaluated by comparing it to other solar ovens available on the market, with due relevance to their size. A table of these results is found below

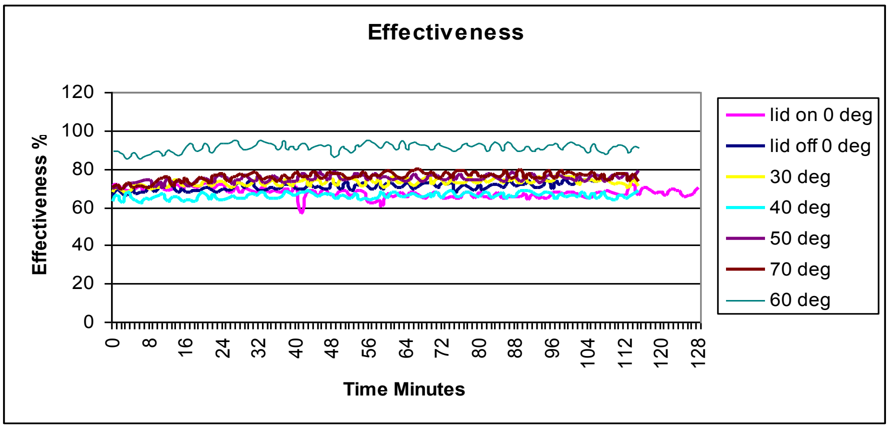
Table 2
Comparison of prices of various solar ovens available

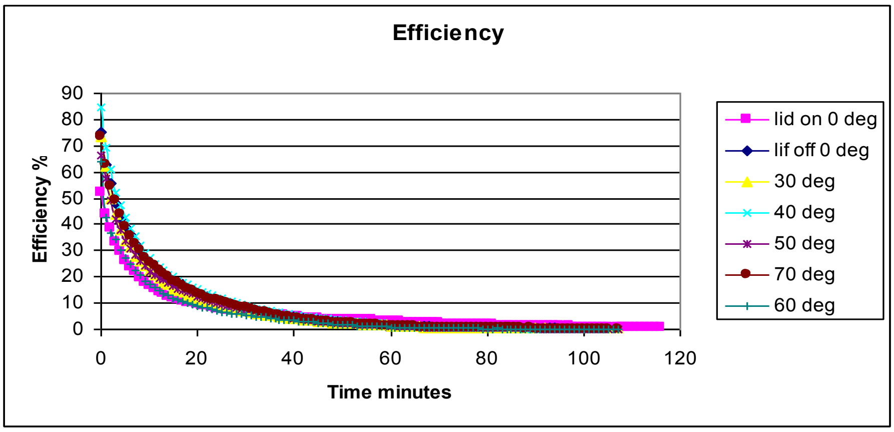
Model	Price $	Price £	size compared to Unit (approx)
R4S3LDB3	24.90	17.14	smaller
SR-GS4702	37.13	25.53	smaller
My Solar oven	**45.53**	**31.27**	**50 x 50 x 50 cm**
WW63711M00	52.95	36.45	25 x 64 x 64 cm
Solar Furnace	89.95	61.92	30 cm diameter
Hot Pot Simple Solar Cooker	99.00	68.14	40 x 40 x 27 cm
Lehmans deluxe sun oven	249.00	171.39	same size
SKU# SunOven001	254.95	175.49	60 x 60 x 38 cm
Global Sun Oven	255.00	175.52	48 X 30 CM

