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Solar Cooker Earth Analog and Comparison of Design efficacy

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Introduction

Earth receives a continuous flux of solar energy. The planet absorbs this energy, gains heat, and radiates an equal amount of energy back into space in a constant maintenance of radiative equilibrium (Pierrehumbert 2008 p13). Greenhouse gases in the earth's atmosphere impair the release of some of this re-radiated infrared energy. These gases, C02, water vapor, methane, ozone, nitrous oxide and CFCs, reflect infrared radiation emitted from earth's surface in multiple directions including back into the planet's system (Varekamp notes 2008). This back radiation drives a subsequent increase in planetary warming required to meet the energy output necessary for maintaining radiative equilibrium.

Earth's climate has fluctuated significantly over the course of geologic time. An accumulation of recent evidence from the geologic record suggests that these "hothouse" and "cold-house" environments and the differing ecosystems they sustain, result ultimately from changes in the greenhouse gas composition of the atmosphere. Among the "long lived" greenhouse gases, C02 plays a major role in determining the blocking power or radiative forcing of Earth's atmosphere. Integrally linked to biotic systems, the cycle of carbon into and out of the atmosphere is continuously influenced by and impacting life (Varekamp notes 2008).

Since the industrial revolution, human mining and burning of the (originally solar) energy stored in fossil fuels, has contributed to relatively rapid increases in atmospheric C02. In 2005, anthropogenic C02 emissions exceeded eight gigatons and yearly emissions continue to rise. Representing a 1.3% increase over the total amount of pre-industrial atmospheric carbon, the 2005 emissions alone indicate a large-scale alteration of the atmosphere, forcing major changes in earth's climate (Pierrehumbert 2008 p66).

The anthropogenic release of C02 and the climate change it catalyzes present a significant problem for the survival of the human species. Combined with present day social structures that facilitate drastic inequalities in resource distribution across the world's population, climate change is already exacerbating a global problem of interconnected socio-environmental injustice. Largely resultant from the disproportionate fossil fuel combustion of the world's richest nations, climate change is likely to contribute to sea level rise, drought, and resource scarcity most immediately felt by residents of some of the poorest island nations (Brodine, 2007).

Our research on the feasibility, efficiency, and energetic impact of solar cookers explores the interconnections between scientific principals, grassroots action, and socio-environmental change. Fueled by tapping in to Earth's system of energy collection and dispersal, the cooker itself becomes a microcosm of energy transfer translatable to an understanding of broader climatic function. Exploring the concepts of reflection, transmission, absorption, convection, conduction, radiation, and insulation we will outline the mechanisms of solar cooking and their relationship to climate.

In harnessing solar energy for heating food and water, solar cookers take a small step in addressing many environmental inequities exacerbated by climate change and the power structures that facilitate resource abuse. By their nature, solar cookers diminish C02 release by freeing the process of cooking from that of fossil fuel combustion. Use of solar ovens can facilitate pasteurization of contaminated water responsible for an estimated 80% of preventable illness in developing nations (solarcooker.org). A release from dependence on cooking fuels can save (majority) women around the world major resources, time, and energy expended in gathering cooking materials (Nichols 1993). Free of smoke, solar cooking eliminates problems with lung and eye disease resulting from everyday proximity to inefficient stoves. The slow cooking required by solar heating retains important nutrients and allows for cooking of nutrient rich foods traditionally limited to fuel-based preparation (solarcooker.org). In countries considered at the top of the "industrial food-chain," such as the United States, building and using solar cookers might be an initial step in reducing a learned and debilitating culture of disconnected dependence on external resources; a beginning to facilitating the major social changes that a reduction in greenhouse gas emissions will necessitate (Pollan 2008).

Employing three distinct cooker designs, we conduct a comparative study of cooker efficiency, and observe the energy transfer inside each device in relation to its design. We will then look at the broader socio-environmental impacts of a widespread shift to cooking with solar energy.

The Physics of Solar Cooking

A genera design for solar cookers as outlined by Pejack (2003) and adopted in this paper features radiation from the sun reaching the space in which the cooker resides. Although degraded along its path to the food, this radiation is reflected off of a reflecting surface, which (due to its angle in relation to the angle of incoming rays) diverts the incoming rays towards the object being heated (food, water, etc). An absorptive (dark) surface accumulates heat energy which it transfers to food (convection). Heat continues to accumulate until heat loss equilibrates with heat gain and the internal cooker temperature reaches thermal equilibrium with the ambient air. This process simultaneously generates heat loss to the surrounding atmosphere (Pejack 2003).

In practice people design a cooker according to the resources available and intended use. In this project we built 3 cookers that fall within a range of input expenses, efficiency based on insulation (heat retention) and efficacy of solar concentration (wattage input). The models include variations of the box cooker oven and the parabolic reflector. Cooking can occur at 70 degrees C.

Solar Radiation and Cooker Illumination

Solar cookers heat food and liquid by receiving and concentrating radiation from the sun (Nichols 1993). The sun is a huge sphere 1.4 km in diameter and 150 million km from earth. It generates energy from the conversion of hydrogen to helium (fusion). Electromagnetic radiation from these reactions leaves the sun radially in all directions but the distance from the earth to the sun is so large that sun rays reaching earth are essentially parallel. The "solar constant" (S) , is the amount of radiation per unit area (w/m2), reaching the earth outside of the atmosphere (Pejack 2003). This is calculated by letting Q equal all of the energy given out by the luminous source (Sun) every second and making R the distance between the Sun and the surface of the receiving sphere (earth). S can then be calculated from the equation S = Q/4piR^2 (Nandwani 2000). Earth's solar constant is about 1353 w/m2. This "constant," fluctuates slightly as the earth moves towards and away from the sun (and R changes) at different points on its orbit. The flux received by an object on the earth surface, in this case a solar cooker, is lower than the solar constant due to absorption and scattering of radiation that occurs in the atmosphere, time of day, time of year, latitude and altitude of cooker locus, and weather (Pejack 2003). The average flux of solar energy hitting the planet's surface is about 240 w/m2 (Pierrehumbert 2008 p99).

Due to the interference of the atmosphere, solar energy hits a horizontal plane on earth's surface in both direct and diffuse form. The direct form is the parallel rays from the direction of the sun while the diffuse form is radiation scattered in many directions by matter and gasses in the atmosphere. Solar cookers are designed to maximize the energy from the direct or "beam" component of this radiation though they are minimally effected by the diffuse energy. On a sunny day only 5 - 15% of radiation reaching a horizontal surface would be in diffuse form, providing ideal conditions for concentrating solar energy. A cloudy day primarily selects for diffuse radiation which is less conducive to concentration with the reflectors on a cooker (Pejack 2003).

The first parameter affecting the function of a solar cooker is "insolation" or incidence radiation from the sun. Describing the radiation reaching a horizontal plane on earth's surface, this radiative parameter is independent of the reflective or transmissive properties of the surface it hits. The angle at which beam rays hit a horizontal surface varies with time of day and the season. The *altitude angle (theta)* which describes the angle between the horizontal surface and the incident ray, is zero at sunrise, growing towards a maximum (90*) at midday, and declining to zero again by sunset. The *zenith or incidence angle* describes the angle between the incidence ray and a vertical plain. The incidence angle and the altitude angle should always add to 90 degrees (Pejack 2003 see Fig. 1).

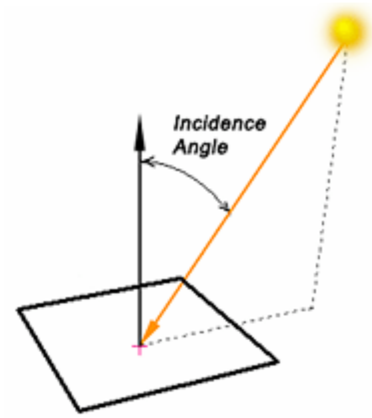


Fig 1 The incidence angle can be determined by arranging a line normal to the surface plain and creating an angle between the normal and a line reaching the position of the sun.

