DESIGN, CONSTRUCTION AND PERFORMANCE EVALUATION OF A SOLAR BOX COOKER

AKINBOLUSERE, AKINWUMI OLUROTIMI
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CERTIFICATION

I certify that Akinbolusere, Akinwumi Olurotimi with matriculation Number PHY/99/4102 carried out this research work in the Department of Physics, Federal University of Technology, Akure, Ondo state. Nigeria.

[illegible]/02/06

A. B. Rabiu. B.Sc. (Ilorin), M. Sc, Ph. D. (Nigeria)
Supervisor.

19/02/06

Prof. (Mrs.) I. A. Fuwape B.Sc., M.Sc., Ph.D. (Ibadan)
Head, Department of Physics.

DEDICATION

This work is dedicated to God the Father, the Son and the Holy Spirit.

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ABSTRACT

The design, details of construction and performance analysis of box – type solar energy cooker are presented. The cooker consists of outer casing, absorber plate (cooking chamber), double-glazing coverlid, booster reflectors, which increases the magnitude of absorber temperature, i. e enhances solar radiation and reduces heat losses. The cooker is made of a 0.001 m thick aluminium tray in form of an inverted truncated square-based pyramid. Its base is 0.7 m x 0.4 m and the slanting height is 0.18 m. The top consists of an aluminium framed double – glazed ilid with a transparent surface area of 0.8 m x 0.5m. The three insolation boosters consist of angle iron-framed, commercially available plane mirror, the bigger booster serves as cover for the box when not in use. The cooker can contain three cooking vessels each capable of holding 6 kg of water conveniently. Thermal performance tests of the cooker were undertaken under no load condition to determine the stagnation absorber plate and ambient air temperature. The workability of the cooker was determined. Sensible heat tests were carried out to determine the time required to boil given quantities of water and the cooking times of various food items. Maximum temperature of 141^0C was recorded during the test period for the absorber plate. The thermal efficiency of water heating, efficiency of solar cooker, and energy efficiency of the cooker were 48.26, 44.85% and 41.37% respectively, this is greatly influenced by the direct radiative intensity, ambient temperature and wind speed.

CHAPTER ONE

Introduction

1.0 Background

Petroleum energy supplies most of the energy for production in industries and agriculture. In most cases these applications are for low temperature energy uses. Due to scarcity and high cost of conventional fuels, their use in the low temperature applications uses such as water heating, water pumping, irrigation and cooking must be cut down low and energy for all these must be substituted by solar energy.

Solar energy can be tapped at a relatively low cost and has no associated danger of fire or other hazards. Therefore the use of solar energy for urban and rural development cannot be overstressed. One application that would be of immediate appreciation is to use it for cooking in the rural communities, which is particularly useful during the period of abundant sunshine and scarcity of convectional cooking fuel for cooking. It is noted that at times of scarcity of kerosene or gas, demand for fuel wood and other alternative energy is very high and this is not peculiar to the rural areas alone. An example of this problem is seen during the political imbroglio in Nigeria between 1993and 1994 when the staff of petroleum and natural gas industries went on strike for many weeks.

It is appreciated that wood is the most important resources for direct energy conversion and it is estimated that 90% of the energy needs of the population of developing countries is derived from wood (Charteji, 1981). Apart from the attendant problem that the ecology is destroyed leading to desertification, particularly in the sahel region, the use of fuel wood may be hazardous and not as clean as other cooking fuels such as kerosene or gas. Such health hazards include respiratory infections, chronic and obstructive lung diseases, and low birth weight and eye infections. It has been suggested that the hazards can be reduced by adopting open air heating system that will reduce the level of concentration of the emissions during wood burning.

The ultimate need of people is not necessarily energy but the services, which it provides. These services include heating, cooking, lighting, and mobility and motive power. Long time ago Ghosh (1986) observed that people are becoming more conscious of the role of energy in human life. The operation of our technological society depends upon the production and use of large amounts of energy. Nigeria which lies in the tropics (latitude $4^{0}\ 16'$ and $13^{0}\ 52'$) is endowed with abundant sunshine. Sunshine is available to Nigeria all the year round with daily sunshine hours in the southern part averaging about 8 hours during the dry season and about 4 hours during the wet months (Adefolalu, 1986).

Higher values of daily sunshine hours are obtainable in the northern part of the country. Nigeria is endowed with divers energy sources most of which can be adopted for cooking. These sources are broadly classified into renewable and non-renewable energy sources.

1.1 Renewable Energy Sources

These are energy sources that are constantly replenished or regenerated and will never run out. Wind energy, solar energy, wave or ocean energy and hydropower are typical examples.

Wind energy is abundant in Nigeria. Wind regimes are high with yearly average value of 25.7 MWh/year for Lagos and 97 MWh/year for Sokoto at a height of 25m (Ojosu and Salawu, 1990). The nation has an estimated coastal length of 300 kilometers, which could be explored for power generation. The overall hydropower resources potential exploitable in Nigeria amount to over 11,000 MW (Odukwe and Enibe,1988).

Of all these renewable energy sources, only solar energy can be directly applied for cooking. Nigeria is blessed with abundant solar energy as it lies within the high sunshine belt of the world. The average yearly solar radiation on a horizontal surface varies from about 3.7 kWh/m^2 day along the coastal areas of the south to about 7.0 kWh/m^2 along the semi-arid areas of the north (Odukwe and Enibe, 1988). On a monthly basis, average solar radiation level ranges from 3.56 kWh/m^2 during the hot season. Greater percentage of the country receives an average of about 5.081 kWh/m^2 of solar radiation (Odukwe and Enibe, 1988). This represents large energy potentials making it the most abundant energy source available in the country.

1.2 Non-Renewable Energy Sources.

These are energy sources that are depletable or exhaustible. But these energy sources play a crucial role in our efforts to meet daily energy needs and perhaps will continue to do so for a foreseeable future.

These energy sources include fuel wood, petroleum, natural gas, which historically, have continued to meet man's energy needs. Wood is the traditional and most popular source of energy for cooking. It is used for domestic cooking, baking, and heating. It is also widely used in small-scale industries such as bakeries. The largest sources of fuel wood are communal bushes and farm lands.

The projected wood consumption for the year 2000 is 23.6 million tones of Oil equivalent. Unfortunately, continued felling of trees causes erosion and desert encroachment associated with deforestation. This has a negative effect on the exploration of environment. There is also no coordinated effort to conserve it. Another source of cooking fuel is Coal. Coal is a black sedimentary rock formed from the remain of decaying plant or organic matter. There is enormous resource of coal worldwide with estimates well over 10^{12} metric tones of which 75% is black coal while 25% is brown coal or lignite. Nigeria's coal resource is estimated at about a billion metric tones. There is an additional estimate of about 22×10^6 tons in Lafia and about $100\text{x}10^6$ tons of lignite along a belt covering Nnewi-Asaba-Ugwashi. Nigeria's coal can be carbonized and converted into smokeless fuel. Although coal has a higher calorific value than wood. It is also more expensive. It should be noted that both wood and coal produce a lot of CO_2 during combustion process and also some toxic CO is produced too. It is suspected that these gases are the cause of respiratory diseases (World Energy Council, 1993).

Petroleum is the dominant primary energy source in Nigeria. Petroleum is a mixture of hydrocarbon produced from sedimentary rock and sand deposit below the earth's surface A peak production of 2.3 billion barrels per day was reached in 1979 (OPEC Bulletin, 1994). Significant quantity of liquefied petroleum gas is produced but about 80% of the gas is flared at the flow station. The operating refineries have a total capacity of 445,000 b/d (Oni, 1992) and kerosene which is one of the end products is used for cooking. Kerosene's stove is widely used in homes. They produce fewer pollutants than coal and fuel wood. Nigeria is also endowed with large reserves of natural gas. Development of the liquefied natural gas industries is now a reality. Cooking gas is obtained from both petroleum and natural gas.

Electricity is a good source of energy for cooking. Two types of electric power generation are employed in the country. They are hydroelectric power generation and thermal –electric power generation. In 1990; National Electric Power Authority (N E P A) had installations that could generate electricity to a capacity of 5988 MW (Sheyin, 1995). The demand for electricity continues to increase. The world is becoming increasingly conscious of the health hazards associated with environmental pollution. This puts electricity at advantages over the rest of non–renewable energy sources. However electricity is by and large capital intensive in generation, transmission and distribution.

One of the common perennial problems in many homes in our nation is the cost of cooking fuel. This problem is often aggravated by frequent scarcity of kerosene and cooking gas. In the process, many people suffer starvation. Consequently, there is a call to harness other energy sources. Efforts are being made to develop solar energy cookers using locally available materials.

1.3 The source of solar energy.

Sun is the source of solar energy. Sun forms an ecosystem with the earth and provides all its energy. It keeps the earth warm, raises our crops, sometimes gives rise to our petroleum and coal, and exerts virtual control on our weather and climate. The Sun is a star, one of the 10^{11} stars in our larger system the Milky way Galaxy. It is an immensely hot gaseous sphere approximately 1.391×0^{9} m and 1.51×0^{11} m from the earth. The Sun's mass and volume are $1.99\mathrm{x}10^{30}$ kg and $1.41\mathrm{x}\ 10^{27}$ m respectively. It is made up primarily of 71% of Hydrogen, 27% of Helium, and 2% of other heavier elements like Carbon, Nitrogen, Oxygen, and various metals (Duffie and Beckman, 1980).

Several fusion reactions takes place in the sun from combination of every four hydrogen nuclei to produce one helium nucleus and converting the unbalanced mass to energy. This energy is produced in the interior of the solar sphere, at temperature of many millions degrees. The Sun has effective black body temperatures of 5762 K. The temperature of the innermost region, the core is estimated between 8×10^{6} to 40×10^{6} K and the density about 100 times that of water. The sun provides directly and indirectly greater part of energy used on the earth. This energy source is renewable, it is replenished or regenerated naturally as it is being consumed. It influences climatic changes and ocean currents. It keeps the earth warm, sustains our crops (photosynthesis) and evaporates water from the earth surface which returns to us as rain.