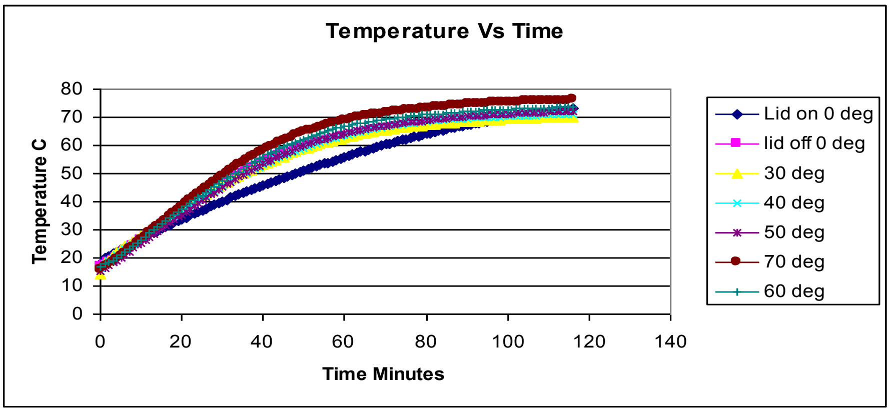
All the prices and data of the solar ovens models was taken from a Google product price comparison search for *solar oven*, see Google (2017). All prices are converted to US dollars, as the USA is the main manufacturer of ovens. Dimension are given where found in the literature of the different solar ovens, otherwise size is estimated compared to the solar oven I have designed. To give a reference point, the size of my solar oven unit is 50x50x50 cm^3. Table 2 has been ordered in terms of price from lowest to highest. Given the prices and sizes of the other models available. I feel that the solar oven that I have designed remains economically competitive.

Results and Discussion









In the ASAE paper *Testing and Reporting Solar Cooker Performance* it outlines a parameter of *Single Measure of Performance* based on the standardised cooking power rating of each test (ASAE, 2003). The value of the standardised cooking power is computed at a temperature difference of 50°C. Using a linear regression method on the data of the power curve shown below, an excel spreadsheet can produce an equation for each set of data.

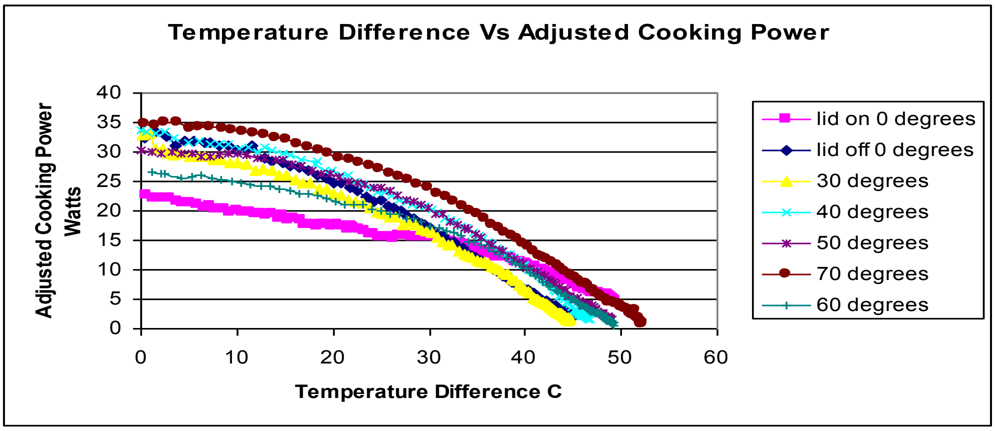


Figure 5. Temperature difference vs adjusted cooking power

Because the equation is based on linear regression, it has the form y =mx +c, for example the equation generated for a 50° angle reflector is $y = -0.6881x + 37.164$

Where y is the adjusted as power in Watts, with this equation we use a value of x of 50°c to generate a value for the single measure of performance for each reflector angle. Another parameter that was generated for each replicate was the coefficient of determination r^2 .The coefficient of determination is described as the total variation in *n* observed values of the dependent variable that is explained by the simple linear regression model. The higher the value of r^2, the better fit the model (Pennsylvania State University, 2017). To validate the results taken the value of r^2 must be above 0.75 (ASAE, 2003). The value of r^2 is calculated by the excel spreadsheet based on the linear regression line. The table below is a summary of these parameters for the different reflector angles.

Table 3
The single measure of performance and r^2 values of each replicate

Angle of Reflector	Single Measure of Performance Watts	Coefficient of determination r^2
0 (without lid)	6.453	0.946
0 (with lid)	-0.552	0.971
30	-0.698	0.971
40	1.39	0.949
50	2.759	0.946
60	2.238	0.948
70	4.676	0.961

The negative values of the single measure of performance are a result of their values being based on the linear regression equation not the exact equation of the data obtained. The exact equation in some cases not having a completely linear relationship whereas the regression method does, causing a potential to obtain negative results. The measure of performance is based up standardised cooking power values and as such represents the cooking power per second (Kundapur & Sudhir, 2009). The table shows that as the reflector angle increases the so does the performance of the solar oven. In addition, it demonstrates that all values of the coefficient of determination are about 0.95, the lowest being 0.9466. The highest value of the single measure of performance occurred at a 70-degree reflector angle.