Energy reaching the solar cooker is maximized (energy density per unit area is highest) when the incident ray is hitting the reflective surface most directly (ie. when the incident angle is closest to zero or the altitude angle is closest to 90). This can be determined by the cosine law, where energy density per unit area is equal to the amount of radiant energy from the sun multiplied by the cosine of the incidence angle (Fig. 2). This property means that surfaces at different angles will receive differing amounts of solar energy at different times of day and year. This is because radiation reaching the reflective surface at altitudinal angles lower than 90 has to pass through a greater atmospheric distance to reach the cooker allowing for greater interference en route (Pejack 2003). In order to maximize the radiation entering the cooker it is important, therefore, to orient the reflective surfaces so that they contact the incoming beam radiation in such a way as to minimize the incidence angle and maximize the altitudinal angle.

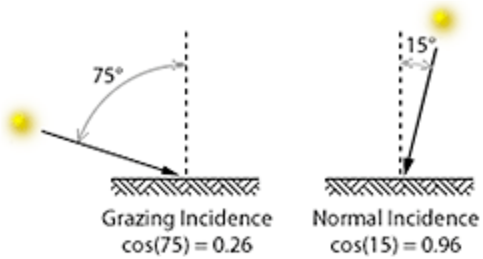


Fig 2. a changing incidence angle determines the energy per unit area reaching a horizontal surface. This can be calculated by multiplying the cosine of the incidence angle by the amount of solar radiation reaching the plain. If the incidence angle is 15 degrees approximately 96% of the radiated energy will hit the horizontal surface. If the Incidence angle is 75 degrees only approximately 26% of the incoming radiation will affect the surface.

Latitude and altitude of the cooker locus also affect the angle at which radiation hits the reflective surface. Latitudinal positions on earth range from -90 at the south pole, reach 0 at the equator and move towards +90 at the north pole. This range effects the altitudinal angle of the beam radiation hitting the cooker based on its latitudinal position. While a horizontal surface in the +/- 23 degree range can access altitudinal angles of 90 degrees at noon, surfaces outside this range can never access such direct radiation. At latitudes outside this equatorial zone, the positioning of the earth on its orbit also changes the altitudinal angle. Because of the 23.5 degree tilt of the earth's axis a given location will be closer to the sun at some points during the year than others. For the northern hemisphere the summer solstice marks the time of greatest proximity (greatest cooker efficacy) and for southern locations the winter solstice. Along with these more consistant factors the presence of clouds, dust, rain, or wind can influence the effective energy concentration of the cooker. At high altitudes there is less atmospheric interference than at lower altitudes (assuming all other parameters are constant) allowing for a greater flux of direct radiation to hit a horizontal surface. (Pejack 2003).

The baseline radiation entering a solar cooker is a function of the amount of beam radiation per unit area reaching the solar locus and the angle at which the incidence rays enter the transmissive surface. Reflectors surrounding the outside of the cooker can be used to further concentrate the incoming rays onto the absorptive surface that will transfer heat to food (Ozturk 2004). This enhanced concentration can be calculated using the Stefan-Boltzmann law, assuming an emmissivity of one for an absorptive black body and using empirical calculations of energy per unit area reaching the cooker, surface area and temperature of the absorptive body, and ambient air temperature (where Net Radiated Power (P) = $A\sigma e(T^4)$ where σ = and where energy radiated out of the cooker = energy into the cooker (Varekamp 2008). The relationship between energy flux with reflectors and energy flux without reflectors can be represented by the *concentration ratio* (flux with reflectors/flux without reflectors) (Pejack 2003).

Direct Solar radiation can be manipulated and concentrated by the cooker's reflective surface according to laws of reflection which describe the angle of reflection as equal to the angle of incidence of the incoming ray. Using this property, the reflective surface can be adjusted to intercept direct radiation at an angle which then focuses the reflected ray out at an angle most effectively transmitted through a transparent (glass/plastic) cover (in the case of a box cooker) or out to free standing absorptive body (in the case of a parabola) (Nandwani 2000).

In the case of a box cooker a transmissive cover is used to let solar radiation through to the absorptive surface and prevent infrared radiation from the absorptive body from coming back out of the cooking chamber (Nandwani 2000). Some Solar radiation is prevented from passing through the cover surface due to absorption of energy by molecules within the cover, and because of refraction that occurs at the contact with the cover. The proportion of solar radiation that makes it through the cover is known as the cover material's *transmittance*. The transmittance of a cover material is also dependent on the angle at which solar radiation is passing through (Pejack 2003). The capacity to transmit solar radiation and block infrared energy makes the accumulation of a sufficient cooking temperature possible.

Thermodynamics of the cooker systen

Universal principles of thermodynamics can be applied to the cookers to understand their differing performances qualitatively with respect to heat transfer and energy transformation. The cookers are systems that via reflector concentration allow an influx of energy through their transmissive "greenhouse effect" surfaces. Upon absorption visible light wavelengths become degraded producing heat that becomes trapped until the cookers reach thermal equilibrium with their surroundings. Although solar energy does not decrease (1st Law, see **fig**.3) it has degraded from ~6000K solar radiation to the aluminum block temperatures recorded (~350K). Exergy accounts for the change in quality of energy experienced as a temperature change and therefore is a more meaningful measurement for solar cooker efficacy (Petela 2005).

Exergy is the irreversible useful work resulting from increased entropy of the system and surroundings. Heat transfer into and out of the system produces increased entropy as put forth by the second law of thermodynamics. Unlike entropy, exergy is not a primary thermodynamic property but a co-property of systems. Irreversibility results from changes in the configurations of the microstates of particles within the system. The transformation energy expended cannot be recovered (Dincer & Cengel 2001).

As our system exchanges entropy with the surrounding air via heat flow from warmer to cooler air, equilibrium is destabilized which continues to drive heat transfer. This heat transfer is the usable work of the system, or the exergy. This heat/entropy exchange with the surroundings induces spontaneous self-organization that manifests in convective heat patterns (Dincer & Cengel 2001).

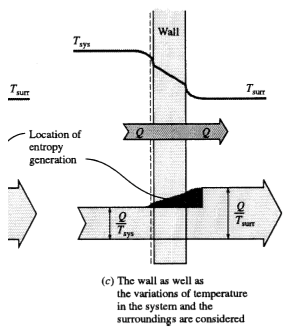


Fig.3 entropy generation during a heat transfer process through a finite temperature difference (Cengel & Boles 2001).

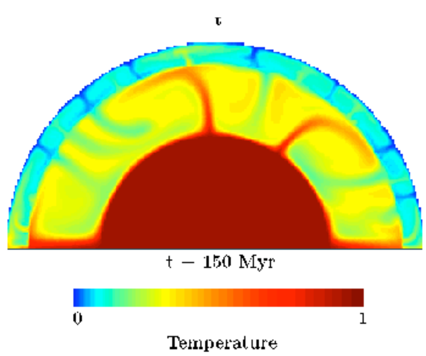


Fig. 4Heat transfer via convection. Earth looses heat to surrounding space (Second Law of Thermodynamics). The Earth system is comparable to the cooker system. The mantle acts like the box walls as the barrier across which heat transfers resulting in a net increase of universal entropy. (Cizkova 1999)

Energy and exergy losses result from unabsorbed insolation (Incident solar radiation, solar radiation received on a given surface at a given time = irradiance), convective and radiative heat transfer to the ambient (thermal energy loss) and the radiative irreversibilities of surfaces (exergy loss and increased entropy) (Petela 2005). When losses equal input, thermal equilibrium is achieved within the cooker. Heat is transferred from the solar cookers via conduction, radiation and convection.

