Thermodynamic Review of Solar Box Cookers

(Excerpted from the thesis of Petri Konttinen for the Helsinki University of Technology. Submitted September 25th, 1995)

3.1 Introduction

A typical solar box cooker consists of two boxes with insulation between them, a black absorber plate at the bottom of the inner box, a transparent top cover and a reflective lid as an energy booster (Fig. 3.1.). There are hundreds of different designs of solar box cookers in use. These vary in size, material, insulation and components used (Grupp, 1991).

Generalisations about what works and what does not work, what is important and what is not important under certain conditions cannot be easily drawn. It is difficult for the non-professional people to understand just by common sense. The reason for this is that there are many variables among the choices: the box, insulation, transparent cover and reflective materials; as well as foods, latitude, month, hour and time of cooking (Pejack, 1992).

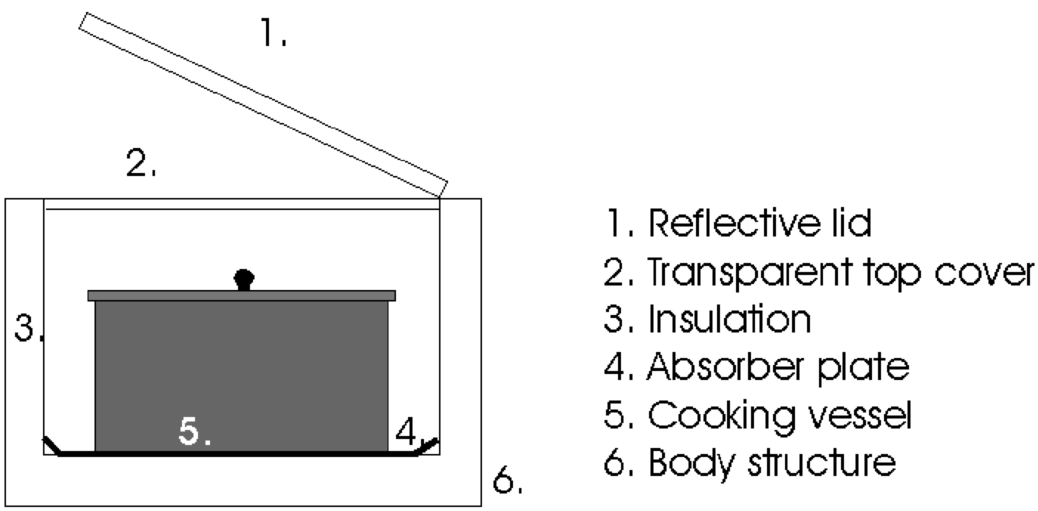

Fig. 3.1. Cross-section of a solar box cooker with a cooking vessel.

This study is not meant to cover all the possible thermodynamical factors of solar box cookers (because of their large number and complexity). The purpose is to give the reader some guide-lines to successful design of an operating solar box cooker. The laws of thermodynamics always determine the function of a solar box cooker, irrespective of its design and materials used (for basic information concerning the utilisation of solar energy in thermal processes, see Duffie and Beckman, 1991).

Instead of covering everything, the most important factors that affect the efficiency of a solar box cooker (excluding operating conditions) will be examined separately. Those included in this study are: heat gain into a solar box cooker, heat loss from the box, heat transfer from the solar box cooker to the cooking vessel, structural materials of the box, materials and design of the reflective lid and transparent top cover, and the volume of the cooking chamber. All of these will be looked at more closely (for more detailed analysis on the thermodynamics of solar box cookers see: Pejack, 1990, 1991, 1992, Thulasi Das *et al*. 1994, Grupp *et al*. 1991, Channiwala, 1989, Allfs, 1992, to name a few).

3.2 Heat gain into a solar box cooker

From a thermodynamical point of view the function of a solar box cooker is to trap and contain the heat of the sun inside it and to transfer the heat to the cooking vessel as efficiently as possible. The heat retained inside the insulated box with a transparent cover is based on the greenhouse effect, which is illustrated in Fig. 3.2.

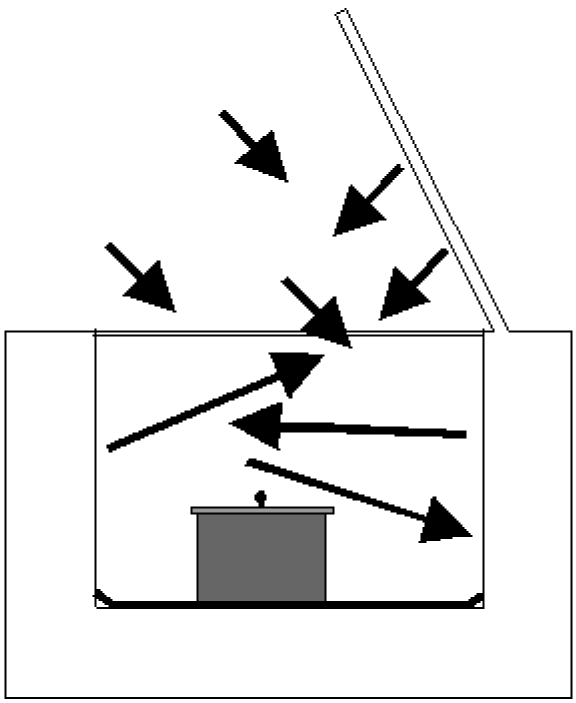

Fig. 3.2. The greenhouse effect. Short-wave sunlight is absorbed into the black materials inside the solar box cooker and converted into longer wavelength heat

Fig. 3.2. illustrates the idea of the greenhouse effect inside a solar box cooker. The light energy (which is short-wave energy) that enters the cooker through the transparent top cover is absorbed by the black pots and the black bottom metal plate. The short-wave light energy is then converted into longer wavelength heat energy and radiated from the interior materials. Most of this radient heat energy is trapped inside the cooker and can (mostly) not radiate back out because of its longer wavelength. Although the transparent cover traps most of the radient heat, some does escape directly through the lid (Aalfs, 1992).