Effectiveness

This single measure of performance is not the only parameter for evaluating the solar cooker's performance. For example, there is also a measure of effectiveness, which is based upon the ability of the unit to convert the solar insolation entering it into thermal energy (Kundapur & Sudhir, 2009). The Figure 6 details the effectiveness of each reflector angle throughout the period of the experiment.

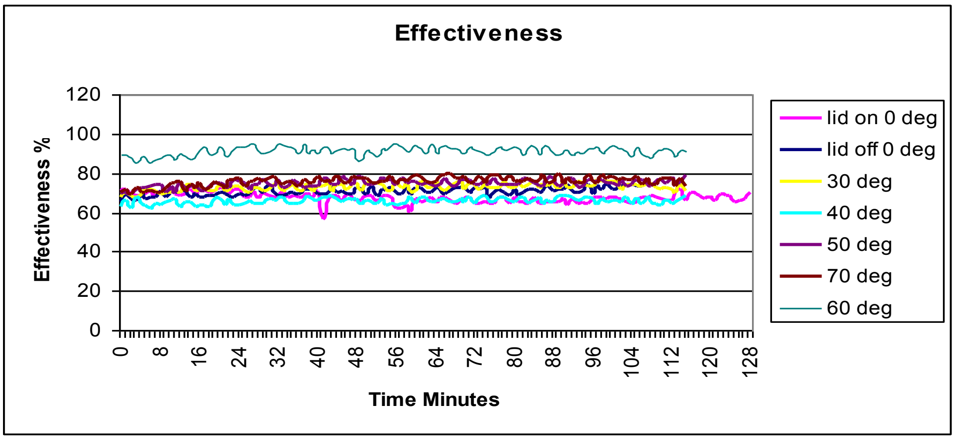


Figure 6. The effectiveness off each reflector angle against tim

The graph illustrates the most effective reflector angle occurs at 60 degrees, the other reflector angles have a similar level of effectiveness. The best behind 60 degrees is a 70-degree angle. The effectiveness of each replicate oscillates throughout the experiment at 60 degrees it oscillates between 85 % and 95 %, the equation for the measuring the effectiveness is:

$$\varepsilon = \left[\frac{I_{aw} - I_r}{I_0} \right]$$

Where

$$I_r = rI_{aw}$$

The letter I standing for insolation in various forms, as such it can be seen that the effectiveness is dependant upon the insolation levels. As these insolation levels oscillate, it causes the effectiveness to oscillate as well.

Efficiency

Another measure of the solar oven's performance is its efficiency. The efficiency is defined in this context as a function of the energy input to the oven in terms of the oven aperture area and insolation levels. It is a dimensionless measurement expressed in percent. The Figure 7 shows the efficiency of the different reflector angles tested.