The sun constantly emits radiant energy. There are reasons why the earth receives only a small proportion of the total energy radiated into space by the sun. First, it is due to the rotation of the earth and the sun's elevation. This gives rise to day and night and also determine the amount of light received at any point on earth at any given time. Secondly, the energy received decreases inversely as the square of the earth –sun distance which is 1.51×0^8 km. The ozone layer prevent the harmful Ultraviolet and infra –red rays from reaching the earth surface. It is the helpful Sun - rays that reach the earth. The energy from the sun per unit time, received on a unit area of surface perpendicular to the direction of propagation of radiation, at the earth's mean distance from the sun, outside the atmosphere is known as solar constant. It is estimated to have a value of about 1353 W/m^2 (Duffie and Beckman, 1980).

Variation of the earth – sun distance, however, does lead to variation of extraterrestrial radiation flux in the range of ± 3% .The dependence of the extraterrestrial radiation on the time of the year is

$$I_{m} = I_{S_c} \frac{1 + 0.033 Cos 360n}{365} \qquad 1.0$$

I - extraterrestrial radiation measured on the plane normal to the radiation on the nth day of the year. Solar radiation is usually of three components namely diffuse, reflected, and direct radiation.

1.4 Application of Solar Energy.

Solar energy is abundant and renewable but it is thinly distributed over a wide area .In order to collect solar energy for specialized application you need new specialized devices. Some examples include solar collector for domestic and hot water production. The applications of solar energy are in the following areas.

- Solar energy cells /photovoltaic technology
- Solar energy --thermal applications.

Photovoltaic systems are used to generate electricity using solar cells. Solar thermal energy can be used in application such as, water heating, crop drying, cooking refrigeration, and space cooling. In view of the problem discussed in the preceding sections, solar energy cooker appear increasingly attractive as supplement to conventional cookers.

The impact of solar energy cookers on the economics of developing countries and the global ecology has been well articulated (Adams, 1976). Its operation is pollution free and environmentally friendly.

1.5 Aims and Objectives

The aims and objectives of this project are to -:

- Design and construct a box - type solar cooker, using locally available materials.
- Determine the performance of the cooker.
- Evaluate the performance of the solar cooker during the rainy season, with a view to modifying it for greater efficiency.

CHAPTER TWO

Literature Review

2.0 History of Solar Cooker.

The history of solar cooking goes far back in time. The first known solar cooker pioneer was a Swiss, Nicholas de Saussure (1740-1799) who built his black insulated box cooker with several glass covers. Even without reflectors he reached a temperature of 88°C(191°F). In Africa the first user was an Englishman, John Fredrick Herchel, in 1837. He used a black box made of hardwood with a double glass window (without reflectors). He buried the box in sand for insulation and reached a temperature of 116°C. In 1878, Williams Adams, in Bombay India used glass planar mirrors arranged in the shape of an inverted eight-sided pyramid that focused light through a cylindrical bell jar into the food container (Meinel and Meinel 1979).

Samuel Langley an American in 1884. He used a Box–type Cooker on Mount Whitney, California, at an altitude of over 4 km (Cheremisinoff and Regino, 1978). It is admitted that solar energy cookers cannot completely replace other types of cookers because it cannot work in the absence of sunshine. However, if it is well improved and used on sunny days, much of the expenditure on energy for cooking will be curtailed.

Pande and Thanvi, (1988), designed and developed a solar cooker cum drier. This dual-purpose device was found useful not only for cooking food but also for dehydrating fruits and vegetables. It was extensively tested for cooking, boiling and roasting different materials viz, rice, potatoes, cabbage and so on. It was found that cooking can be done within 90 minutes during summer and within 120 to 180 minutes during winter, if the cooking is started by 11.00 am. Nahar (1993) developed a large sized solar water heater cum solar cooker. Its performance was satisfactory. The device could be used as a non-tracking hot –box solar cooker. Although the device was comparatively expensive, it has an estimated life span of 15 years.

In Nigeria, some scholars have made notable efforts in this area of research. At Sokoto, Bajpai and Musa (1989) constructed a hot –box solar cooker. A booster reflector was added to improve its performance. On testing, a maximum temperature of 158°C was attained by the absorber plate. At Nsukka, Nworie and Nwibe (1994) constructed another model of hot-box solar cooker. Onyishi (1992) designed and constructed a concentrating solar cooker. Experimental result showed a concentration ratio of 37.78 and an efficiency of 13.69 %. At Akure, Adegoke and Fasheun (1998) designed and constructed a box – type cooker. A temperature of 50°C above ambient temperature was attained on 1200 ml of water in a pot inside the box cooker over about 4 –hour period. Mean collector efficiency, and instantaneous was 15.4% and 32.7%. At Ile – Ife, Pelemo, et, al (2002) designed and constructed a focusing – type solar cooker. The thermal efficiency was measured to be 60%.

2.1 Different Types of Solar Cookers.

Since the days of the earliest pioneers, hundreds of different types of solar cookers have been invented and tested (Grupp, 1991). The laws of thermodynamics determine those factors that make a solar cooker fit for use.

The solar cookers in use usually belong to one of the three main categories.

- ➢ Box type solar cookers
- ➢ Parabolic concentrators
- Flat –plate collector system. (Grupp, 1991 and Kuhnke, 1990).

2.1.1 Box type Solar Cooker

A typical box type solar cooker consists of an insulated box with a transparent cover made of glass or plastic (Fig 2.1). Usually, the box also includes one or more adjustable external flat reflectors (boosters) in order to enhance solar radiation into the cooker (Grupp, 1991). The operation of a solar box cooker is based on the greenhouse effect. The maximum temperature is about 150°C. Classical box cookers are more practical in use than concentration cookers, since they do not need tracking. On the other hand, their thermal performance are often quiet poor, mainly due to a bad heat transfer into the pot.

2.2 Parabolic type concentrating solar cooker

A parabolic concentrator solar cooker has a collector, which consists of either a reflecting or transmitting concentrator concentrating the solar irradiation onto a focal point (Fig 2.2) the cooking pot is placed at the focal point. The advantages of this type of concentrator system is that they can reach high useful temperature, on the other hand, the need for frequent tracking forces the user to work in the sunshine under particular strenuous condition of heat and glare (Grupp, 1991).

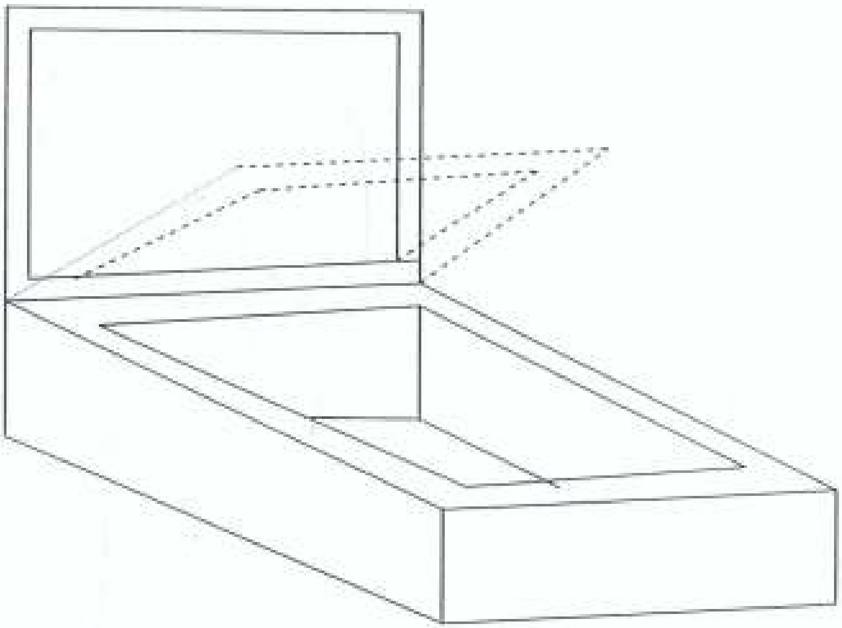
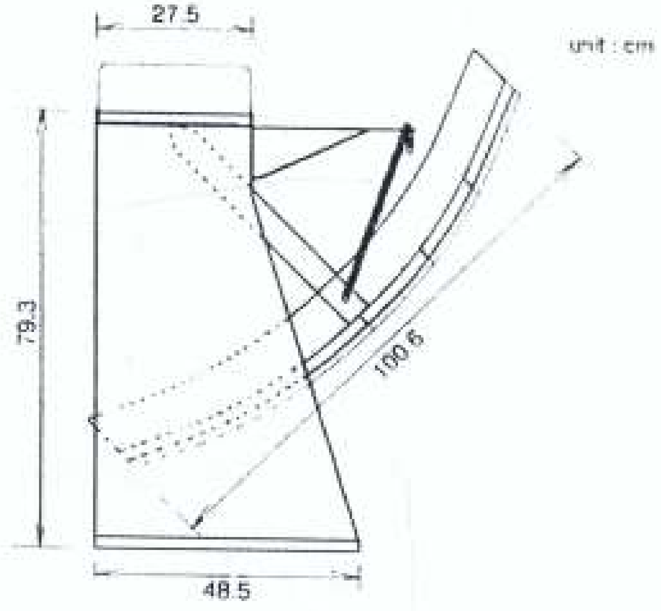