3.3 Heat loss from solar box cookers

Heat loss from a solar box cooker consists of conduction, convection and radiation. Heat is lost by conduction, when it travels through the molecules of aluminium foil, glass, cardboard, air, bottom metal plate, and insulation, to the air outside of the box.

Hot air has a tendency to move upwards due to its lower density. If there are any cracks around the top lid, or side door, or construction imperfections, the hot air travels (convects) out of the box and cooler air from outside enters. This lowers the temperature inside the cooker.

The third heat loss mechanism is radiation. Any hot object give off heat waves, or radiates, to its surroundings (which are at a lower temperature). These heat waves are radiated through air or space. Most of the radiant heat given off by the warm pots inside the cooker is reflected back from the foil, bottom metal plate and the glass. The transparent top cover (usually glass or plastic) traps most of the long-wave radient heat, but some does escape directly through the glazing (Aalfs, 1992).

The main heat loss mechanisms are conduction from the walls and floor, convection from the cover and re-radiation out of the cover (Pejack, 1990). These will be examined separately.

3.3.1 Heat loss from walls and floor

Heat loss from the walls and floor (The floor of the cooker is treated the same as the walls) consists of conduction, convection and radiation.

Conduction from the walls can be reduced by increasing the thermal resistance of the walls. Thermal resistance can vary significantly, depending on the construction and insulation materials used. At the operating temperatures of solar box cookers *thermal resistance* can be defined as

$q''= T1 - T2 /R$ (1)

where q'' is the heat flux (W/m2) and R is the thermal resistance in units of (m2 W/°C). T1 and T2 are the temperatures of the opposing walls of the cooker (in absolute Kelvin).

An empirical equation (Incropera and Dewitt, 1985, eq. 9.38) predicts a thermal resistance of 0.39 units for the 5.0 cm thick wall (with only air in between), when T1 = 368 K (95° C) and T2 = 298K (25° C). Doubling of the wall to 10.0 cm results in only about a 6 % increase in resistance R.

Inserting a thin parallel plane of material, or a baffle, causes impediment to the convection currents (and also diminishes radiation) between the walls. An empirical equation (Incropera and Dewitt, 1985, eq. 9.40) predicts a resistance of 0.66 units when using one parallel plane. Theoretically, inserting many planes would cause the overall resistance to approach 2.0 units, but planes touching each other would "short" the resistance by conduction.

The *radiation component* of the heat flux across the cavity between the walls is given by the equation q´´r = (T14 - T24) (2)

where is the emissivity of the wall surfaces and is Bolzmann's constant of 5.67 x 10-8 W/m2K4. Emissivity is a property of the wall material and it varies from less than 0.1 for polished metals to 0.8-0.9 for wood, paper, etc.

The *total wall resistance,* by combining in parallel, is

R = RradRc /(Rrad + Rc) (3)

where Rrad is the radiative resistance and Rc is the convective resistance.

The relative radiation heat loss (using emissivity of 0.9 for paper, and the wall space of 5 cm) is three times more than the heat loss by convection, therefore it is important to reduce radiation through the walls. This can be done by lowering the emissivity of the walls; for example, covering the wall(s) with common household aluminium foil (= 0.05). Another way is to insert parallel lines (radiation shields) between the walls. A certain level of thermal resistance is needed for a sufficient cooker operation. Pejack (Pejack 1990) has empirically measured that cooking at or above 100° C would require a wall resistance of about 1 unit or more for a cardboard box cooker. (see Fig. 3.3).

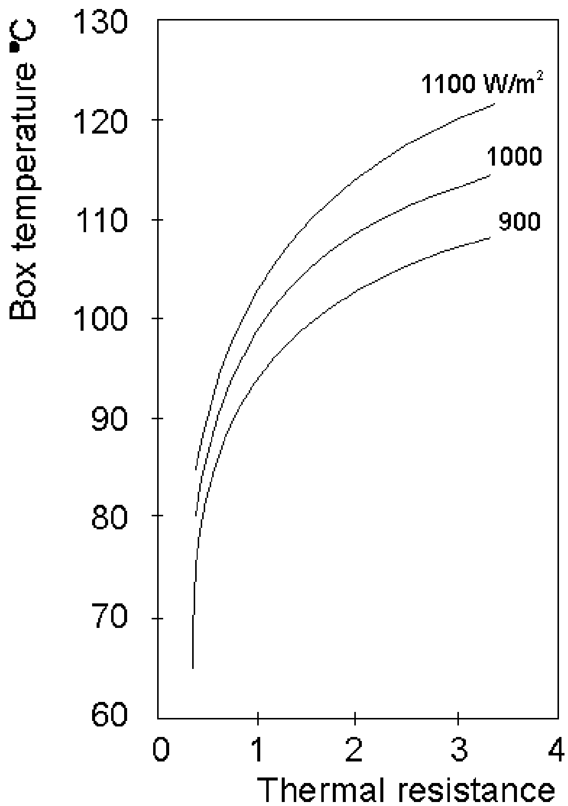

Fig. 3.3. Box temperature as a function of wall resistance for several values of input solar flux. (Pejack, 1990)

In his test procedure Pejack used corrugated cardboard as a box material. The thickness of cardboard was 4.3 mm, 1¼ corrugations per cm, and a mass density of 0.87 kg/m3. The internal dimensions of the cooker were 30x40x60cm.

Fig. 3.4 shows box wall experimental values of resistance with different insulation materials. As we can see, there are many ways to reach the level of 1 unit.