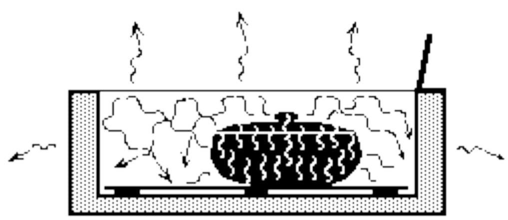


Fig.5 convective and long wave radiative heat loss.

Heat Loss & Insulation

The temperature the cooker can rise to depends on the amount of radiation coming in and the amount going out. Of course, the cooker does not retain 100% of the heat it receives from the incoming solar radiation; some of it escapes out through the walls of the box. The amount which escapes depends on both the thickness and area of the walls of the box and on the material from which the walls are made. The equation below defines heat loss quantitatively;

$$Q_{loss} = A_c \ \Delta T/R$$

where A_c is the area of the wall of the box, delta T is the temperature difference between the box and the surroundings and R is the thermal resistance of the wall.

Q_{loss} can therefore be minimized by either reducing ΔT or A_c or increasing R. Because heat is transferred from areas of high heat to low heat, as the cooker becomes warmer than the ambient temperature, heat moves from the cooker to its surroundings.

ΔT represents this transfer, and cannot easily be reduced. The area of the box wall can only be reduced at the expense of the volume of the cooker; reducing A_c would decrease the amount of space in which to cook. Increasing R, the thermal resistance of the wall, is the best way to lessen the heat loss without minimizing cooking space. Thermal resistance is a factor of both the thickness of a material and the properties of the materials from which it made. It is measured in units of W/m^2 per ºC. These properties which determine the thermal resistance of a material are coined thermal conductivity (k), or the properties which govern the material's capacity to conduct heat. Thermal conductivity is measured in W/m per ºC (Pejack 2003).

The thermal conductivity of a material can be experimentally determined in a variety of ways in a laboratory. Value ranges are on the order of small fractions to thousands of W/m per ºC. For example; air has a very low thermal conductivity of .03 W/m per ºC, while aluminum has a very high k value of 200 W/m per ºC. Because air has such a low thermal conductivity, porous materials often also have low thermal conductivities because the contain air in their pores. However, air currents passing through a porous material can transport heat and increase the thermal conductivity so that, even though air is not very conductive, too much air space can increase heat conduction.

In order to minimize the heat loss from the solar cooker, the walls can be made thicker to increase thermal resistance and then insulated with materials which have low thermal conductivities. Foam, fiberglass, corkboard, wool felt, cotton, sawdust and paper all have thermal conductivities similar to that of air, .03 - .06 W/m per ºC, and make good insulators for the walls of a solar cooker. The cooker can be insulated from the top by using two plates of glass with a small gap between them. The air between these plates will prevent heat from escaping back through the glass (Pejack 2003).

Heat in/mass/heat out

In regards to thermal properties, a Solar Cooker can be regarded as prototype Earth. Ovens, like Earth, respond to varying solar flux and constantly changing angles of incidence of solar radiation. The oven temperature results from the difference between the heat gain and the heat losses. *The optimal cooking temperature is reached when the solar gain equals the heat losses.* (Pejack 2003) This section will take into account the heat gains and losses as we focus on the process of heating a Mass (M) in the cooker and discuss the theory behind cooker efficiency.

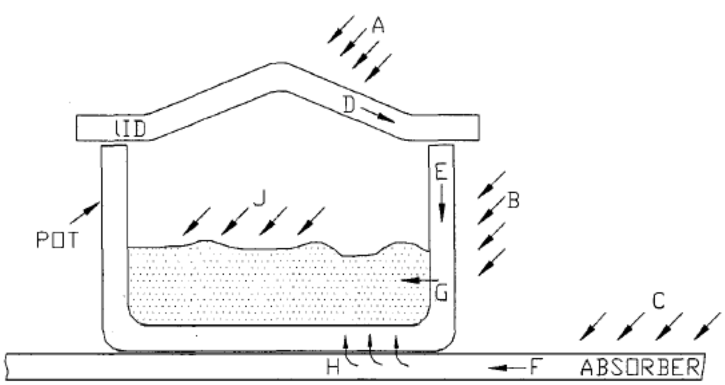
The heat losses, which have already been discussed in this paper, can be placed into five categories as outlined by C. Alan Nichols:

1. Reflective Losses
2. Absorption Losses
3. Transmitted Losses
4. Leakage Losses
5. Food Losses

Clearly, overcoming the many losses and leakages present in the system requires a great amount of input energy as well as an efficient design and choice materials. As previously described, the amount of solar gain depends on the amount of solar radiation reaching the cooker (a function of many factors such as time of day and year, latitude, altitude, the amount of solar absorption by the atmosphere) as well as the effectiveness of the design to harness and retain that energy (reflectors, glass). Leakage Loss can be described as a function of the difference between the temperature inside the box (T) and the ambient temperature (Ta) and modeled with the following equation: $Q(loss)= Ac\ \Delta T/R$. (Pejack, 2003) Leakage Loss is related to the Second Law of Thermodynamics, which is one of the most fundamental physical properties at play in a solar cooker, describes entropy (can be reduced to disorder) and the process by which heat flows or falls from high to low temperatures. Absorption Losses occur with the transfer of solar radiation to heat energy and are dependent on the "absorptance" of the material. (Pejack, 2003) Transmitted Losses occur with the passage of solar radiation through sunlight passes through the glass on the way into the box. The Food Losses can be described as heat losses to the temperature of the box however, they would not be considered a loss to the overall system.

There are three ways in which heat is transferred to the mass inside a cooker. These three mechanisms are: one, direct solar radiation (the reflectors increase the amount of solar radiation received); two, convection, which is through heat transfer in the air (molecules spread out as they become less dense); and three, conduction that starts with the absorptivity of the container's material as well as the thermal conductivity of the materials used for the cooker. (Nichols) When the solar radiation hits the (opaque) container/ heat collection device (whether that be a pot filled with food, or a block of aluminum metal), some of it is reflected and some is absorbed. The absorbed incident radiation becomes heat energy. The amount of solar radiation that is absorbed as heat energy depends on the material's absorptance of short wavelength (solar) radiation. (Pejack, 2003)

The following is a diagram that briefly explains the variety of heat transfer processes involved with the cookware in a box. It also has the added component of an absorber plate.



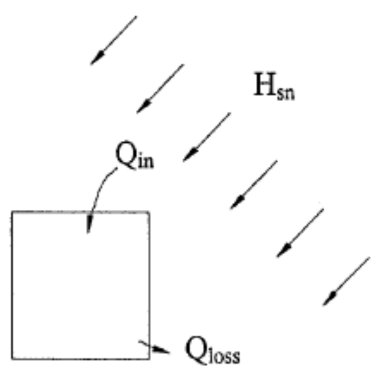
A cook pot. Solar rays may be absorbed at the lid at A, on the side at B, at an absorber plate at C, or in the case of a transparent lid, directly at the food at J. Heat conducts along the lid at D, down the pot wall at E, along the absorber at F and into the food at G and H.