Fig 2.1 Box-type solar cooker



Side elevation of the solar cooker

Fig. 2.2 Parabolic type Solar cooker

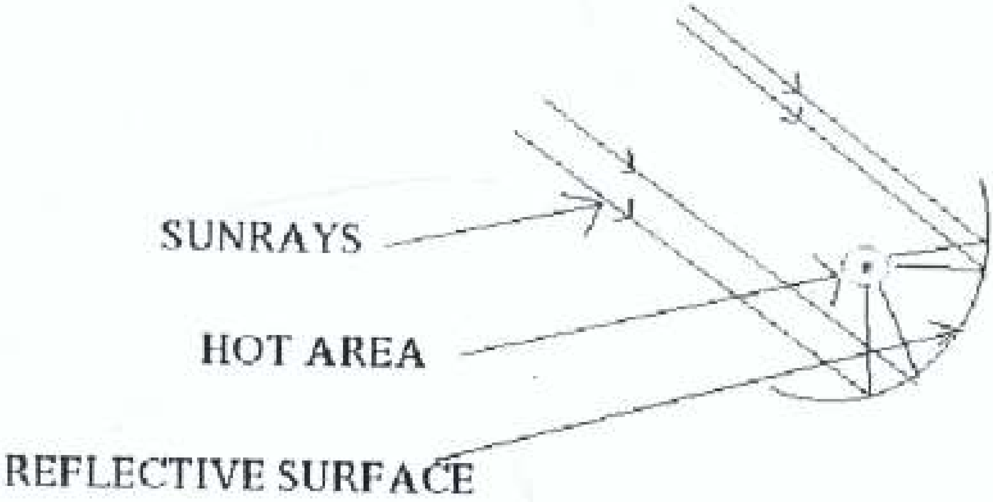


Fig .2.3 Concentrator Concentrating the Solar Irradiation onto a Focal Point

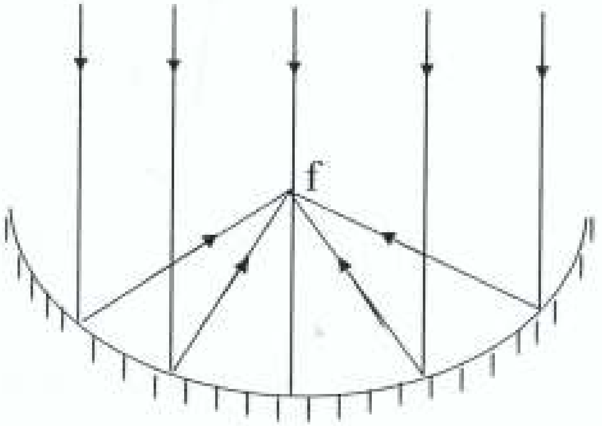


Fig. 2.4 Parallel beam on a concave mirror

Parabolic concentrators have good thermal efficiency and reach high temperature, but require frequent "tracking"that is, changing the position of the device according to the Sun's position. Different configuration of this concentrator range from shallow –dishes to deep –dish models (Hougshen and Sears, 1995). Some are made to have a continuous reflecting surface while others have series of concentric rings which are so supported to focus radiation at an angle point, as shown in Figure 2.3 and 2.4. The focal point is considerable diffuse due to imperfect fabrication. A temperature range of 150°C to 400°C can be obtained at the focal point and with carefully constructed collectors a temperature of 500°C and above can be attain at the focal point (Garg, 1976).

2.2.1 Problems of concentrating Solar energy Cookers

Concentrating solar cookers have some inherent problems .The problems are related to optics, geometry, operation and cost. Viz:

- Frequent re-orientation of the concentrator is needed for the purpose of proper tracking of radiation.
- Cooking must be done under the hot direct radiation of the Sun. This could be very inconveniencing to users. Only the cylindrically parabolic type can be designed to avoid this problem.
- Users may suffer burns or eye injury when in contact with regions near the focus.
- They cannot work in the absence of sunshine. And their efficiency under diffuse radiation is poor.
- Concentrating reflectors are very scarce, difficult to produce and expensive.

2.2.2 Advantages of concentrating solar energy cooker.

In spite of the above limitation, concentrating solar energy cookers have many remarkable advantages over the solar box –cookers.

Some of the advantages are;

- Fast cooking is achievable because of inherent high temperature of operation.
- Need for maintenance is minimal.
- Some can be adapted for remote cooking.
- They offer users more convenient access to pot.

2.3 Flat plate collector systems.

A solar cooker is called a flat plate collector system if its collector part and its cooking vessels are physically separated, either in different cases or in different compartments of the same casing and if its collector system is of a flat plate type, within or without booster mirrors (Kuhnke, 1990).

The flat plate solar cooker consists of two main units namely the flat plate collector and an insulated cooking chamber. Flat - plate collectors can be designed for application requiring energy delivery at moderate temperature, up to perhaps $100^{0}C$ above ambient temperature. They use both beam and diffuse solar radiation and do not require tracking of the sun (Grupp, 1991). Usually the collector is made up of tubes, which are thermally bonded to highly conductive fins and are fitted in a well insulated box as in Fig 2.5. The lid of the box is made of two sheets of glass that are framed and hinged on one side. The entire collector is mounted on an inclined stand in a way that would permit maximum solar energy reception. When water contained in the collector pipes is heated, steam is generated, this is directed to the cooking chamber by means of an insulated hose.

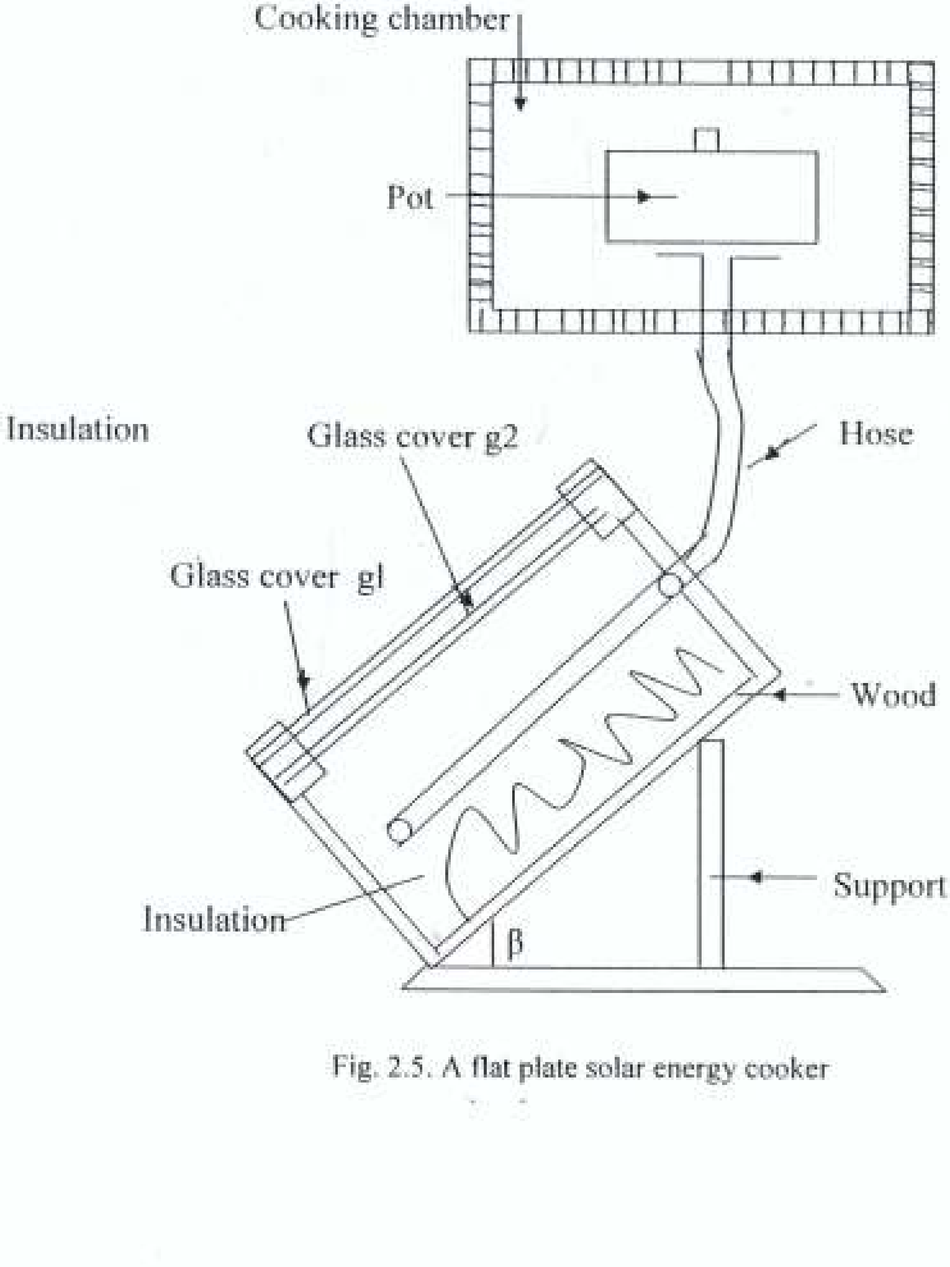


Fig. 2.5. A flat plate solar energy cooker

Steam in this operation is below 100°C. Cooking time is comparatively long. It is best suited for preparing food items that require long and slow boiling. It can be adopted for indoor cooking (Pejack, 1990).

The advantages of a flat plate collector are; they do not need tracking, they allow for unattended cooking in the shade, if the kitchen part is situated in a building or under a roof.

2.4 The working principles of Flat Plate collectors.

A Solar collector is a special kind of heat exchanger that transforms solar radiant energy into heat. It differs in several respects from mere conventional heat exchangers. The latter usually accomplish a fluid –to – fluid exchange with high heat transfer rates and with radiant energy as an unimportant factor. In the solar collector, energy transfer is from a distant source of radiant energy to a fluid. The flux of incident radiation is approximately 1100 W/m^2. The wavelength range is from 0.29 mm to 2.5 mm, which is considerably shorter than that of emitted radiation from most energy absorbing surfaces.

The basic features of a flat plate solar collector are shown in Fig. 2.6. Both the outer cover and the inner cover are made of materials, which have high transmissivity. Solar radiations that impinge on the collector surface get to the absorber plate by transmission through the covers. This raises the temperature of the absorber plate to a very high degree. Heat is transferred from the plate to fluid in the conduit. This is the ultimate function of the collector. The essence of the covers is to reduce convective and radiative heat losses from the surface of the plate.