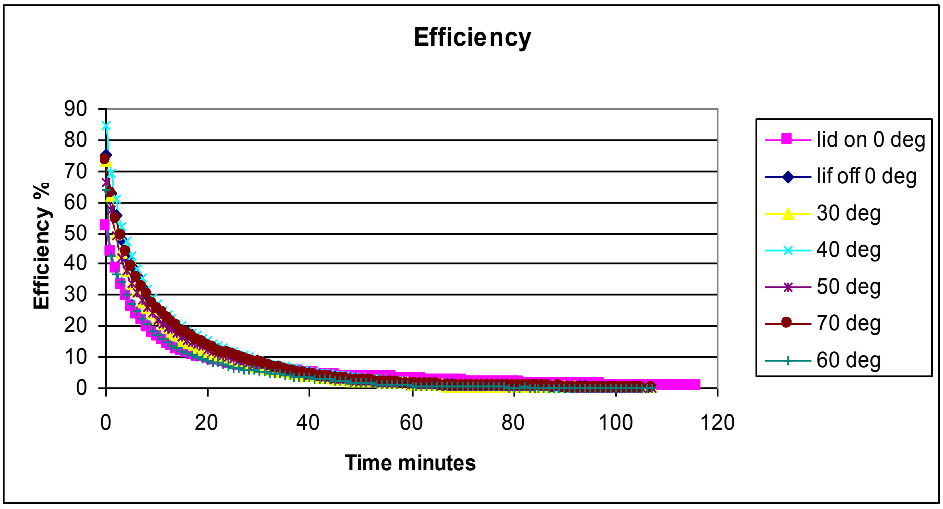


Figure 7. Time Vs Efficiency at Different Reflector Angles

As the time in minutes progresses the efficiency decreases at an exponential rate, having initially very high levels efficiencies but declining rapidly. All the replicates by approximately 30 minutes into the experiment had 10% efficiency or less. The angle that is most efficient varies at different time points in the experiment. For the first 40 minutes, the 40 degree angle reflector is most efficient, followed closely by the 70 degree angle reflector. After approximately 50 minutes, the baseline replicate conducted without a reflector and the saucepan lid on became the most efficient. Indicating that the lidded pot retains efficiency better than the replicates without a lid as the temperature increases with time.

Temperature generated

Purely in terms of the kinetic energy of the water, the temperature profile of each replicates gives an indication of its performance. The graph below shows the temperature variation with time of the different replicates.

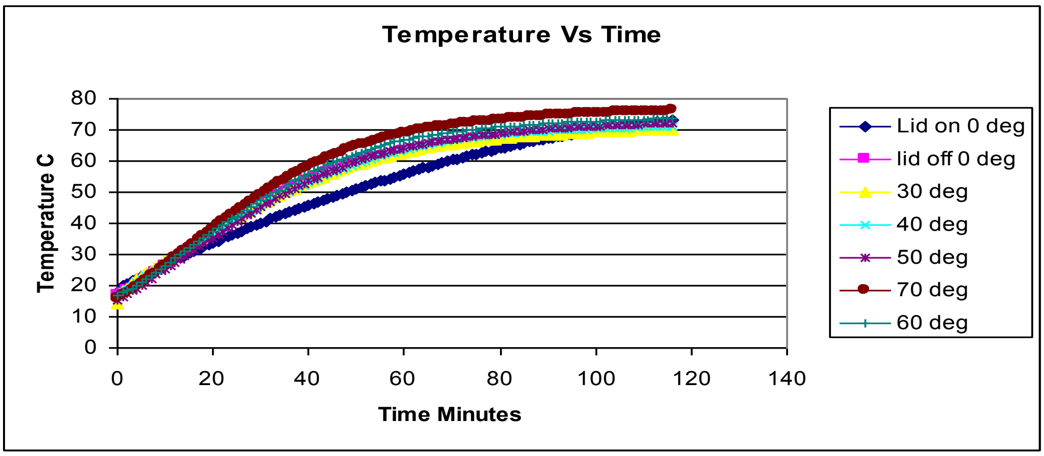


*Figure 8***.** The Temperature Variation with Time of the Different Reflector Angles

The 70 degree reflector angle gave the highest temperature of all the replicates, followed by the 60 degree reflector angle. The replicate conducted with the pan lid kept on showed linear curve than the replicate with the lid off the pan. Its characteristics are linear, it achieved the higher temperatures slower, and its final temperature in comparison is higher than the other replicates except 70 degrees and equal to the 60-degree replicate. With are reflector angle of 70 degrees, by 120 minutes, the solar oven was able to heat the pan of water to 78 degrees Celsius.

Corrigenda for Adjusting Transmittance of Halogen Light Source Compared to Sun light

I used halogen lights to simulate sunlight in this experiment. The spectra of natural and artificial halogen light and their characteristics are not uniform. To take this into account of the results analysed they shall be contrasted to illustrate the differences between the sources. This is also important to the application of the unit, as it was designed to be used in a real life, natural light situation not under artificial sources. The temperature at which a black body radiator that has been heated corresponds to the light colour of a source is the colour temperature of that source (Colsmann et al., 2011). This quantity can be used to determine the level of irradiance of a light source. The table below shows the colour temperature of different light sources, both artificial and natural in Kelvin.