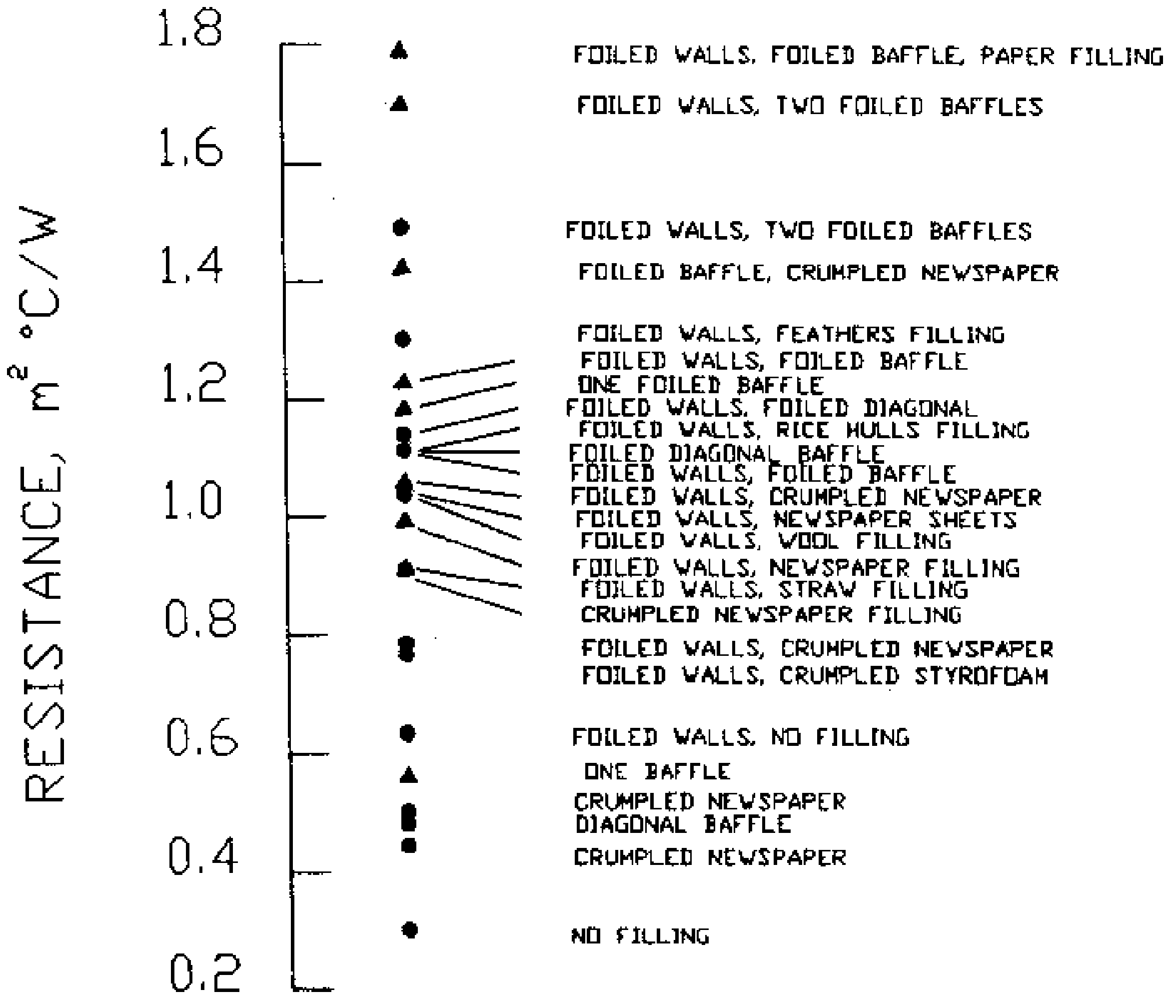

Fig. 3.4. Experimental values of resistances of the test walls. Circles and triangles represent 5 and 10 cm wall spaces. (Pejack, 1990)

In practise an adequate thermal resistance can be achieved either by inserting foiled baffles between the walls or by foiling the walls and adding some filling material in between. Using all of these together brings the maximum resistance.

3.3.2 Materials used to prevent heat loss, experiences from Namibia

Cardboard sheets, aluminium foil and newspaper (or other similar filling) can be fairly easily found in developing countries. These materials are relatively low-cost and easy to use.

In Namibia we used very strong and robust reinforced aluminium insulation foil, newspaper filling and cardboard walls. The foil is very waterproof, which is a big advantage considering the lifetime of the cooker. The price of the foil was 295 Namibian dollars (about 70 US$) per 50 m2. It is more expensive than a normal kitchen foil, but it also lasts ten times longer.

3.3.3 Heat loss from cover

Heat loss from the cover occurs by convection from the cover, re-radiation out of the cover and through channels such as sealing, edges and corners. Estimation of top heat losses is a complex problem due to the tray-shaped absorber plate and the presence of combined convective and radiative modes of heat transfer.

Channiwala and Doshi (Channiwala and Doshi, 1989) have experimentally evaluated the top heat loss coefficient. They measured the cooker's temperatures with 12 thermocouples, installed at various places in the cooker. Their measurements were made in three stages:

1. A single glass cover with the absorber plate temperature range of 50 C to 180C

2. A single glass cover at different wind speeds, varying from 0 to 3.33 m/s.

3. The number of glass covers is changed to two, three and four respectively and each one is tested at different wind speeds as in stage 2.

Their total results (for one and two glass covers, respectively) are shown in Figs. 3.5 and 3.6, where Nc = number of glass covers, Ta = Ambient temperature, Tpm = Mean temperature of the absorber plate; Ut = top heat loss coefficient, and V = wind velocity. The correlation curve is obtained from theoretical calculations (Channiwala and Doshi, 1989, pg. 494). As it would require several pages to explain it, it is not included in this study.

It can be clearly seen from figures 3.5 and 3.6 that as the absorber plate temperature increases, the top heat loss coefficient increases due to higher losses at higher temperatures. Wind velocity increases the convective heat losses significantly and thus reduces the cooker's temperature. Therefore it is important to place the cooker in a sunny spot out of the wind in the cooking area.

An increase in the number of glass layers affects the reduction of the heat loss coefficients due to the increase in thermal resistance offered by successive air layers. However, increasing the number of glass covers from one to two only has the effect of about a 20 % decrease in the heat loss coefficient. Therefore in good solar conditions, e.g., in Namibia, it is not necessarily worth the trouble and cost to use a double-glass. (Of course this depends on other factors also). For windy and/or moderate sunshine conditions two glasses might prove necessary.