Considering Fig.2.7. Energy balance on the fluid flowing through a single tube of length y can be expressed thus;

$$\{m/n\}\ C_p\ T_f|_y - \{m/n\}\ C_p\ T_f|_{y+y} + yqu = 0 \qquad 2.0$$

The maximum possible useful energy gain (heat transfer) in a solar collector occurs when the whole collector is at the inlet fluid temperature. At this point, heat loses to the surrounding are at a minimum. As mentioned earlier on the ultimate function of the collector is to transfer heat to the working fluid. Therefore, the actual energy gain Qu, is a very important parameter. It is expressed in terms of the collector heat removal factor and the maximum possible useful energy gain.

$$Q_u = A_c F_R [(S-U_L) T_f - T_a)] \qquad 2.1$$

The useful energy gain of a collector is a measure of its effectiveness. (Hottel, 1958) have shown that the above generalization relationship apply to all non – concentrating collectors.

Where -; Q_u - actual energy gain,

n - Number of parallel tubes,

Ac - aperture area,

S - surface area of collector,

U_L - overall loss coefficient.

m - total mass flow rate kg/s

T_a - ambient temperature

F_R – collector heat removal factor,

T_f - outlet fluid temperature,

2.5 Shortcomings of Solar Box –Cookers.

Like the concentrating cookers, the solar box –cookers have some inherent problems. They include;

- They can only be used on sunny days.
- Long cooking time.
- Cooking must be done under the Sun, except for flat plate solar cooker, which can be adopted for in-door operations
- Maximum operating temperature of solar box cookers is lower than that of concentrating cookers.

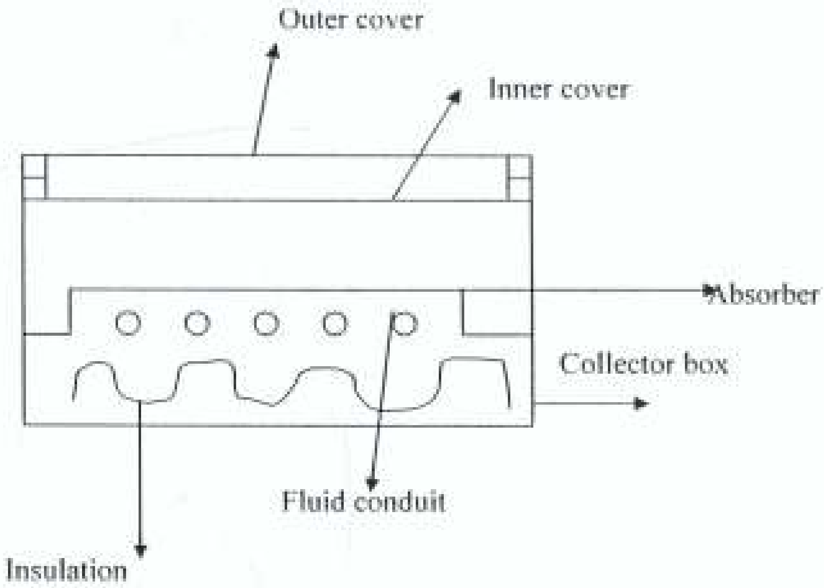


Fig.2.6. A cross –section of a flat –plate solar collector.

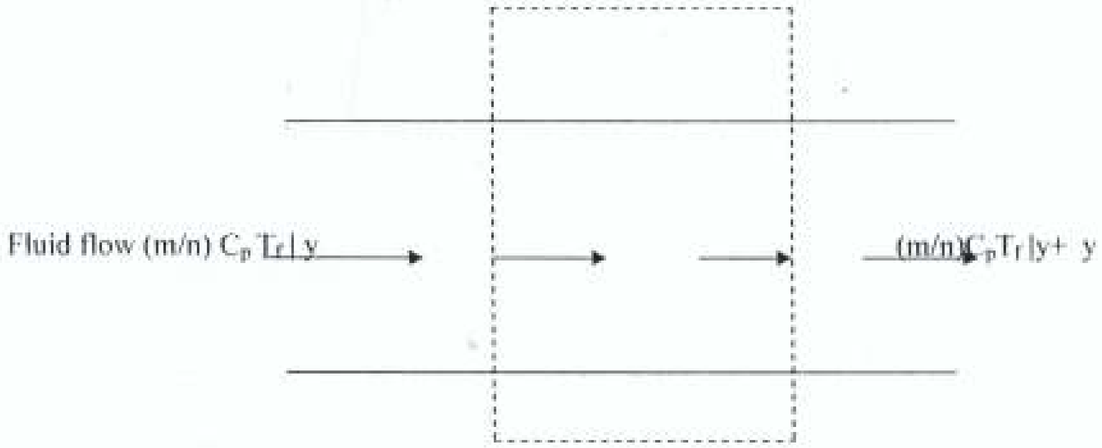


Fig 2.7. Energy balances on fluid element.

2.5.1 Advantages of Solar- Energy Box –Cooker

In spite of the limitations, solar energy box cooker have several advantages,

- Simple to operate.
- Ease of construction.
- Tracking of the sun is not necessary.
- No risk of sunburn.
- It uses both direct and diffuse radiation.
- Can be made with locally available materials anywhere.

2.6 Principle of Solar Box Cooker Design.

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. 2.8. There are hundreds of different designs of solar box cookers in use. These vary in size, material insulation and components used. (Grupp, 1991). The law of thermodynamics always determines the function of a solar box cooker, irrespective of its design and material components. (Duffie and Beckman, 1991). The most important factors that affect the efficiency of a solar box cooker excluding operating conditions include; 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. (Grupp, 1991).

2.6.1 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

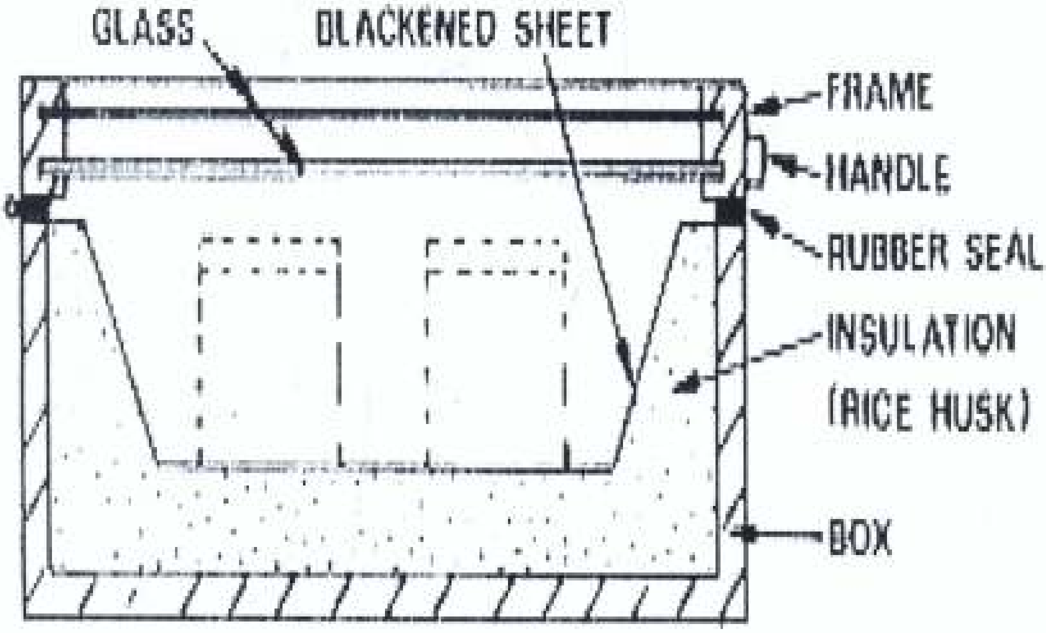


Fig .2.8. cross-section of a solar box cooker with a cooking vessel.

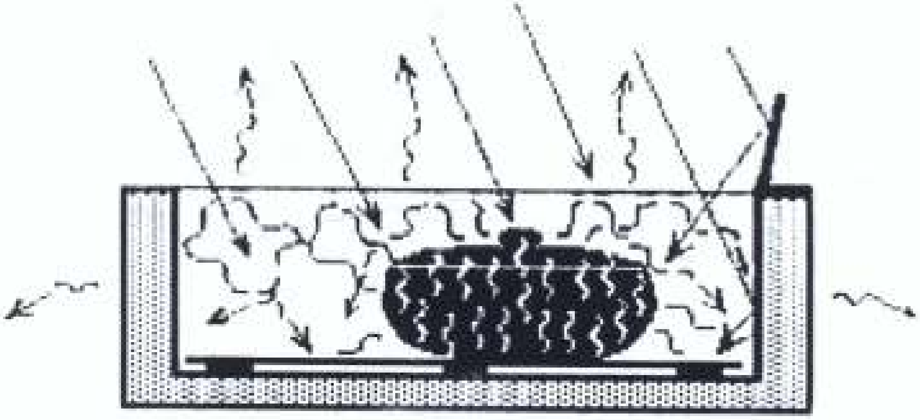


Fig .2.9. The greenhouse effect.

Fig. 2.10a

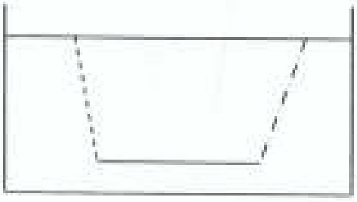


Fig. 2.10b

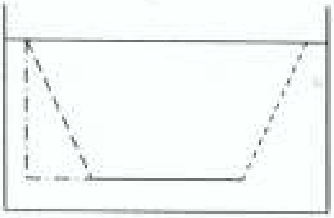


Fig.2.10c

efficiently as possible. The heat retained inside the insulated box with a transparent cover is based on the greenhouse effect illustrated in Fig.2.9. The light energy (which is short-wave energy) that enters the cooker through the transparent top cover is absorbed by the black pot 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 radiant 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 radiant heat, some does escape directly through the lid (Aalfs, 1992).