Table 4

The value of colour temperature in Kelvin of different light sources, all data sourced and adapted from Davidson (2015)

Natural Light Source	**Colour Temperature (K) kelvins**	**Artificial Light Source**	**Colour Temperature (K) Kelvins**
Sky Light	12000 -18000	500 Watt Tungsten lamp	3200
Overcast Sky light	7000	200 Watt Lamp	2980
Midday Sun Summer	5000-7000	100 Watt lamp	2900
Midday Sun Winter	5500-6000	75 Watt Lamp	2820
Average Midday light	5400	40 Watt Lamp	2650
Northern Hemisphere		Gas Light	2000 - 2000
Sunrise, Sunset	3000	Candle Light	2900

We know that as the temperature colour (T_F) increases at a given wavelength the relative intensity of the light source increases.(Ibid)

As halogen, lamps and other forms of artificial lighting have lower temperature values. They consequently will have less intensity than if the unit was tested in direct sunlight. Sunlight's wavelength falls within the visible light spectrum of 400-760 nm, were as the wavelength of halogen lamps is further into the Infrared spectrum.

As shown by the emission spectrum of varioces light sources (Roberts 2012) is an issue that needs to be considered as, the levels of transmittance of light (and energy) through the glass at the top of the oven alters with the wavelength of the light.

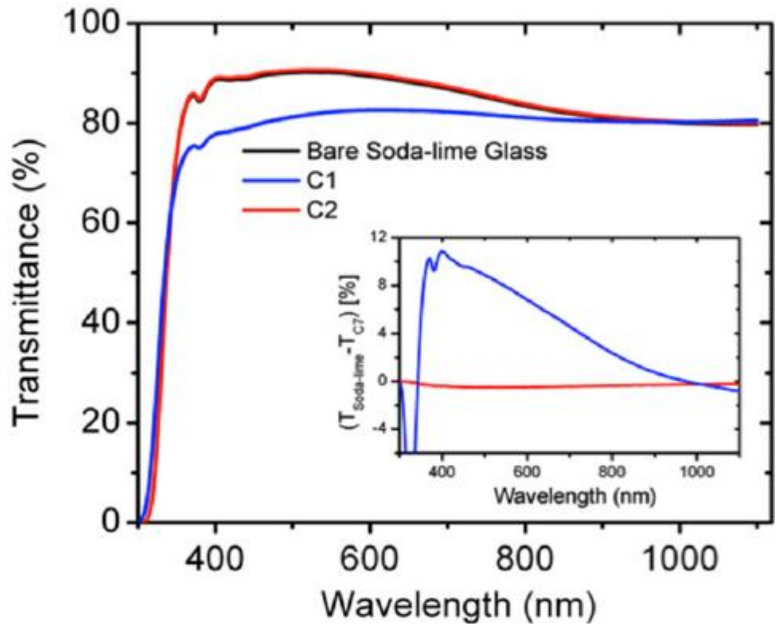


Figure 9. The transmittance of Soda-lime glass at specific wave lengths, from Schaeffer et al. (2015)

The plot of Soda-lime glass wavelength against transmission illustrates that higher levels of transmission into the solar oven occur at the lower levels of the visible light spectrum, i.e. between approximately 450 nm and 650 nm. The level of transmission decreases as the wavelength progresses into the infrared wavelength of the spectrum. From this, it can be concluded that the performance of the solar oven using a halogen lamp in place of natural direct sun light will be slightly lower.