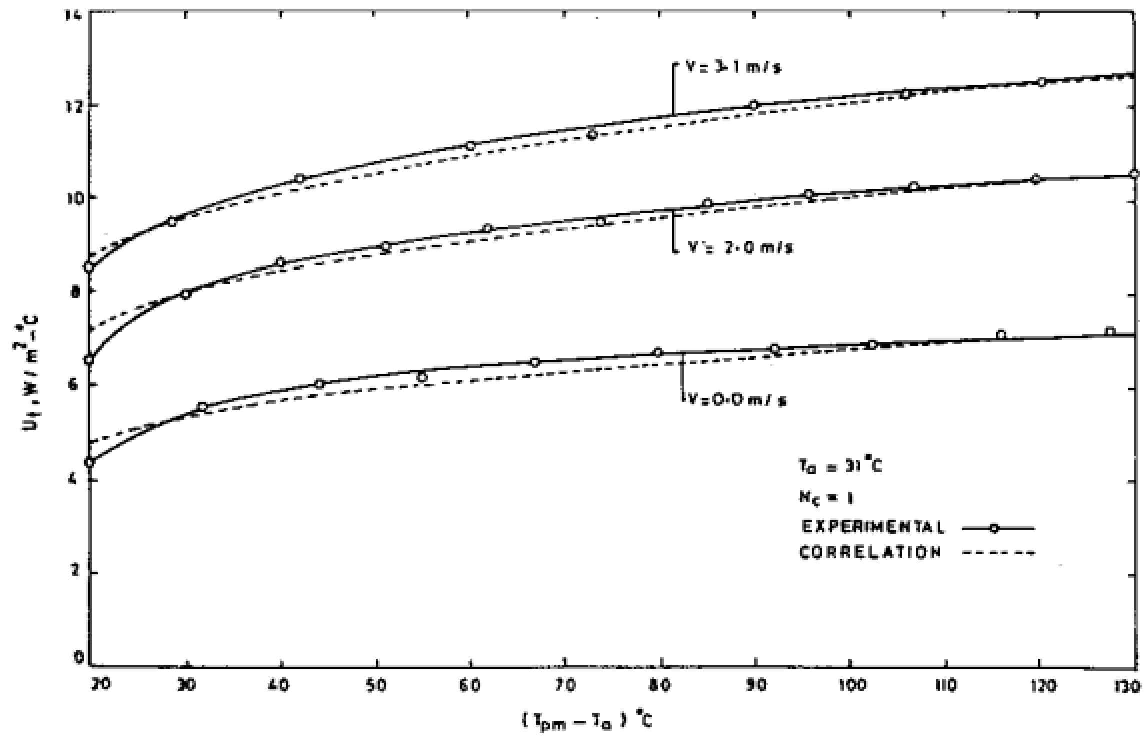

Fig. 3.5. Top heat loss coefficients (Nc = 1). Channiwala and Doshi (1989)

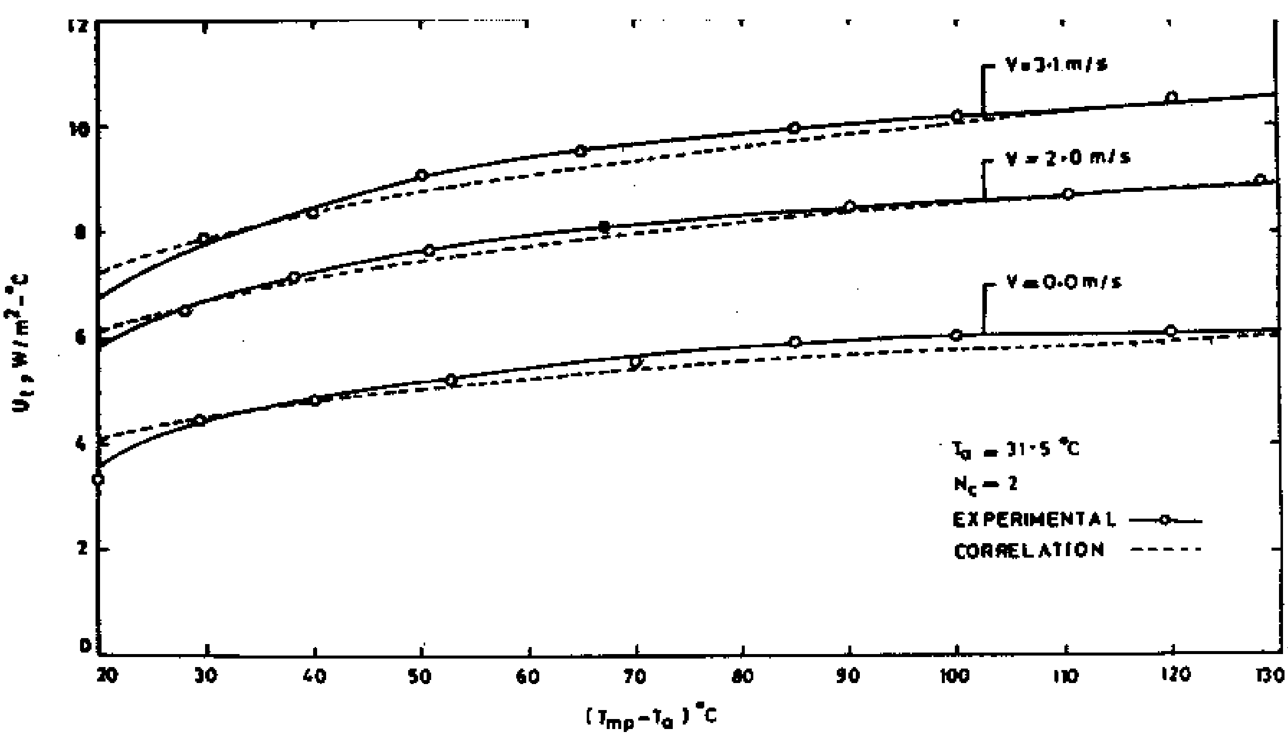

Fig. 3.6 Top heat loss coefficients (Nc = 2). Channiwala and Doshi (1989)

Increasing the glass number from one to three or four decreases the heat loss coefficient up to 40 % (Channiwala and Doshi 1989), but it becomes even more difficult (and expensive) to construct.