2.6.2 Heat Loss from Solar Box Cooker.

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 aluminum 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 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 gives of heat waves, or radiates to its surrounding (which are at a lower temperature). These heat waves are radiated through air or space. Most of the radiant heat given of by the warm pots inside the cooker is reflected back from the foil, bottom metal plate and glass. The transparent top cover (usually glass or plastic) traps most of the long- wave radiant heat, but some does not 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)

2.6.3 Heat Loss from Walls and Floor

Heat loss from the walls and floor consists of conduction, convection, and increasing the thermal resistance of the walls can reduce radiation, conduction from 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,

$$q^{*} = \frac{T_1 - T_2}{R} \qquad 2.2$$

Where $q^{"}$ is the heat flux (W/m^2)

R is the thermal resistance in units of m^2W/K

T_1 and T_2 are the temperature of the opposing walls of the cooker (in absolute Kelvin)

An empirical equation (Incropera and Dewitt, 1985) predicts a thermal resistance of 0.39 units for the 5.0 cm thick wall (with only air in between), when $T_1 = 368$ K (95^0C) and $T_2 = 298$ K (25^0C). Doubling of the wall to 10.0cm results in only about a 6% increase in resistance R.

Inserting thin parallel plane of material, or a baffle, causes impediment to the convection currents between the walls. An empirical equation (Incropera and Dewitt, 1985) 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 total wall resistance is;

$$R = R_{rad}(R_c/R_{rad} + R_c) \qquad 2.3$$

Where R_{rad} is the radiative resistance

R_c is the convective resistance

The relative radiation heat loss 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 aluminum foil. Another way is to insert parallel line (radiation shields) between the walls. A certain level of thermal resistance is needed for a sufficient cooker operation. In practice an adequate thermal resistance can be achieved either by inserting foiled buffles between the walls or foiling the walls and adding some filling material in between. Using all of these together brings the maximum resistance (Pejack, 1990).

2.6.4 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.

As the absorber plate temperature increases, the top heat loss coefficient increases due to higher temperature. Wind velocity increases the convective heat losses significantly and thus reduces the cooker's temperature. 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. Increasing the glass number from one to three or four decreases the heat loss coefficient up to 40% but it becomes even more difficult and expensive to construct (Channiwala and Doshi, 1989).

2.6.5 Heat transfer from solar box cooker to cooking vessel

Experiment shows that 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. The cooking time was minimum for glass of 0.5 mm and 1.0 mm thickness. However, to ensure a good thermal contact between the vessel base and the plate, the plate and vessel base have to be smooth, even and rigid. Hence, the use of a 1.0mm thick plate is advisable. The plate should be painted dull black. (Thulasi, Das, et.al. 1994).

2.7 Structural materials used for a solar box cooker

The materials used for solar cookers 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 needs, plastics, clay, cloth stiffened with glue etc.

Finally the cost, availability, personal wishes and humidity of the climate determine which ones is applicable in each case (Aalfs, 1992).

2.8 Moisture Resistance

Water that vaporizes from food while cooking will soak the materials of the cooker if it is not prevented from entering the structure. For example, a strong, plastic-coated aluminum foil can be used to seal the inside of the inner box so, that moisture cannot penetrate through the foil to the box.

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

The material of the transparent top cover can be glass, plastic or some other suitable heat resistance 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. Glass is still preferable 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. 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 special heat resistant polyester that is also somewhat resistant to the effects of ultra-violet light (SCI Resources Co-ordinator, 1995)

The reflective lid can be just a thin plane, which is coated with aluminum foil. The area of the lid should be equal to or bigger than the area of the window. Boosters can be used to maximize 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. 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 as shown in Table 2.1.

TABLE 2.1 REFLECTIVE MATERIALS

Material specular Reflectance	**Durability**	**Cost**
Mirrors	Breakable	Very high
Aluminum foil	Tears	Moderate
Aluminium sheet	Good	high
Aluminised polyester	Tears	moderate
Metal from fuel tins	Rusts	moderate

2.10 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 1983).

The cooking chamber volume is reduced by changing the inside of the box from a square shape by tilting the inner angle to four different shapes and get a considerable improvement in its performance as shown in Figure (2.10a-c)

They calculated that the optimization factor (F_o) of the optimized cooker is:

F_o = Volume of chamber/Area of window 14 cm provided the concentration ratio of the reflecting assembly is 3.6.

Tilting it too much is not advisable because the base tray surface area (= main heat condition surface area) also decreases.

CHAPTER THREE

DESIGN AND CONSTRUCTION OF SOLAR BOX COOKER

3.1 Description of the Cooker

The experimental solar energy cooker illustrated in Fig. 3.1 consist of two boxes, the outer box, rectangular in shape made of metal sheet of gauge 18, the inner box tapered and the walls are inclined at an angle 80°. The inner box is an aluminum sheet rest on the insulation and contains the cooking utensils with the food material (referred to as the cooking chamber). The dimension of the outer box are 90 cm x 60 cm at the base and at the top and 25 cm high while the dimension of the inner box are 80 cm x 50 cm at the top, 70 cm x 40 cm at the base and 18cm high. The sidewalls have the shape of an inverted, truncated, rectangular-based pyramid. The absorber plate is painted matt black. The collector surface is a double-glazed lid with the outer glass and the inner glass of almost the same area, and are fixed in frame and one hinged to the box and served as the box door. Three framed reflectors are also incorporated, the bigger reflector which served as the cooker cover is of 90 cm x 60 cm and the two additional reflectors are of 60 cm x 60 cm in dimension. They serve as an insolation booster and cover to the glazing when the cooker is not in use.

The angle of the bigger reflector can be adjusted depending on the angular position of the sun. Solar radiation that impinges on the glass surface is of three components. They include direct (beam), diffuse radiation from the sun and reflected beam from the boosters. The cooking vessels (pots) are cylindrical in shape and have flat bases so as to ensure good thermal contact with the absorber plate. The major mode of heat transfer to the vessel is by conduction via the absorber plate. Access to the cooking chamber is by raising the hinged lid.

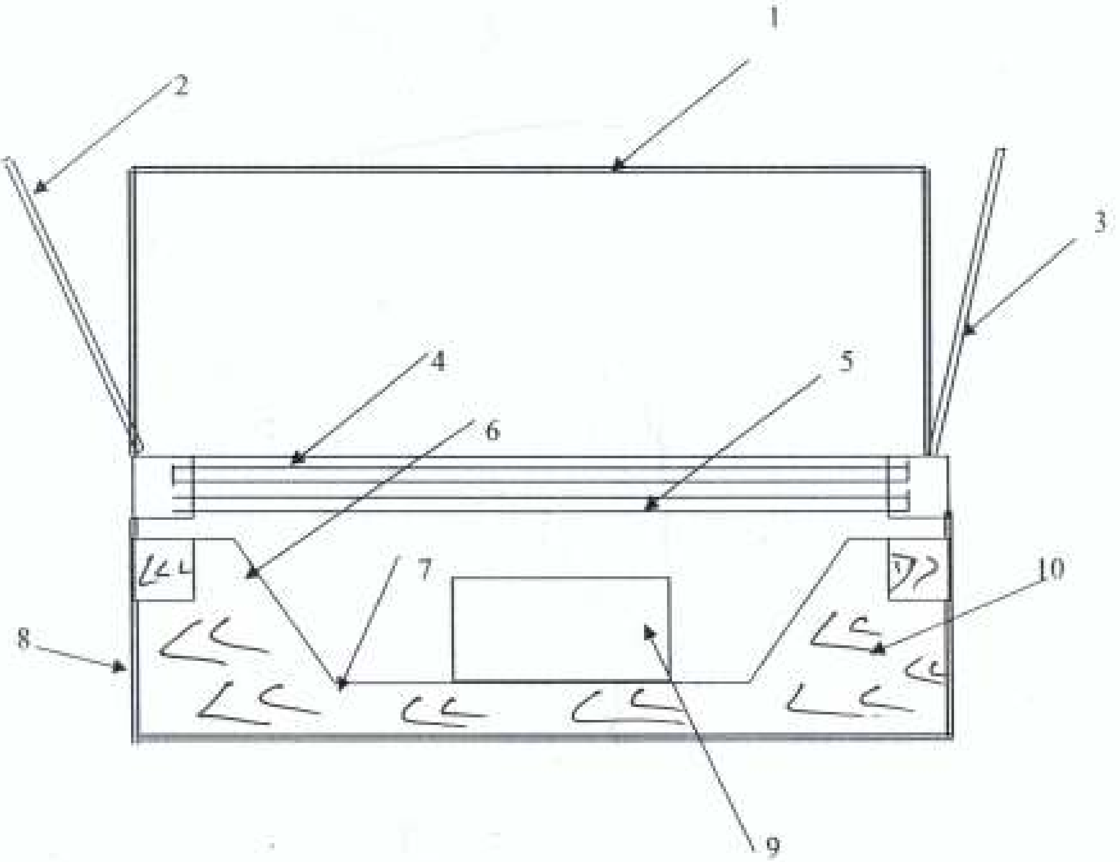


Fig. 3.1: Schematic Diagram of the experimental solar box cooker

1. Plane reflector
2. Plane reflector (left side)
3. Plane reflector (side right)
4. glass cover g1
5. glass cover g2
6. side wall (aluminum)
7. absorber box (aluminium)
8. metal box (rectangular)
9. cooking vessel
10. insulation (sawdust)

3.2 Design principle of solar box cooker (basic) Parameters

Initial water temperature; $T_1 = 28\ ^{\circ}C$

Final temperature of water attainable, $T_2 = 100\ ^{\circ}C$

Heat capacity of water at constant pressure $C_p = 4200$ J/kg.K

Mass of water to boiled $M = 1.5$ kg

Time for complete boiling $t = 60$ min

Ambient air temperature $T_a = 28\ ^{\circ}C$

Desired maximum heat loss through walls $Q_2 = 5\%-6\%$

Total Insolation $G_T = 698.02\ W/m^2$.