There are many existing models for obtaining the efficiency of a solar cooker. Funk and Larson present a parametric model with three controlled parameters (solar intercept area, overall heat loss coefficient, and the thermal conductivity of their absorption plate) and three uncontrolled variables (insulation, temperature difference, and load distribution) that can be used to predict the cooking power of most box cookers. The model outlined by Pejack, however, proves to be the most applicable to our solar cooker project, and will thus be explained in detail. His equation is a basic efficiency that

contains constant qualities that represent incoming solar flux, various losses, as well as heat capacities of materials.
The following are constants:

Hsn = the solar flux (W/m2) on a surface
Ai = area of the glass (area that intercepts solar rays)
Ac = cooker area (this is part of a heat loss function
M= Mass being heated
Cp =heat capacity as measured by the specific heat in kJ/kgC of M
Ta= ambient temperature
R = thermal resistance °Cm2/W of Ac

Qin is the rate of heat in. Qloss is the heat rate that is lost to the ambient air , which has been described in the previous section, as being a function of Ac ΔT/R, where A_c is the area of the wall of the box, delta T is the temperature difference between the temp box and the temp ambient, and R is the thermal resistance of the wall.



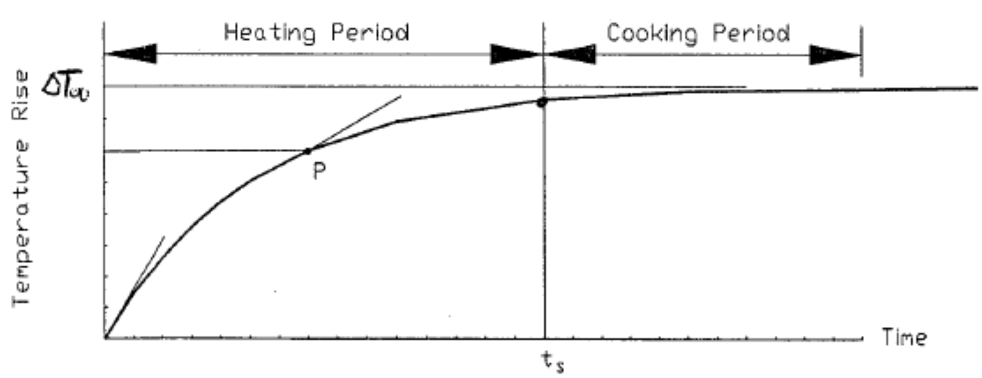
The difference between Qin and Qloss is the value of Mass M heating up. If we assume that the temperature of M equals the ambient temperature at the beginning of the experiment, we can describe the heat loss in the beginning as zero. The heat loss, then, increases as “Food Loss,” which feeds an increase in the temperature of M. Eventually the Qloss may reach the value of Qin, which would mean the cooker (and its contents) reached its maximum temperature.

Consider the following scenario: As incoming solar radiation reaches the cooker through the glass, the temperature inside the cooker begins to rise. At first, when there is a greater difference between the cooker system and its surroundings, the temperature rises quickly. As the system reaches equilibrium with it surroundings this curve levels off to a constant temperature. This temperature curve can be modeled by

$$\Delta T_\infty = R\ \eta_o\ H_{sn}\ A_i / A_c$$

ΔT(temp difference Qin-Qloss) = (Thermal Resistance)(*n*o)(Solar Flux)(Area of rays intercepted by the cooker)/(Area of cooker that is losing heat due to the temperature difference between the cooker and the ambient temperature). This model negates the variables of heat transport through the mass and heat loss through evaporation; it assumes that the mass has a uniform T and the energy lost to evaporation is neglected.

If R, *n*o, and Hsn remain constant, delta T will increase until Ai = Ac. As the cooker warms, it will lose more heat due to the temperature difference between the inside of the cooker and the surrounding air. As the heat loss reaches the heat input, the temperature will level off. This can be called the ideal cooking time.



Planck

The theory behind blackbody radiation is an important factor to consider in our discussion of solar cooker heat transfers. “Blackbody radiation” refers to the process by which an object (or system) absorbs all the incident radiation and re-radiates this energy as infared heat energy. Thus, Black bodies have a with an emissivity of 1. Planck's law describes the quantum theory of electromagnetic radiation (of all wavelengths) of a blackbody at a temperature T.

$$I(\nu)d\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

I(ν)dν, is the amount of energy per unit surface area per unit time per unit solid angle emitted in the frequency range between ν and ν+dν in which;
h = Planck's constant (6.63 x 10^-34 J/s)
c= the velocity of electromagnetic waves (3 x 10^8 m/s) or the speed of light
k= Boltzman constant (1.38 x 10^-23 J/K)

The application of this law lies in examining the spectrum of energy emitted by the black body energy from the incoming solar radiation. (Nandwani)

Cooker "Efficiency"

Examining the "efficiency" of a cooker is a useful tool for quantifying the success or effectiveness of a model. An efficiency model is ideally modeled with actual performance plotted against maximum possible performance. Efficiency is the power output divided by the input power. (Schwarzer, da Silva) The incoming radiation is measured in W/m2 and is multiplied by the surface area of the surface of interception. The term "optical efficiency" refers to "the property of the system without any thermal losses and it is determined from the value of heating-power near ambient temperature." (Schwatzer, da Silva) Pejack defines his efficiency model is "as the ratio of initial heat rate into the mass M divided by the intercepted solar power." This number should have a value between 0 and 1.
Pejack's efficiency equation takes into account the following constants and variables:
M= mass in cooker

Cp= specific heat of material

Ai= area if light intercepting surface

Hsn= solar flux

Φ= initial slope of temp increase vs. time

$$\eta_o = M\, C_p\, \Phi_0 / (H_{sn} A_i)$$

The denominator of the equation may be considered constant if an average or consistent solar flux measurement is used. (Hsn) is the solar input and is multiplied by the solar intercepted area (Ai). The specific heat of the material, the mass of the material, and the slope of the initial temperature rise are multiplied. The final value of the "optical efficiency" can be examined against the maximum possible performance. A simple test of efficiency can take the net power received by mass M divided by the solar power input.

Experimental Methods

Design

In order to understand and analyze the physical properties of solar cooking and their relation to climate principals and socio-environmental initiatives we designed and constructed three different models of solar cooker, tested their efficacy under varying levels of insolation, and calculated and compared efficiency parameters between models. Experiments took place in Middletown CT (41.562N, -72.651W) in the last week of April and first week of May 2008.

Fig.6 small box cooker (L), big box cooker (R).

Fig. 7 Tire hybrid cooker

Small Box

The most accessible cooker design we found is a common and quick cardboard box with an extended flap that when covered in tinfoil and angled correctly reflects light into the box. For insulation the box is fitted into a slightly larger box and the space between the two is stuffed with newspapers. The entire oven interior is coated with tinfoil and a few layers of clear plastic wrap cover the opening to allow rays in and trap them as heat.

Big Box

The second box model we made involved more resource input. This box is a smaller box within a larger box made of plywood, and the two inch space between the two is insulated with foam. The heat is trapped by double paned glass and the dimensions of the box sides make it so the glass is angled at 45 degrees to optimize ray input. The reflectors are appended by hinges that can adjust to visibly concentrate solar intensity according to need (i.e. more intense yet smaller target coverage).The design of the Box Cooker was modeled relatively successfully off the internationally- marketed Global Sun Oven.® The Global Sun Oven, however, boasts of four highly reflective, large-area reflectors that funnel up and out from the box, and which, according to Nichols, are optimally configured as they are as wide as the width as well as the height (or depth) of the cooker.