3.4 Heat transfer from solar box cooker to cooking vessel

Thulasi Das *et al.* (Thulasi Das *et al.* 1994) have computed the different heat transfer mechanisms for various absorber plate thicknesses, cooker size and other parameters. They found out that by far the most important heat transfer mechanism is by thermal conduction between the absorber plate and the pot . Therefore a good thermal contact is absolutely essential!

They computed the cooking times for plates with a thickness of between 0.1 and 10.0 mm. (Fig. 3.7)

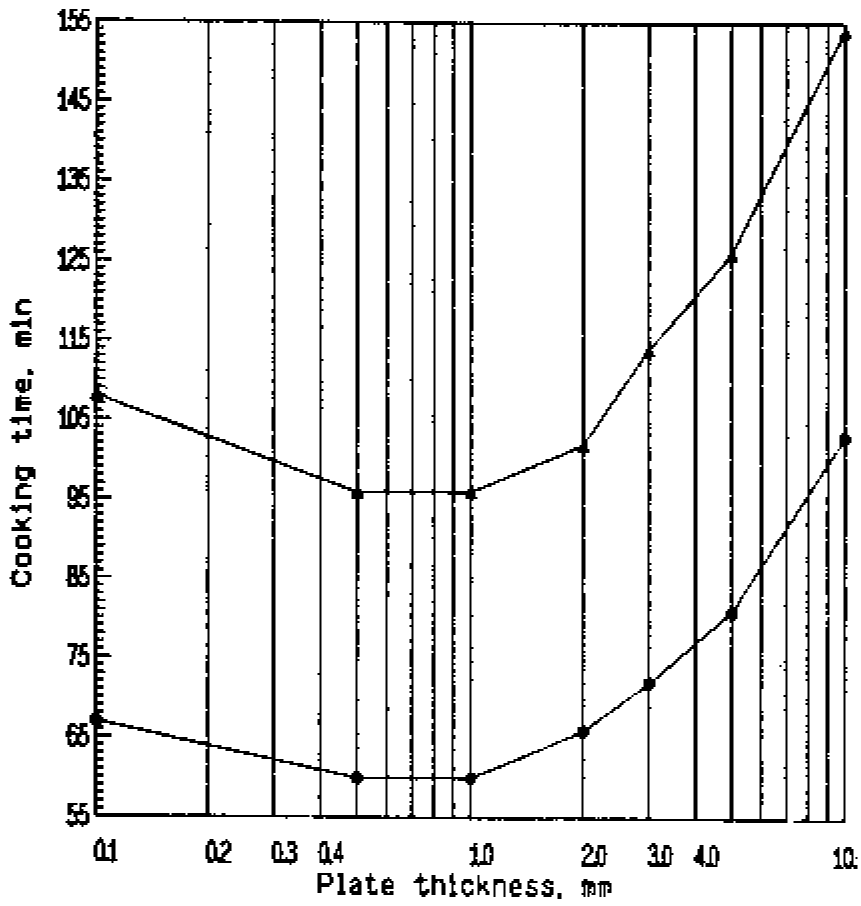

Fig. 3.7 Effect of absorber plate thickness on cooking time.Circles 15th April, triangles 10th December (Thulasi Das et al., 1994)

The cooking time was minimum for plates of 0.5 and 1.0 mm in thickness. However, to ensure a good thermal contact between the vessel base and the plate, the plate and the vessel base have to be smooth, even and rigid. Hence, the use of a 1.0 mm thick plate is advisable. The plate should be painted dull black.

Thulasi Das *et al.* computed the meaning of other parameters, such as emissivity of the vessel and the contact resistance between the vessel base and the plate. These are shown in Table 3.1.

S. No.	Upb (W/m2 K)	e	in (cm)	Cooking time (min)
1	100	1.0	10.0	60
2	100	1.0	7.5	62
3	100	1.0	5.0	66
4	100	0.5	7.5	66
5	50	0.2	7.5	72
6	20	1.0	7.5	84

Table 3.1. Effect of contact resistance, emissivity and insulation on cooking time (Thulasi Das et al. 1994)

Thulasi Das *et al.* considered an insulation thickness of 7.5 cm adequate. The emissivity e (of the cooking vessel) between 0.5 and 1.0 (compare S. No. 2 and 4) did not make much difference. This was because the radiative transfer to the vessel was not very significant. Hence, weathered (oxidized) stainless steel (e = 0.5) or aluminium (e = 0.4) vessels can be used without the black paint. On the other hand, users might consider a black exterior aesthetic, and when they paint the base tray black they could use the left-over to paint the pots. Paint also protects the outer surface of the pot.

With the increase in the contact resistance (1/ Upb) the cooking time increased considerably. Therefore the plate and the vessel base should be as smooth, even and rigid as possible to ensure a good thermal contact as mentioned earlier. A thin glycerol film between the vessel base and the plate can enhance the coefficient (Upb) by threefold and thus improve the thermal contact.

Grupp *et al.* (Grupp *et al* 1991) have computed that elevating the absorber plate slightly has the advantage of higher air temperature inside the cooker. Its drawback is a larger heat transfer between the absorber and the air in the box, which means higher heat losses. Elevating the absorber plate does not give any significant advantage, therefore it is not necessary.

3.5 Structural materials used for a solar box cooker

3.5.1 Introduction

Structural materials used for solar box cookers in industrial countries can be anything technologically appropriate. They (and thus the price of the cooker) depend only on the customers' wishes. This is not the situation with most of the people in the developing countries. Materials used for their cookers (and why not for ours, too) should be easily available, inexpensive, easy to repair and replace. The more the materials can be manufactured locally, the better. The possible materials for the structure include cardboard, wood, plywood, masonite, bamboo, metal, cement, bricks, stone, glass, fiberglass, woven reeds, rattan, plastic, papier mache, clay, rammed earth, tree bark, hardboard, reed, adobe bricks, cloth stiffened with glue, etc. (Aalfs, 1992). The list could be continued endlessly. Finally the cost, availability, personal wishes and humidity of the climate determine which ones are applicable in each case.