To achieve zero heat loss, a wall of an infinite thickness is needed in which case the equipment is too bulky for handling. The cooker is expected to function under fluctuating insolation.

3.3 Energy input to the Cooker.

The only source of energy input to the cooker is the sun. Solar radiation that impinges on the glass surface of the collector (glass-cover gl) is of three components namely: direct radiation, diffuse radiation and reflected beam from the boosters. The overall instantaneous solar irradiance (G_T) incident on a unit surface area of the solar cooker (horizontal) surface with reflectors is expressed in terms of beam, diffuse, and reflected radiation as in the following equation.

$$G_T = Gb_g + G_{dg} + Go. \qquad 3.1$$

Where $G_{bg} = A \exp(-B/\sin\beta) \cos\Theta_g$. 3.2

$$G_{dg} = AC \exp(-B/\sin\beta)\, f_{gs} \qquad 3.3$$

$$G_o = \rho m G b r\, f_{rg} \cos\Theta_{rg}. \qquad 3.4$$

$$G_{br} = A \exp(-B/\sin\beta) \cos\Theta_r \qquad 3.5$$

Where G_{bhg} and G_{dg} are the beam and diffuse components of the solar irradiance on the horizontal surface respectively, G_{n} the beam irradiance on the cooker surface reflected on the reflector and solar altitude angle β, f_{gs} is the view factor between g_1 and sky (dimensionless), f_{rg} is the exchange factor, θ_{rg} is the is the angle of incident of reflected beam of glass – cover g_1 and θ_r is the reflected angle inside the glass medium.

3.4 Measured Overall Heat Loss Coefficient, U_L

The overall heat loss, U_L can be obtained from the parameter and the properties of the cooker materials. Thus U_L is the sum of the top loss (U_t), side loss (U_s) and bottom loss (U_b)

$$U_L = U_t + U_b + U_S \qquad 3.6$$

The overall heat loss coefficient is an important parameter since it is a measure of total heat loss from the collector in W/m^2K.

3.4.1 Top heat loss coefficient

A schematic diagram for a two-cover system is shown in Fig. 3.2. For evaluating the top heat loss coefficient U_t, convection and re-radiation losses from the absorber plate in the upward direction need to be determined. It is assumed that:

(i) the transparent covers and the absorber plate constitute a system of infinite parallel surfaces.

(ii) the flow of heat is one-dimensional and steady

(iii) the temperature drop across the thickness of the covers is negligible.

(iv) the interaction between the incoming solar radiation absorbed by the covers and the long wavelength outgoing re-radiation may be neglected.

If the cover material is glass the glazing will be assumed to be opaque.

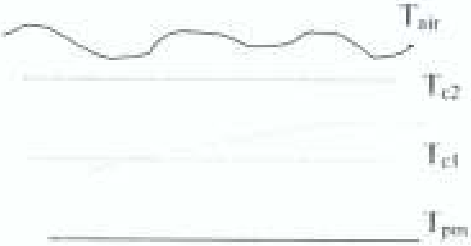


Fig. 3.2: Two-cover system

$$\frac{q_t}{A_p} = h_p - c_1(T_{pm} - T_{c1}) + \left(\frac{\sigma(T^4{}_{pm} - T^4{}_{c1})}{\left[\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1 \right]} \right) \qquad 3.7$$

$$= h_{c1} - c_2\left(T_{pm} - T_{c2}\right) + \frac{\sigma(T^4{}_{pm} - T^4{}_{c2})}{\left[\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1 \right]} \qquad 3.8$$

$$= h_w(T_{c2} - T_a) + \sigma\varepsilon_c(T^4{}_{c2} - T^4{}_{air}) \qquad 3.9$$

Where

ϵ_p = emissivity of the absorber plate

ϵ_c = emissivity of the covers

T_{c1}, T_{c2} = temperature of cover 1 and cover 2 respectively

$h_p - c_1$ = convective heat transfer coefficient between the absorber plate and the first cover.

$h_{c1} - c_2$ = convective heat transfer coefficient between the first cover and second covers

h_w = convective heat transfer coefficient between the outermost cover and the ambient air.

T_s – sky temperature

T_{pm} – mean plate temperature

3.4.2 Heat losses from the transparent cover to the Ambient air

As earlier mentioned, the heat losses from the transparent cover to the ambient air are due to radiative and convective exchanges, which the wind velocity affects. Radiative exchanges are influenced by ground, surrounding condition and long wave radiation from the sky, especially when there is a very clean sky (i.e. when the sky temperature is significantly lower than the ambient air temperature.

Swinbank relates sky temperature (T_{sky}) to the local air temperature (T_{air}) by

$$T_{sky} = 0.0552\ T_{air}^{1.5}\ (K) \qquad 3.10$$

Whiller recommends a simple formula

$$T_{sky} = T_{air} - 6 \qquad 3.11$$

Where temperatures are in Kelvin

For design purposes, it is recommended to use a single formula, which accounts globally for radiative and convective losses.

The linear equation for Mac Adams is given by

$$U_a = 5.7 + 3.8\ V \qquad 3.12$$

Where U_a = heat transfer coefficient from cover to the ambient air (W/m^2K)

V = Wind velocity (m/s)

3.5 Bottom heat loss coefficient

For determining the bottom heat loss coefficient U_b, conduction and convection heat losses from the absorber plate in the downward direction through the bottom of the collector need to be calculated. Here the flow of heat is also one-dimensional and steady.

The thickness of the insulation provided is such that the thermal resistance associated with conduction dominates and the convective resistance may be neglected. The bottom loss coefficient is given by

$$U_b = \frac{K_i}{\delta_b} \qquad 3.13$$

$$U_b = \frac{0.11}{0.07} = 1.571\ \mathrm{W/m^2K}$$

Where K_i = thermal conductivity of the insulation material (as shown in Table 3.1)

δ_b = thickness of the insulation

3.6 Side Loss Coefficient

It is assumed as in the case of the bottom loss coefficient that the conduction resistance dominates and the flow of heat is one-dimensional and steady. This is because the side loss coefficient is always much smaller than the top loss coefficient.

Let the dimensions of the absorber plate be L_1 and L_2 and the height of the collector casing be L_3, then the area of the sides across which heat flows is $2(L_1 + L_2) L_3$

The temperature drop across which the heat-flow occurs varies from $(T_{pm} - T_a)$ at the absorber plate level to zero both at the top and bottom.

Assuming that the average temperature drop across the side insulation of thickness δ_s is

$$\delta_s = \frac{T_{pm} - T_a}{2} \qquad 3.14$$

$$q_s = 2L_3(L_2 + L_2)\frac{T_{pm} - T_a}{2\delta_s} \qquad 3.15$$

$$q_s = 2\,(L_1 + L_2) \quad \frac{T_{pm} - T_a}{2\delta_s} \qquad 3.16$$

$$U_s = \frac{(L_1 + L_2)\ L_3 K_i}{L_1 L_2 \delta_s} \qquad 3.17$$

Where q_s – the rate at which heat is lost from the sides

$$q_s = U_s A_p (T_{pm} - T_a) \tag{3.18}$$

Where -:

L_1 – length

L_2 – breadth

δ_s - insulation thickness

T_a – ambient air temperature (K)

T_{pm} – mean plate temperature (K) (average temperature of the absorber plate).

A_p –aperture area

3.7 Materials For Solar Cooker (Box type)

To design and construct solar cookers for heating purposes, knowledge of the properties of the materials and characteristics of the various components is necessary to predict the performance and durability of the cooker. These are classified into three categories-thermo-physical properties – which include thermal conductivity, heat capacity, and radiant heat, transfer characteristics.

- Physical properties – these include density, tensile strength, melting point, and modulus of elasticity.
- Environmental properties – include resistance to UV degradation, moisture penetration, corrosion resistance, and degradation due to pollutants in the atmosphere.

3.7.1 Absorber plate

The absorber plate material should have high thermal conductivity, adequate tensile and compressive strength, and good corrosion resistance. Copper, aluminium and steel are considered most appropriate (in respective order) in terms of the desired material properties (Gray, 1997). A list of materials generally employed for the absorber plate is given in Table 3.1. Copper is the most suitable material due to its high thermal conductivity and non-corrosiveness, but it is scarce and expensive.

Consequently, aluminium, which is next to it, is used and painted matt black to enhance its absorptivity and non-corrosiveness. A plate thickness of 1mm is used as this is commercially available.

3.7.2 Cover (Lid) Plate

The functions of cover plates are to transmit maximum solar energy to the absorber plate, to minimize upward heat loss from the absorber plate to the environment, to shield the absorber plate from direct exposure to weathering.

The following are the factors to be considered in the selection of cover plate materials, they are the strength, durability, non-degradability and solar energy transmittance.

Tempered glass is the most common cover material for collectors because of its proven durability, stability when exposed to ultra-violet radiation high resistance to breakage both from thermal cycling and natural events.

Transparent plastic materials such as tedlar, mylar, lexan may also be used for cover plates. The main advantages of plastic materials are the resistance to breakage, reduction in weight, and reduction in cost, but plastic material have limited life because of the effect of ultra-violet radiation in reducing their transmissivity, plastics materials are also partially transparent to the long-wavelength radiation and are, therefore less effective in reducing radiated heat losses from the absorber plate. Most of the glass and plastic materials of interest have refractive indices of about 1.5. Taken all these factors into consideration tempered glass was chosen.

The number of glazing depends on the extent of the solar radiation and the temperature difference between the collector plate and the ambient air. The cooker is designed to maximize the input of solar radiation, which will require large glazing area. Increasing the glazing area would also mean increasing heat loss from the inner box to outside. Therefore, the glazing area should be such as to transmit enough solar radiation to provide adequate sunlight and heat required by the cooking chamber. But glass is a good conduction of heat and therefore single glazing is not preferred, multiple glazing with some air space in between is used to reduce the heat loss. The multiple layers (double glazing) is employed in the design not only to reduce the heat loss by the process of conduction and convection but also by radiation, because the glazing temperature goes on decreasing. The trapped air spaces reduce both the conductive and convective heat losses. Double glazing layer of 6 mm-8 mm air space give R values of 0.271 ($m^{2\cdot}$°C/W) when R is the reciprocal of heat transfer coefficient (U) known as resistance to heat flow.