Hybrid Cooker

We constructed a hybrid cooker from found materials that uses a parabolic reflective surface to concentrate radiation at a focal point located at the height of a black-painted tin tube that acts as a stand for a cooking pot. This is where the bulk of the parabola's radiation is theoretically focused. The tin parabola flowers off of a tire covered with a circular piece of plexi-glass where the black tube protrudes from. The tire acts as a low temperature warming space insulated at the bottom with black-painted plywood and in its sides with newspapers. Window insulation tack was used to approximate a tight fit between the tire lip and the plexi-glass oven lid and between the black tube and the hole in the plexi-glass it emerges from . The black tube is perforated with drill holes in the oven space to theoretically allow heat transfer from the focal point to the oven.

Experiments

During each of four test-runs an aluminum block (A =64cm2), painted black so as to most closely emulate a radiative black body with an emissivity of one, was placed at the center of each box cooker and in the focal compartment of the parabola. Each block, or absorptive body, was then connected to a metal probe attached to a thermo-couple that transmitted a temperature reading (degrees C) at regular intervals to the data processing program Logger Pro. Tests varied in length from one to three hours and included exposure to relatively low, medium, and high insolation scenarios (for the time of year, latitude and elevation) and to artificial light sources. We then analyzed data using excel to compare data sets, cooker efficiency and concentration ratios. Net radiated power (P) was calculated with Stefan-Boltzmann's Law (P=AσeT^4
where σ = 5.6704 * 10^-8 e = 1 T = temp of metal block for reflective
T = temp of ambient air for theoretical non reflective A = area of metal box exposed to radiation). Concentration Ratio was calculated by dividing P empirical with reflectors by P theoretical without reflectors. The efficiency of the Big Box was calculated using the following:
a solar flux of 0.015 W/cm2
the specific heat of aluminum at 0.9 (J/g °K)
an initial slope of 0.0135
a solar interception area of 3416 cm2

$$\eta_o = M C_p \Phi_0 / (H_{sn} A_i)$$

The efficiency was calculated as a value of .128, or 12.8%.

Results

On the cloudy cold day temperatures in any cooker failed to get above 75 degrees. The small box heated most quickly but was eventually surpassed by the larger box cooker which heated more slowly but better maintained heat through variable radiative conditions. The parabola both accumulated and retained the least heat, fluctuating most closely with solar illumination and cloud cover (Fig 8 and Fig 9).

The results for the sunny and cold day show a moderate but steady increase in temperature in the small and large boxes. The smaller box heated more quickly and stayed above the other couples (Fig 10)

The sunny day showed a significant increase in the (perhaps) equilibria temperatures of all cookers. The small box again took the lead but was eventually surpassed by the large box which exceeded 94C. The parabola still showed the lowest temperature (though it increased) with the temperature of the lower "warming" area often exceeding the central focal heater (Fig11)

In each case the Net Radiated Power (P) is greater with the empirically added reflectors than it is when calculated theoretically for a scenario without reflectors. The concentration ratio remained close to 2 in all cases, though the parabolic cooker consistently showed the lowest ratio. All ratios went up with increased insolation (Fig 12 and Fig 13)