A common and widely available totally free or low-cost cost material is corrugated cardboard. It has been criticised for poor durability and not being waterproof. However, if the box is designed and constructed properly, it is possible to make a cardboard cooker, which lasts for years with everyday use.

I saw cardboard solar box cookers in Namibia that have been used continually since 1992. Most of those cookers are still in very good operating condition. Only one of them has become a little bit soaked, but it stayed out night and day for eight months last year.

3.5.2 Moisture resistance: using a vapour barrier

When using cardboard (or any other material that will be easily soaked) it is crucial to make a good vapour barrier inside the box. Water that vapourises from food while cooking will soak the materials of the cooker if it is not prevented from entering to the structure. For example, a strong, plastic-coated aluminium foil can be used to seal the inside of the inner box so, that moisture can not penetrate through the foil to the cardboard. This has to be done very carefully, as hot steam or water vapour can penetrate the smallest holes.

3.5.3 Practical experiences of materials in Namibia

I made one cooker from corrugated plastic (polypropylene profile or fluteboard, idea: Magney 1992) in Finland and brought it to Namibia. In comparison to a cardboard cooker of a similar design (Figs. 3.8-3.9) it proved very effective (and being a beautiful white, also attractive to the people). In Namibian autumn conditions the maximum cooker air temperature inside the polypropylene cooker was 20 C higher than the maximum air temperature inside the cardboard cooker.

Due to primitive test conditions and lack of equipment I could only measure water temperature inside the pot of the cardboard-cooker. I assumed that the water temperature inside the pot of the polypropylene-cooker was similar, due to strong steam formulation from both pots at the same time. The only difference might be a slightly faster increase in temperature, which has no real importance under those conditions. Anyway, it took exactly two hours for water to reach the boiling temperature in the morning, and it continued boiling till the end of the test in late afternoon. Clouds appearing in the sky (which can be seen as three sudden drops in the radiation level in Fig 3.9), had a delayed lowering effect on the air temperature, but the water temperature remained constant from the beginning of boiling. The wind was from low to moderate during the whole testing time.

Solar radiation was very good on the test day morning. Perpendicular radiation flux was more than 1000 W/m2 from the very beginning of the test, therefore one could begin solar cooking when the sun came up. This would speed up solar cooking if the cook is in a hurry. At the other end of the day, perpendicular radiation remained high until the end of the test at four o'clock.. My experiments between February and May in Namibia showed that solar cooking can be continued up until 5-7 o'clock, depending on the weather and month. By using an adjustable reflective lid, horizontal radiation can be transferred almost totally perpendicularly to the cooker and thus extend the available cooking time.