3.7.2.1 Collector surface area

Power supplied to the glass surface is equal to the sum of power to boil a specified quantity of water, power loss to walls and power loss due to absorptivity and reflectivity.

It is thus stated as

Power supplied to the glass surface = Power required to boil water
+ Power loss to the walls
+ Power loss due to
absorptivity and reflectivity

Hence:

$$G_T - A_c = \frac{MC_p \Delta T}{t} + Q_L + G_r(\rho + \alpha) \qquad 3.19$$

$$= Q_u + Q_L + G_r(\rho + \alpha) \qquad 3.20$$

$$A_c = \frac{Q_w + Q_L + G_r(1 - \tau)}{G_T} \qquad 3.21$$

Where -: M = mass of water,

t = time interval,

Q_L = power loss to the walls,

C_p = Specific Heat Capacity,

ΔT = Temperature change

G_r = reflected radiation

Ac = collector surface area m^2

Qw = actual useful energy gain per second, W

ρ = Reflectivity

α = absorptivity

τ = transmissivity

3.7.2.2 Earth-Sun Angles

For computing solar radiation and designing solar cooker, the knowledge of sun's path in the sky on various days in a year at a particular place is a fundamental pre-requisite. We make use of following angles, namely the zenith angle (θ_z), solar altitude angle (θ_A). Incident angle, of beam radiation on reflector (θ_r) and the angle of incidence of reflected beam on glass cover (θ_{rg}) as shown in Figure. 3.4. For Akure, which is at latitude of 07.17°N, longitude 05.18°E. The solar altitude angle (θ_A) is defined as the angle in a vertical plane between the sun's rays and the horizontal projection of the sun's rays. The Zenith angle θ_z is the angle between the sun's ray and a line perpendicular to the horizontal plane. The angle of incidence of beam radiation is the Zenith angle of the sun (θ_z), which is expressed as

$$\text{Cos } \theta_z = \text{Cos } \delta \text{ Cos } \text{Ø} \text{ Cos W} - \text{Sin } \delta \text{ Sin } \text{Ø} \qquad 3.22$$

The declination can be found from the following equation

$$\delta = 23.45 Sin\left[\frac{284+n}{365}360\right] \qquad 3.23$$

Where n = the Julian day number. For April

$= \quad 31 + 28 + 31 + 15$

$= \quad 105$

$$\delta = 23.45 Sin\left[360\frac{284+105}{365}\right] \qquad 3.24$$

$\delta \quad = 9.41^0$

The declination δ of the sun is the angular displacement of sun from the plane of the earth's equator, this angle varies between $+ 23.5^\circ$ and -23.5° (Garg and Prakash, 1982).

At an hour angle of -30°, which corresponds to 9.00 a.m. solar time, the Zenith angle can thus be obtained.

$\text{Cos } Q_2 = \text{Cos}9.41^\circ \text{ Cos } 7.17^\circ \text{ Cos } (-30^\circ) + \sin 9.41^\circ \text{ Sin } 7.17^\circ$

$= \ 0.8693$

$\theta_z \quad = \ 30^0$

Solar altitude angle $\beta = 90^\circ - \theta_z = 60^\circ$

3.7.3 Effective Transmittance

A fraction of all the total insolation is lost due to reflectance and absorptance of the cover material. It is therefore not all the total insolation that reaches the collector surface that is transmitted to the cooking chamber. It is only the quantity that gets into the cooking chamber by transmittance that is utilized.

The collector is a double-glazed panel, each glass cover is 4mm thick. The absorptivity, reflectivity and transmissivity of the two parallel glasses can be expressed in terms of surface properties. This is stated as

$$\alpha_1 = \tau \frac{\left[1 - \exp(-KL / Cos\theta)\right]}{1 - \rho^2 \exp(-KL / Cos\theta)} \qquad 3.25$$

$$\rho_1 = \frac{\tau^2 \rho \exp(-2KL / Cos\theta)}{1 - \rho^2 Cos\theta)} + \rho \qquad 3.26$$

$$\tau_1 = \frac{\rho^2 \exp(-KL / Cos\theta)}{1 - \rho^2 \exp(-2KL / Cos\theta)} \qquad 3.27$$

Where ρ - reflectivity

α - absorptance

τ - transmissivity

θ - refracted angle inside the glass medium, and is related to the incident angle by the Snell's law

L - thickness of the glass plate

K - monochromatic absorption coefficient and is related to the extinction coefficient K and wavelength λ by $K = 4\pi k/\lambda$.

The surface properties are related in this form

$$\alpha_1 + \rho_1 + \tau_1 = 1 \qquad 3.26$$

The equations for determining properties of multi-layer glass systems is formulated using the surface properties [Ojosu and Salawu, 1990) and are given as.

$$\alpha_n = \left[\alpha_{n-1} + \alpha_{n-1\frac{\tau_1\rho_1}{\rho_{n-1}\rho_1}}\right] + \left[\alpha_1 \frac{\tau_{n-1}}{1-\rho_{n-1}\rho_1}\right] \qquad 3.28$$

$$\rho_n = \rho_{n-1} + \frac{\rho_1 \tau^2{}_{n-1}}{1-\rho_{n-1}\rho_1} \qquad 3.29$$

$$\tau_n = \frac{\tau_{n-1}\tau_1}{1-\rho_{n-1}\rho_1} \qquad 3.30$$

Where, n – number of glass plates in the system. For a single layer glass system, n = 1, and for double layer glass system, n = 2. For any value of n

$\alpha_n + \rho_n + \tau_n = 1$

In the far infrared band (at wavelength of about 5μm or above) glass is opaque (Hsieh and Su, 1979).

Thus $\tau = 0$

$\alpha_1 + \rho_1 = 1$ for a n glass layer, resulting in $\alpha_1 = 0$

For a normal incidence condition the integrated glass reflectivity is 0.107 (Hsieh and Su, 1979)

$\rho_1 = 0.107$

$\tau_1 = 1 - 0.107 = 0.893$

The effective transmittance τ_2 is calculated as

$$\tau_2 = \frac{0.893 \times 0.893}{1-0.107} = 0.807$$

The insolation on the absorber plate of the cooker is $\tau_2 G_T$

$\therefore Q = \tau_2 G_T = 0.807 \times 698.02 = 563.3 W/m^2$

3.7.4 Power Required for Boiling

The cooker should be able to raise the temperature of 1.5 kg of water from (28°C) to 100°C in 50 minutes

Power Q_w is given by

$$Q_w = \frac{MC_p\Delta T}{t}$$

$$\frac{1.5 \times 4200 \times 72}{3000} = \frac{302}{10} = 151W$$

3.7.5 Heat Loss to wall

The desired maximum heat loss through the walls

Q_L is 5% of the total power delivered to the cooking chamber

$$Q_L = 5\% \text{ of } Q$$

$$= 0.05x563.30 = 28.17W$$

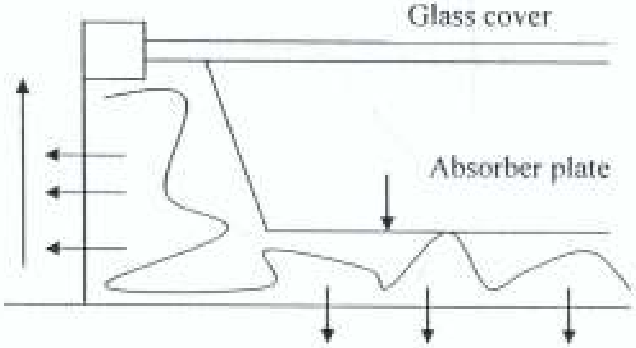


Fig. 3.3 The thickness of insulation

Fig. 3.4: Angle of Incidence of Reflected beam on Glass surface.

3.8 Insulation

Several thermal insulating materials, which can be used to reduce heat losses form the absorbing plate, are commonly available. The desired characteristics of an insulating material are low thermal conductivity, stability at high temperature (up to 200°C) no deposing up to around 200°C, self-supporting feature without tendency to settle, ease of application, no contribution to corrosion. The properties of some of the insulating material are shown in Table. 3.1. (Buchberg and Roulet, 1976)

TABLE 3.1 CONDUCTIVITY OF MATERIALS

Material	**Thermal conductivity at 200°C (W/m°C)**
Foam	0.017
Cellular foam	0.093
Glass wool	0.044
Sawdust	0.11
Thermocole	0.035
Spintex 300 Industrial	0.975

Due to the availability and the cost sawdust is chose.

3.9 Booster Reflectors

The booster reflectors enhance or increase energy input to the system. Reflector of high quality and good specular reflectance properties are required. Due consideration must be given to the effect of accumulation of dust and contamination, stability of reflective coating, environmental effects, cleaning problems and cost. A variety of mirrors in use include, the glass reflectors, stainless steel, metallized plastic films, polished aluminum surfaces.

Polished aluminum surfaces have reflectivities of 80-85%, while new and front surface glass reflectors have 95% or better reflectivity. However, it is the reflectivity, which is retained after several years of exposure that is of interest, glass reflectors (mirror) is chosen for the design of the cooker. The reflectivity of the mirror is 0.89.

3.9.1 Effect of the Booster Reflectors G_o

The reflectors are always oriented to face the sun, (i.e. facing the east before solar noon and west after solar noon). The increase in energy input due to the booster reflectors, G_o can be evaluated for every value of beam irradiance G_{bg} at any hour angle. Recall that

$$G_o = \rho \times G_{bg} \times f_{rg} \cos \theta_z$$

The Zenith angle θ_z is a major parameter that affects the variation of G_o. Three distinct conditions are observed at solar noon. They include very low, moderate, and fairly high values of zenith angle. At very low zenith angle, the values of G_o is close to zero. This implies that the effect of the booster reflectors is very small in this condition. Months that show very low zenith angles at solar noon are, March, April, August and September. At moderate values of θ_z the value of G_o rise. Months with moderate values of θ_z at solar noon May, June, July, and October Go varies from 37 W/m^2 to 67 W/m^2 in these months. Lastly of fairly high θz, the value of Go are considerably high. Month with fairly high θz at solar noon are November, December, January and February. This implies that at solar noon in the months with high values of θ_z, the reflector makes significant impact to the energy input.