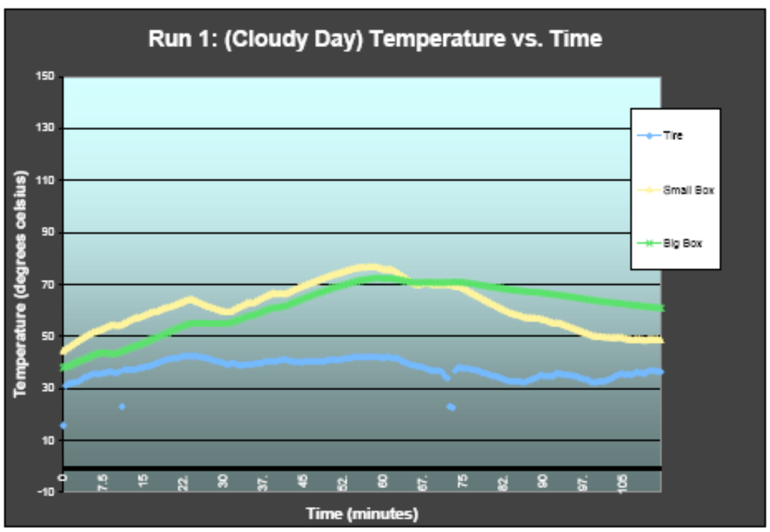


Fig 8

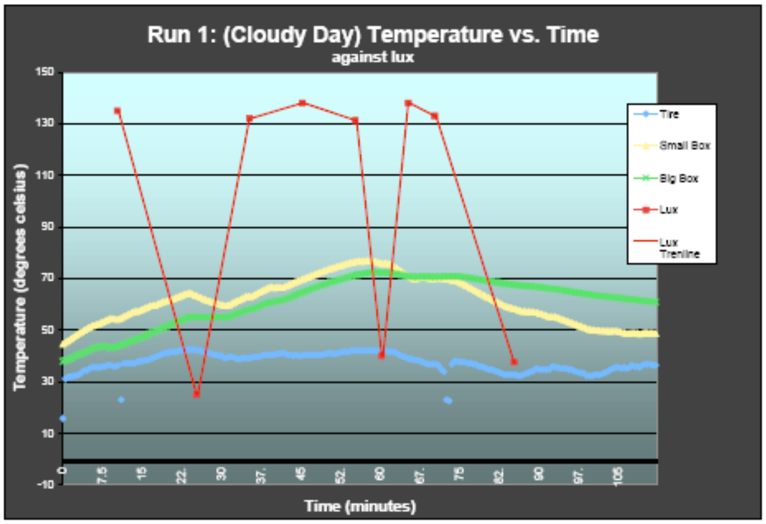


Fig 9

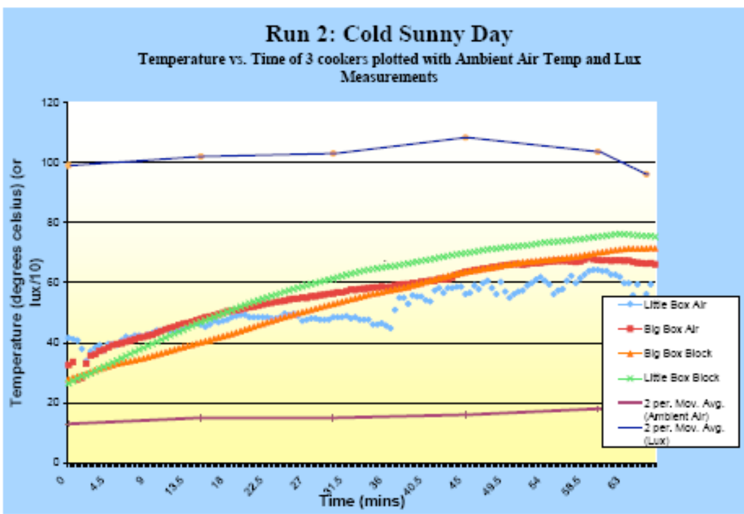


Fig 10

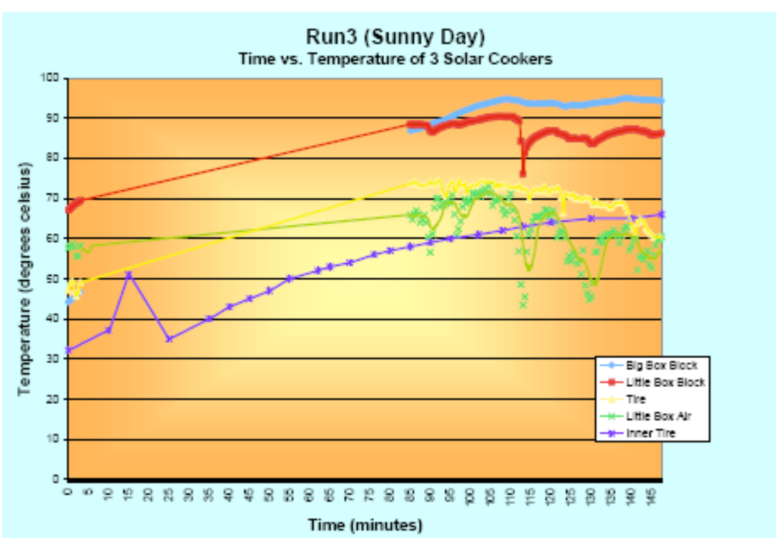


Fig11

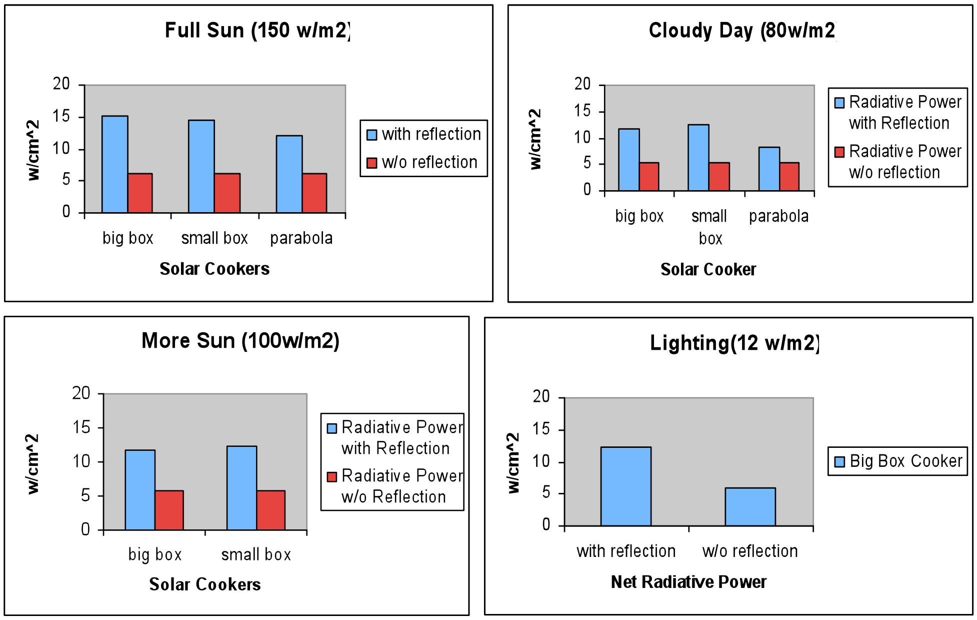


Fig 12

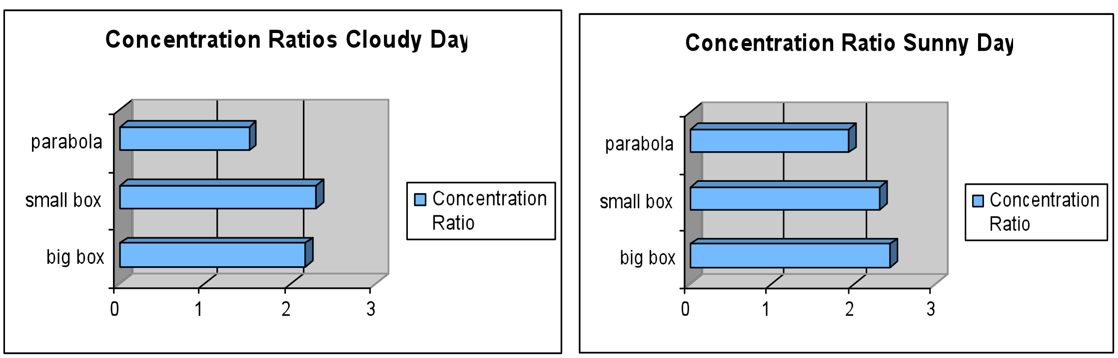


Fig13

Discussion

Assuming a black body emissivity of one, the net radiated power from the aluminum block should equal the amount of solar radiation going into the cooker. The discrepancy in the values for theoretical non reflector P and empirical P with reflectors suggest that the reflectors do have a concentrating effect on the solar radiation reaching the cooker surface. The concentration ratio results suggest that the large box cooker was most effective at concentrating solar radiation, while the parabolic cooker was the least effective. The parabolic cooker, however, was most susceptible to changes in solar radiation. This points to the increased insulating properties of the boxed models which create a greater buffer between changes in solar radiation and changes in inside-cooker temperature. These calculations offer approximate comparisons. They are not completely accurate, however, as the solar radiations in w/cm2 were rough estimates due to a misguided attempt to measure in lux and the emmissivity of the aluminum block was probably not one as the absorptive power was probably not that of a true black body.

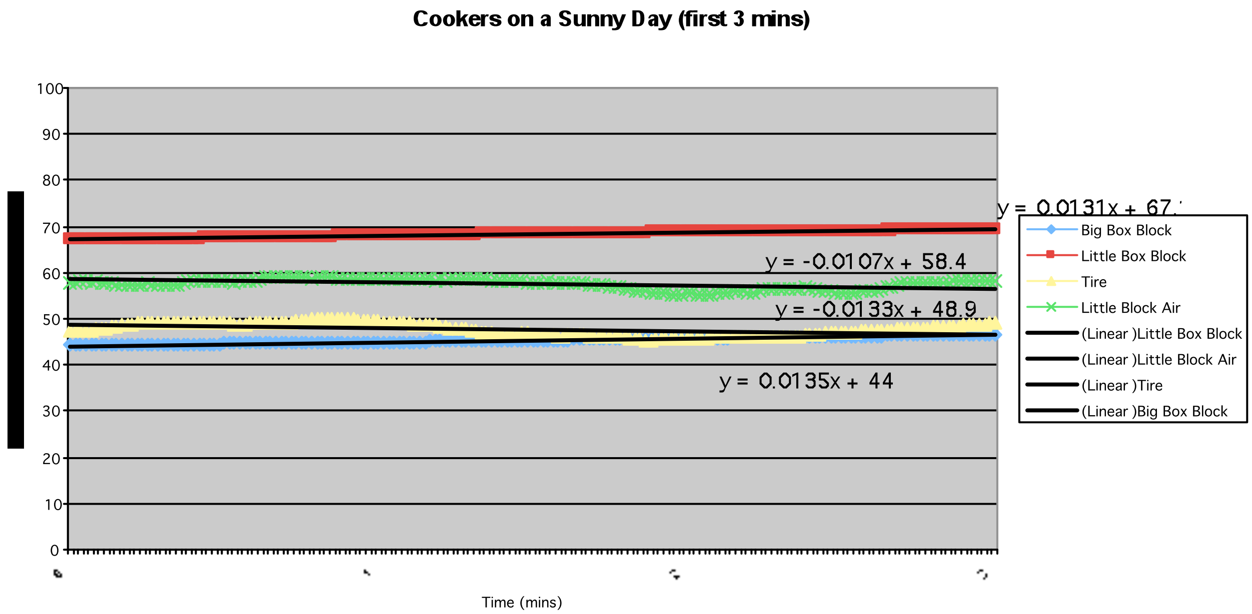
The small box probably heated most quickly because of the large reflective surface ratio to cooking area ratio. While the larger box cooker heated more slowly due to a smaller ratio between reflective surfaces and cooking area the increases insolation and larger air space around the absorptive surface meant that it retained heat longer as the small box fluctuated more closely with external conditions. The fact that the smaller box remains hotter in the second experiment is probably a function of the short duration of the experiment (one hour). Because of its lack of insulation and reliance almost exclusively on incidence radiation (rather than accumulating some diffuse rays), the parabola cooker faired poorly in variable or cloudy climates. Its temperature very closely responded to the rise and fall of external light and temperature. The fact that the sunny day data favored high temperatures in the lower warming part of the parabolic cooker demonstrates the importance of building a highly mobile parabolic design that can maintain its ideal orientation towards a changing angle of incidence. This is the only way to maintain an elevated temperature on the cookers focal point without a transmissive, heat retaining compartment.