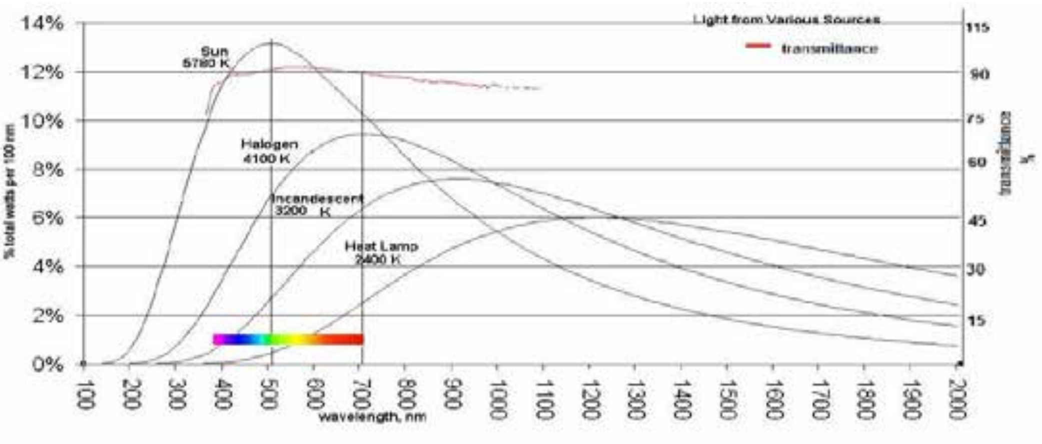


Figure 10. Transpose of graphs of the spectral data and transmittance of different forms light source at a given wavelengths.

Above the figures have been approximately transposed to illustrate that although there will be a reduction in transmittance to the solar cooker using halogen light sources it is only a few percent and as such will not cause major issues to apply the results of the research to real life applications.

Conclusion

I feel that the solar oven that I have designed is economical given the prices and sizes of the other models available to be purchased. Whilst still being durable enough to last for a long time, as such I feel that it meets the requirements I had set initially for the project, the main drawback being its size and weight making it less portable. The reflector angle that is most effective at increasing the efficiency of the solar oven is partly dependant on what definition of efficiency is applied. The reflector angle with the greatest ability to convert the solar insolation into thermal energy (termed effectiveness).

It is not the same as the reflector and angle that caused the solar oven to retain the thermal energy over the given aperture area and time period of 600 seconds (termed efficiency here). The most effective reflector angle i.e. the reflector angle with the greatest ability to convert the solar insolation into thermal energy is the 60 degrees reflector. It would seem that at this angle the greatest amount of solar insolation is concentrated on the cooking pot itself. Causing the greatest conversion of insolation to thermal energy, the angles below and above 60 degrees causes the insolation to be focused above or below the pot, making them less effective.

The most efficient reflector angle occurs at 40 degrees followed closely by 70 degrees, but this is only true for the first 40 minutes of cooking time. After this point, the replicates conducted with the lid on the pot and no reflector becomes the most efficient. Similar results are obtained for the adjusted power-rating curve of the different reflector angles, 70 degrees having the highest power rating followed by 40 degrees. Also as with the efficiency ratings the replicate conducted with the lid on the pot and no reflector started with a lower power rating than the other replicates but towards the end of the experiment it exceed them. The temperature profile of the all the replicates shows that the 70 degree reflector angle produces the highest temperature consistently. After 18 minutes into the experiment, the 70 degree reflector produces the highest temperature of all replicates until the end of the experiment, followed closely by the 60 degrees reflector angle. Over the series of different methods for evaluating the best reflector and angle, it would seem that a 70 degree angle is consistently highest in most of the tests. Ideally, then, if cost were less of an obstacle, a simple motor could be fitter that adjusted the angle of the reflectors at different periods to maximise cooking power or efficiency. However, this is not within the remit of the experiment as it stands.

Excluding economics and durability, the most important characteristic of the oven for its use in developing nations would be achieving the highest temperature in the quickest time, reducing the waiting time to cook a meal or pasteurise water. However, this may vary on the preference of the individual and culture and circumstances involved. Considering this, I feel a reflector angle of 70 degrees is in general the best option for the solar oven of box design as it is one of the most consistently high-ranking angles in each performance evaluation test. The analysis for adjusting the results for natural light showed that the difference between the results would have been minimal, in the region of a few percent. As such I feel that my results are comparable to the use of the solar oven in natural sun light and do not need to be adjusted. If more time and resources were available additional tests that could be carried out, include running repeat tests of each reflector angle to validate the results obtained initially, as well as increasing the number of angles tested. The unit could be tested outdoors to demonstrate and contrast the differences between the controlled conditions and the actual application of the unit. It could also be tested in different seasons or on a monthly basis to demonstrate how the performance varies throughout the year.

In conclusion, I have achieved my objectives of designing a solar oven that is a compromise between economics and efficiency enough to be disseminated with moderate success, and also finding the optimum reflector angle for it, which is 70 degrees.

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