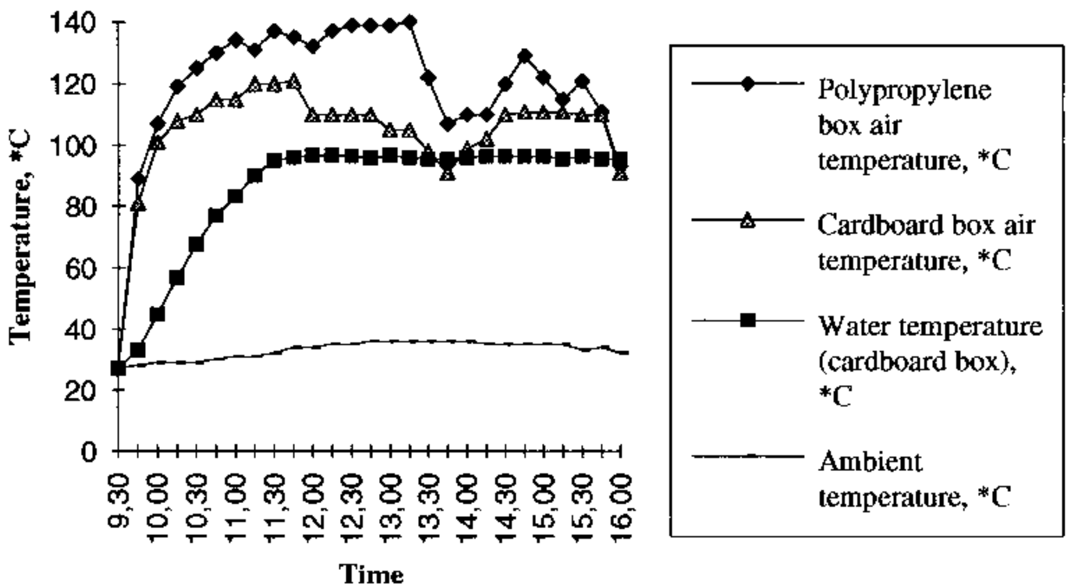

Fig. 3.8. Solar box cooker test, temperatures

Ongwediva, Namibia, April 4th, 1995

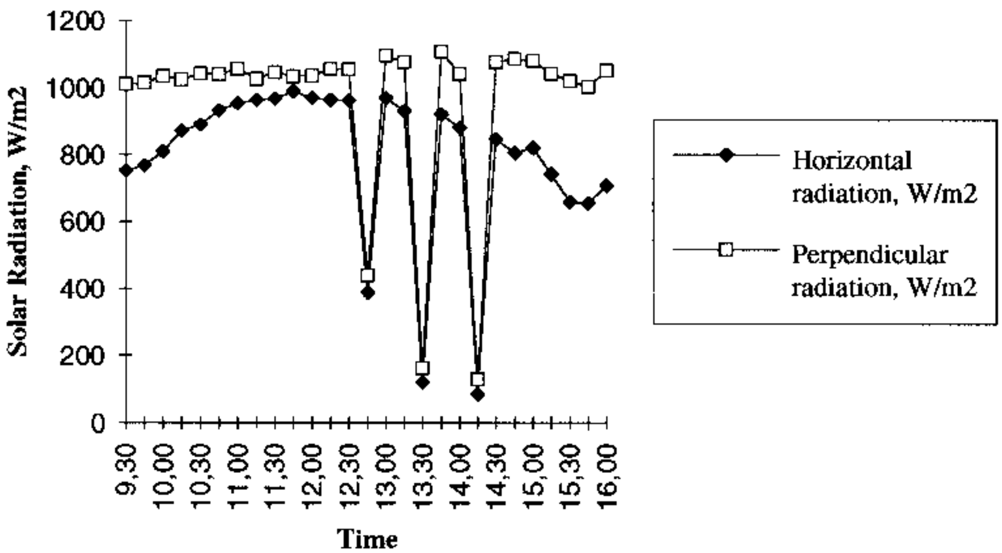

Fig. 3.9. Solar box cooker test, solar radiation

Ongwediva, Namibia, April 4th, 1995

Figs. 3.8-3.9 shows that irrespective of the fact that the polypropylene cooker reached considerably higher temperatures, the cardboard cooker is perfectly sufficient for good solar radiation areas, such as Namibia. The sudden drops in temperatures and radiation are caused by clouds. If the weather would have continued cloudless, the curves would have followed (almost) linear lines till 14.30, when the clouds disappeared.

Test equipment: Two solar box cookers (Design: Appendix two, polypropylene model made by myself, cardboard model made by women at the building course). Two 5-litre pots with glass lids with one litre of water at ambient temperature inside each (manufacturer: Hackman Oy Ab, Finland). Two oven thermometers, (manufacturer: Suomen Lämpömittari Oy, Finland) and a Fluke 51 thermometer with j-type bi-metal probe.

3.6 Materials and design of the transparent top cover and reflective lid

The material of the transparent top cover (or window) can be glass, plastic or some other suitable heat resistant material. Glass is widely available in developing countries and therefore by far the most common material used. Glass has some disadvantages; it is heavy, awkward to carry and it breaks easily. Despite these facts glass is difficult to surpass, because it is a relatively low-cost material, and easy to get and replace. One other important aspect is that when glass gets hot it does not become distorted, as many plastics do. If many cookers are planned, for example, to be transported by aeroplane to refugee camps, a heat resistant plastic window is a good choice because it is light and durable compared to glass.

Several substitute materials for glass are under development. For example, Solar Cooking International (SCI) is using a plastic film on some of their cookers. It is a special heat resistant polyester that is also somewhat resistant to the effects of ultra-violet light. It is produced experimentally by the 3-M Company. (Source: electronic mail from Kevin Coyle; SCI Resources Co-ordinator, 22.6.1995)

Whichever window material and number used, it is very important to seal them properly. Air leaks between the window and the cooker frame reduces the temperature drastically. A suitable sealing material can be silicone sealing strip with silicone glue (see Appendix two). Another possible sealant, if silicone is not available or it is too expensive to use, could be strips cut from common plastic foam, or even a narrow strip of cardboard (in a case of emergency).

The reflective lid can be just a thin plane, which is coated with aluminium foil. The area of the lid should be equal to, or bigger than, the area of the window. Boosters can be used to maximise solar radiation transfer to the box. One way to do this is to make an extra reflector, which is attached vertically to the lid. The extra reflector can be a little bit bent (convex) to concentrate solar radiation inside the box.

If the food is to be kept warm after cooking, it is advisable to design the lid to help in this task (see Appendix four). A thin lid does not prove effective enough to prevent the heat from escaping through it and the glass, after the solar radiation to the box has ceased. A thicker lid with some insulation in between (and good sealing to the glass) helps to keep food warm even several hours after cooking, when closed carefully. Heat retention can be rendered even more effective by putting a blanket on top of the closed lid.

The reflective material should have high specular reflectance, high durability, and, of course, low cost (Funk and Wilcke 1992).

Material	**Durability**	**Cost**	**Specular reflectance**
Mirrors	Breakable	Very high	0.88
Aluminium foil	Tears	Moderate	0.86
Aluminium sheet	Good	High	0.85
Aluminised polyester	Tears	Moderate	0.75-0.85
Metal from fuel tins	Rusts	Moderate	not available

Table 3.2. Potential reflector materials and normal specular reflectance

(Funk and Wilcke, 1992)

None of the available materials can fulfil all the necessary expectations. It should also be easily available locally in developing countries.

In Namibia, the same reinforced aluminium insulation foil, which was used for foiling the inner walls of the box, was also used as reflective material for the lid. It proved to be much more tear resistant than normal aluminium foil and thus is to be recommended. Its specular reflectance is not available. It looked slightly dull compared to the kitchen foil, but it worked adequately well.

3.7 Size of cooker and volume of cooking chamber

The size of the cooker is an important factor not only for the amount of food it cooks, but also it dictates the cooking time. As a rule, the bigger cooker (and thus the bigger surface to receive solar radiation) you have, the more and faster you can cook. However, the design of the cooker is a much more important factor than it would seem at first sight.

Malhotra *et al*. have measured the effect of reducing the cooking chamber volume (Malhotra *et al*. 1983). They changed the inside of the box from a square shape by tilting the inner angle to four different shapes and got a considerable improvement in its performance (see Fig. 3.10)