Solar radiation reaches earth in two forms, direct or beam radiation coming in parrallel rays from the sun and diffuse readiation that arrives scattered in all directions after hitting ozone, water, or particulate matter in the atmosphere. On an intermittently cloudy day, such as the one in which most of our data were collected, the majority of radiation hitting earth's surface is diffues (Pejack p 2). This makes collection by a solar cooker more difficult (even if a decent amount of radiation is making it to the cooker area) as there is no ideal angle of reflection that will reflect a large amount of energy into the cooker body.

Because highly reflective surfaces, such as mirrors, express most of their reflectivity as specular radiation they are often more effective than less shiny surfaces that reflect a larger portion of incoming beam radiation as diffuse radiation in all directions. Our use of aluminium for the big box cooker probably allowed for a greater translation to diffuse radiation than mirror reflectors would have, thereby reducing efficiency. The salvaged metal of the parabolic design may have reflected an even greater proportion of diffuse radiation which would have particularly effected its ability to focus reflected rays onto a central point. This may explain the trouble we experienced heating the above tire block and the relative efficacy of the underlying warming area (which may have received more diffuse radiation than expected). In trying to maintain a warming area underneath the focal area of the parabola we sacrificed some of the potential efficacy of the parabolic concentrator which must continually be oriented to maximize the angle of incidence and maintain optimal reflection (Schwarzer and da Silva, 2008).

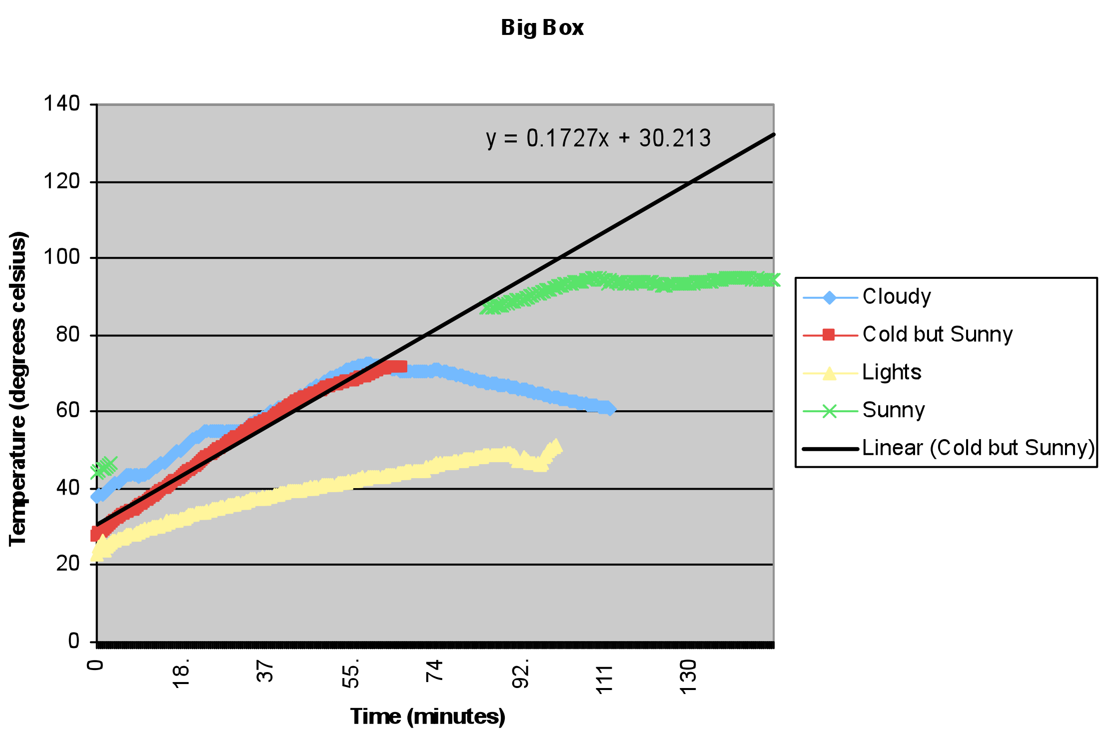
An attempt to compare the efficiencies of different cookers requires an extraordinary data input with great attention to detail and specifics, described by Schwarzer and da Silva. Some of these are: the solar cooker tracking period, the unattended cooking period, the heat losses without solar insulation, the continuous cooking, and the area hit by incident solar rays.

The results of our data can be interpreted as illustrating a range in cooker efficiency. The initial temperature rise vary slightly between models, which can be seen in the difference in steepness of the slopes of the lines. The following graph contains data taken in the first three minutes of the “sunny run” and records the initial temperature rise, a variable used for calculating efficiency. Looking at this graph, it is clear that three of the lines plot similar positive slopes (with the big box slope being the steepest at 0.0135, while the tire shows a negative slope. This data cannot tell us much, due to the short time range in which the data was taken (though the large number of data points make a very precise graph).



The resulting value of the efficiency of the "big box" cooker is 0.128, or 12.8%. For a comparison, one study found an efficiency value for a solar box cooker with two reflectors at about 28%. (Nahar) This data corresponds with a location at a much lower latitude, which would have a much higher solar flux than that reaching our solar cookers in early may at 42 degrees Latitude. This efficiency equation does not take into account many other design elements as well as physical properties (such as reflection and concentration of solar rays, and convection and conduction or the air and materials). As discussed above, the discrepancy between the empirical P (with reflectors) versus the theoretical P (without reflectors) suggests the positive concentration effect of the reflectors. The "net radiative power" values of the box (with reflectors) are greater than the "net radiative power" values of theoretical solar radiation, leading to the conclusion that the design of the box is efficient in ways in which the efficiency equation does not account.

The graph that plots the four temperature curves of the "big box" illustrates how varied the temperature readings can be depending on the solar flux and weather conditions. The "sunny" day that had relatively low wind and a constant temperature of about 21° C without solar flux variations, recorded a curve with the highest temperature values. This curve did appear to level out around 94ºC, but this is most likely due to a decrease in solar radiation, and increase in shading from a nearby tree, and insufficient tracking (to keep the incident solar radiation square within the box). The cold but sunny day shows a strong incline (having a slope of 0.1727), which perhaps indicates the success of the insulation of the cooker. The temperature curve of the box on the cloudy day has a strong initial incline as the rate of temperature change is much greater, which may be attributed to the large difference between the ambient air and the inside cooker air). As the rate slows down, and the temperature loss increases (Qloss {to food} starts to equal Qin), the curve flattens and begins to fluctuate as it is influenced by cloud cover and wind. The curve that describes the temperature of the box during the controlled light experiment illustrates the disparity between the incident radiation of the sun and the incident light radiation. In the "Rock Room," there were no factors such as low ambient temperature, wind, or cloud cover that would influence the temperature of the box negatively. The higher ambient air temperature, however, does decrease the temperature difference ($\Delta T = T - Ta$), perhaps accounting for the shallower curve.



Social Impact

Solar cookers have a tremendous social and environmental impact. This impact is especially dramatic for one third of the world that still cooks with wood, and for half of those people for whom wood and other biomass are already scarce (Blum 2005). Many of these people live in sun-rich areas, and solar cookers provide a way to take advantage of this abundant and free resource instead of using wood fuels that are in short supply and that have extremely harmful effects on the environment. In these areas, mostly rural and underdeveloped and around the equator, solar cookers could be used around 200-300 days a year and two to three hours of sunshine is sufficient to cook food for 5-6 people with some cookers (Metcalf).

The environmental benefits to solar cooking instead of using wood burning energy sources are obvious. Solar cooking not only reduces CO2 release from the burning of the firewood, but not cutting down the trees is obviously beneficial in its own right as preserving the limited forests of that landscape and leaving the trees to sequester CO2. Solar cookers inherently reduce CO2 emissions by using solar energy in the place of burning wood or fossil fuels to cook. When 90% of energy used in underdeveloped countries is used for cooking food, which is mostly from burning wood, the reduction in CO2 emissions and deforestation that solar cookers could give is significant. Using wood for cooking fuel is problematic in many places. Already, one quarter of humanity is affected by a fuel wood shortage; by the year 2000 the shortage will affect at least 2.4 billion people (UN/FAO estimate). The corresponding deforestation to this shortage of fuel wood causes soil erosion, water pollution, a loss of soil fertility, and ultimately, desertification. Sub-Saharan Africa is a graphic example of this process (Sperber 1990).

It is crucial not to underestimate the impact of shifting use of firewood to solar energy: 2.5 billion people, over one-third of humanity, depend upon traditional fuels (mostly wood) for cooking. For those who depend upon wood fuel, it takes about two pounds of wood to cook each person’s food each day. For a family of five, that’s 3,650 pounds of wood a year. In 40 of the world’s poorest countries, over 70%

of their fuel comes from dwindling supplies of wood, or, in towns and cities, from charcoal inefficiently made from wood. In Tanzania, with 32 million people, over 90% of the country's energy comes from wood/charcoal. That's about 60 million pounds of wood burned to ashes every day! This is clearly not a sustainable source of energy and is a critical issue to much of the world (Metcalf).

Solar cooking and reducing the amounts burned of other fuels can result in a substantial reduction in CO_2 emissions. Based on a year-long field test of one solar cooker company, an average family in Southern Africa can save 30 liters of kerosene, 30 kg of Liquid Paraffin Gas and almost a ton of firewood per year. This means an estimated CO_2 reduction of 3.5 tons/year per solar stove (http://www.sunfire.co.za/generalinfo.htm). Another study found that one solar cooker saves about one ton of wood per year thereby reducing carbon dioxide emissions by 1.8 tons per year (Solar Cookers International).

Not requiring firewood as fuel also often has huge social implications in developing countries where collecting firewood can mean long hours of work and can be very dangerous. It is not uncommon for women to be attacked when they venture further and further distances from their homes for firewood. In addition, the time normally spent by women and children collecting firewood is freed up by solar cooking, allowing for more potential to do other things with their day, possibly increasing the opportunity to attend schools (Sperber 1990).

Economically, solar cookers are a huge resource because they can be made comparatively cheaply (there is a wide price range where the capital outlay can be anywhere from $3-$20, but even $20 is equated with the amount for one or two weeks of regular cooking fuel purchases) and do not require people to continually spend part of their income on fuel (Sperber, Solar Cookers International). Many families living on less than one dollar a day spend a third of it for cooking fuel. This cost often means less food to eat. Solar cookers typically reduce fuel needs by a third and pay for themselves in two months of fuel savings (Solar Cookers International).

Solar cookers can also help improve many people's health. Solar cookers can be used to sterilize water by heating it to 65°C; an application incredibly important to the 1.2 billion people who do not have access to safe drinking water and who often suffer sickness or death as a result (Metcalf). Many people suffer respiratory and eye ailments because of the extremely smoky cooking conditions in homes burning fuels. Solar cooking is obviously smokeless and so eliminates this problem as well as reducing the incidence of burns or other fire-related injuries. The under-cooking of food (because of the shortage of fuel) can also lead to severe malnutrition (Sperber 1990), but the gentler temperatures of box and panel types of solar cookers cook food thoroughly and also preserve more nutrients (Solar Cookers International). Solar cookers can also help health conditions by being used to disinfect medical instruments. (Sperber 1990).

However, it is condescending to think that solar cooking is only applicable to less developed nations when our experiment indicates that you can reach some effective cooking temperatures as far from the equator as Connecticut. In more developed parts of the world (Global North) solar cooking can have just as important an impact as in other parts of the world by being an effective part of social change movements and reducing our own tremendous greenhouse gas emissions. The dramatic but necessary change to more sustainable living in part begins with grassroots initiatives like solar cooking, which can help educate, raise awareness, and prove an effective tool for reducing people's carbon footprints. All the unsustainable energy that goes into cooking and thus contributes to global warming could be transferred to pollution free, zero CO_2 emission solar cookers. There are also many indirect positive effects to solar cooking, such as the fact that unlike using indoor ovens which can heat up the kitchen adding to the load of air conditioners and refrigerators in summer months, adding on to fossil fuel consumption (and the price of utility bills), solar cooking outdoors avoids this issue and takes advantage of the natural sun and heat of the summer (http://solarcookers.org/basics/why.html). Another environmental component of solar cooking is that it is clearly easy to use recycled materials to create your own as we did with our tire/parabola cooker. By reducing waste, and using solar energy solar cooking provides a multiplicity of ways to improve our effect on the environment.

Just how much of a difference could an American choosing to use a solar cooker make? Let's say it takes one hour to cook a pot of beans on an electric stove using one kilowatt. The coal fired power plant that supplied the electricity consumed one pound of coal and released 17.5 cubic feet or two pounds of CO_2. The power plant also consumed 0.7 gallons of ground water and released traces of SO_2 as acid. Suppose instead of using your electric stove you are cooking outside on the grill. Five pounds of steaks on a grill will use a ten pound bag of charcoal and five ounces of lighter fluid. This fire will produce approximately 160 cubic feet or fifteen pounds of CO_2 and untold air pollution. Wood fires are even worse. In general, cooking at home in America takes over 100 hours a year, consuming approximately 1,175 kilowatt hours. At a cost of $0.10 a kilowatt hour this amounts to $117 a year. During the summer cooking adds $50 to the air conditioning bill bringing the total to $167 a year. In Arizona, solar cooking can replace 70% of the cost of cooking. This will save 1,675 pounds of coal and 3,000 pounds of CO_2 generation from coal fired electric utilities (Nichols).

An extrapolation- just for fun:
The average American releases about 3273 pounds of CO_2 into the atmosphere every year from the processes involved in a food diet of about ½ pound per day. This data, according to a carbon calculator model by Green Progress can be compared to a carbon calculator (Carbonify) that estimates about 1500 pounds of CO_2 emitted per person per year. If we extend the lower of the two values (which accounts only for energy used in cooking food), we can extrapolate the amount of CO_2 we would be saving if our class used solar ovens to cook all of their meals for an entire year. We would collectively reduce emissions by 54000 pounds, or 27 tons. If all 300 Million Americans used solar ovens to cook all their meals, we would emit 225,000,000 fewer tons of CO_2 into the atmosphere.

Solar cookers reduce CO_2 emissions and in this way help stop global warming, but in themselves they are similar to miniature models of our climate. The double glass top insulates the cooker as the atmosphere does the earth, creating trapped heat similar to a greenhouse effect. All the physics and components of our cooker discussed above: reflection, transmissivity, absorptivity, convection conduction, and thermal resistance are all crucial to understanding our climate on a macro scale in addition to understanding how our solar cooker works. Thus, while solar cooking can be very beneficial to the environment and be part of steps to preventing global warming – it also serves as a model warning: don’t let Earth become a solar oven and cook us all!

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