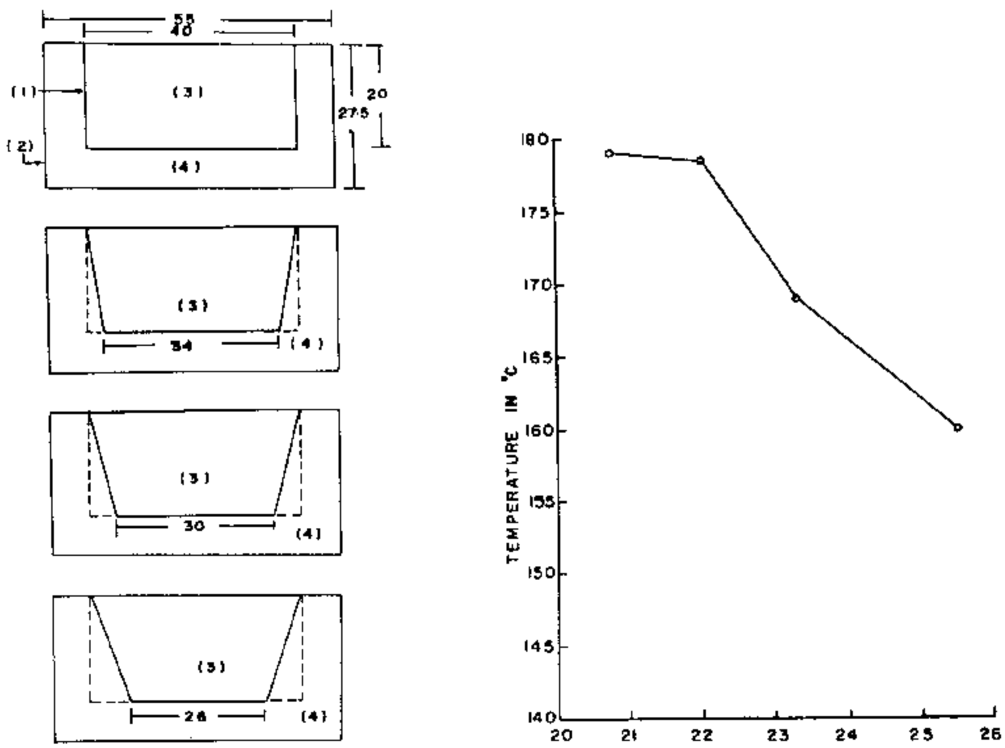

Fig. 1. All dimensions in cms (1) Inner shell. (2) Outer shell. (3) Cooking chamber. (4) Fibre glass insulation.

Fig. 2. Volume of cooking chamber in thousand Cu. cm.

Fig. 3.10. Effect of cooking chamber volume on the air temperature inside.

Malhotra et al. (1983)

They calculated that the optimisation factor (Fo) of the optimised cooker is:

Fo = Volume of chamber/Area of window 14 cm (4)

provided the concentration ratio of the reflecting assembly is 3.6.

In any case, Fig. 3.10 can be seen more as a guide-line to the tilting of the inner side of the box. Tilting it too much is not advisable because the base tray surface area (= main heat conduction surface area) also decreases.

3.8 Estimate of efficiency of solar box cookers

Estimating the power efficiency of a solar box cooker in theory is a complicated task due to multiple heat gain, loss and transfer mechanisms (for calculating energy balance alone, see Thulasi Das *et al*. 1994). I do not even try to include these calculations here, because deriving even a rough estimate would require several pages. An estimation of thermal efficiency found from literature is between 20 % and 50 % (Kuhnke *et al.*, 1990). Another estimation says the power efficiency may be about 20 % (Currin, 1994). Still, due to sunshine being an energy source totally free of cost, the cost - efficiency ratio is more important than the power efficiency alone.

The users I have met in Namibia are more concerned about the temperature reached and the heat transferred to the food, or the cooking potential of a cooker.

My experiences from Namibia are, that one solar box cooker (TFL - type, see Appendix two) cooks enough food for at least 11 persons for one meal. The time needed was about two hours at midday, and the perpendicular radiation was around 1000 W/m2.

The results presented in this thermodynamical review are mostly based on measurements and experiments. One has to take into account his or her needs (amount of food needed to be cooked, money willingly paid for a cooker, etc.), when designing or choosing a proper solar box cooker for any climatic condition.

3.9 Conclusions (and sources of error)

This chapter deals with the most common factors of optimising a solar box cooker. It is based mostly on literature (as shown in previous chapters), as well as my own experiences from Namibia.

Solar box cookers reported in researches are different in size, design and construction. Research conditions and the equipment used are not equal either. Therefore the results shown in this chapter should be read critically and they should be seen more as guide-lines to the quite complex matter; design of a low cost, reliable and robust solar box cooker.

The main functions of a solar box cooker are to heat up (and contain heat) properly and to transfer this heat to the cooking vessel effectively. By far the main heat transfer method is by conduction from the black base tray to the bottom of the cooking pot (if there is enough space in the cooker to allow the light to reflect to the bottom).

Materials for the box can be cardboard, hardboard, wood, etc. Polypropylene plastic proved to function very well (see Figs. 3.8-3.9) and also to be attractive to the users. Cardboard must be coated with foil, painted or otherwise treated properly to make it waterproof (at least to some extent).

Heat loss from the cooker walls can be reduced by using extra aluminium foiled baffles between the walls of the cooker. A wall and floor thickness of 5 cm is adequate with proper insulation. The walls should be foiled in order to be waterproof and reflective (to the base tray). Insulation material can be rolled newspaper, feathers, rice hulls, dry loose material, etc. Heat loss from the transparent top cover can be minimised by using several cover layers, sealing them properly and placing the cooker in a windless place. In good solar conditions even one glass cover is good enough.

The absorber plate should be 1-2 mm thick for maximum heat transfer efficiency. It should be dull black, smooth, even and rigid. There should be a good thermal contact between the absorber plate and the cooking vessel to ensure maximum heat transfer. A thin film of glycerol can be used to enhance this.

The cooking vessel should have a tightly closing lid to prevent steam from escaping. The material of the vessel can be weathered (oxidised) stainless steel or aluminium, even without black paint. However, the paint protects the surfaces and is aesthetic. The bottom of the cooking vessel should also be smooth, even and rigid.

The material of the transparent top cover can be glass or heat resistant plastic. Glass is more widely available, but it is heavy and it breaks more easily than plastic. The cover should be sealed properly to prevent air leaks between it and the box frame. The reflective lid can be coated with reinforced aluminium foil or some other available reflective material. Boosters can be used to maximise reflection. The lid should be a few cms thick with some insulation in between, if it is supposed to keep the food warm after cooking.

The inner walls of the cooker can be tilted to enhance the operating temperature and to maximise the solar radiation reflection to the base tray.