3.10 Casing

The casing is to provide a rigid and strong structure for the insulation and house the inner box, the absorber plate. The casing being the outer most part, it should have appreciable aesthetic qualities. Materials considered appropriate for this application are fibre glass, reinforced epoxy resin, plywood plastics and metal sheet. Metal sheet is chosen for its availability, ease of construction and strength. A commercially available gauge 18 metal sheet is considered adequate for its rigidity.

3.11 Cookers Construction Plan

The schematic description of the cooker is illustrated in Figure.3.1. The work is organized in components and was constructed separately. The components include, collector surface panel (cover plate lid), inner tray, insolation booster panel, metal box casing, support for booster panels, booster panel adjuster and insulation.

Construction drawings with complete dimensional details are given as appendix A. References are often made to these drawings. Precautions are stated whenever necessary.

3.11.1 Construction of metal box casing

The details of the dimensions of the metal box casing were given in the drawing Figure 3.6c is the isometric view. A full G18 metal sheet was cut for making of the open end box (no lid) as shown in Figure 3.5

After folding of the metal sheet, arc welding method was used to join all the four edges of the box, a box with dimension of 90cm x 60cm x 25cm was formed.

3.11.2 Reinforcement

Four pieces of 90 cm x 5 cm x 3 cm hard wood were cut. Each of these pieces was chamfered at 45" at both ends so as to form right angle with adjoining pieces as shown in Figure 3.6a. The inner surface of the hardwood was chamfered to align with the slant side of the inner tray. Pieces of reinforcing hardwood were set at the top edges of the sidewalls as shown in figure 3.6b and nailed to the topside walls with 70 mm nails. The reinforcement provided support for the inner tray and also prevents it from getting in contact with the metal box, which prevent heat transfer from the inner tray to the metal box.

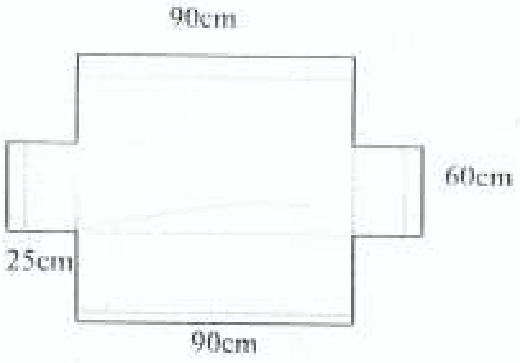


Fig. 3.5 shown the folding lines of the metal sheet.

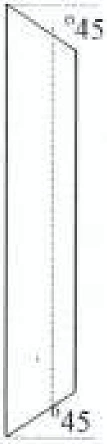


Fig 3.6a

Hard wood with a chamfered side and chamfered end.

Fig. 3.6b A cross-section of the side-wall reinforced with the hardwood.

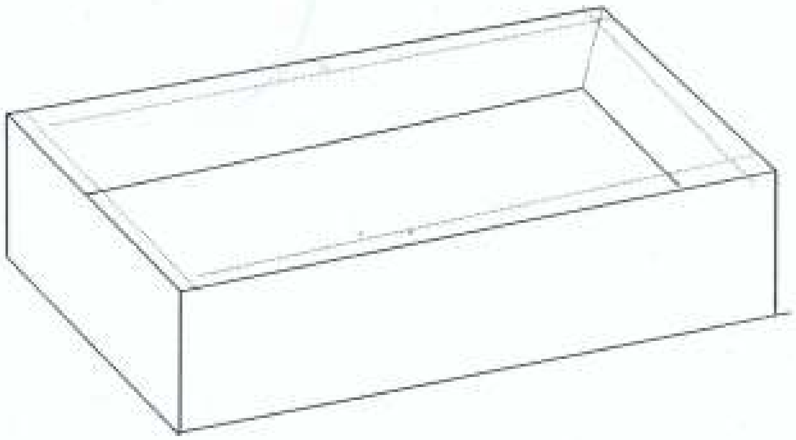


Fig. 3.6c: An isometric drawing of the metal box

3.12 Insolation Booster Panel

The unit was made up of a rectangular plane mirror, which was fitted into a metal angle joint frame with a thin plywood protective cover at the back. A cross-section of the booster panel is shown in Figure 3.7. One-inch metal angle joint of 300cm length was formed into a rectangular metal frame to form a slot for the mirror. The final dimensions of the frame structure were 90 cm x 60 cm on the interior edges and 90.3 cm x 60.3 cm x 59 cm x 0.36 cm was set on the frame. Finally plywood of size 90 cm x 60 cm x 0.5 cm was placed on the back of the mirror. Three stoppers were made on the metal frame two of which were welded to the frame and one screwed to the frame, this is to keep the mirror in position.

This booster panel serves as cover to the cooker. Additional two booster panel were also constructed with the same method but of dimension 60 cm x 60 cm as shown in Figure 3.8. The mirror was handled with utmost care to avoid breakage. Two-booster panel adjusters were made. Each piece of 40 cm long steel bar. One fixed at each sides of the booster panel. Six holes of 5 mm diameter were drilled on each adjuster and a pin stopper welded to the two sides of the frame at the top of the cooker. By changing the holes, with the end of the pin the position of the booster reflector was adjusted. The other two-booster panels were clamped to the two sides of the cooker.

3.13 Collector surface Panel

The collector surface panel serves as a lid to the cooking chamber. It is a double-glazing lid, made up of two parallel glass sheets of 4 mm thickness separated by 20 mm of stagnant air and are rigidly fitted into aluminum frame. The dimensional details are shown in drawing and a cross-section of the panel is shown in Figure was 3.9 and 3.10. The properties of some cover materials are shown in Table 3.2.

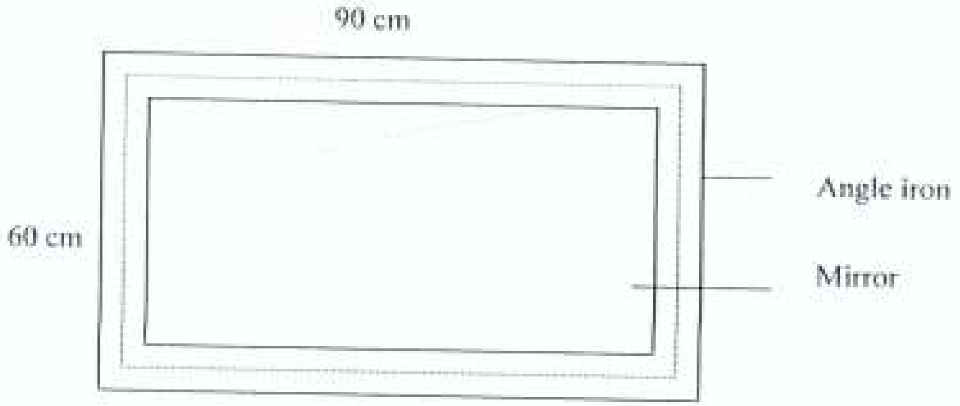


Fig. 3.7: Showing the booster panel

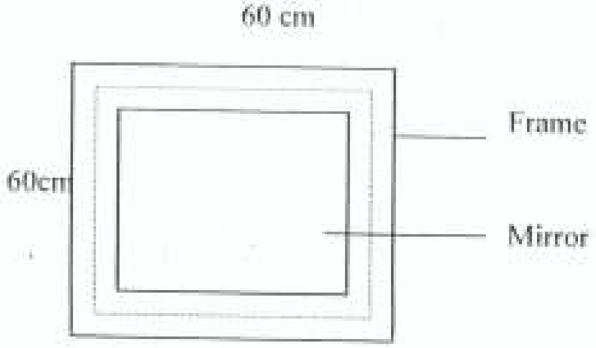


Fig. 3.8: The sides' booster panel

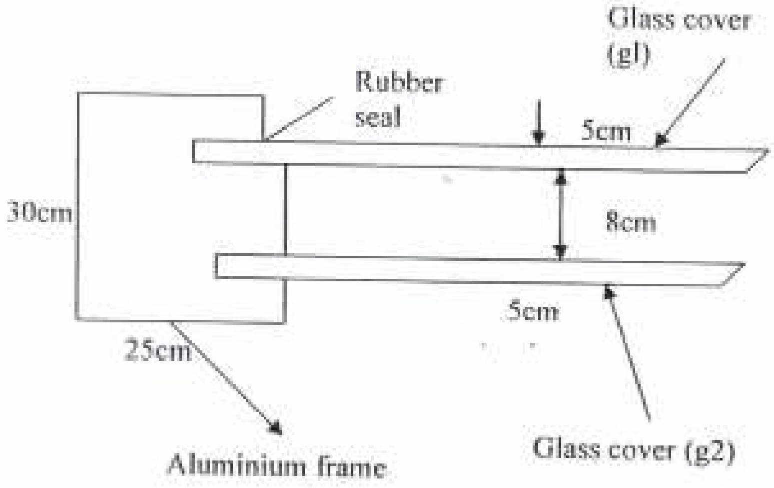


Fig. 3.9 A cross-section of the collector surface panel

TABLE 3.2 PROPERTIES OF COVER PLATE MATERIALS.

Materials	**Index of Refraction**	**Normal Incident Short Wave Transmittance (λ = 04-2.5μm)**	**Normal Incident long-wave transmittance (λ =2.5-40μm)**	**Thickness (m)**	**Density (Kg/m^3)**	Specific heat **($J/^0K\ K_g$)**	**Thermal capacity (W-hr/^{0}k-m^3)**
Glass	1.518	0.840	0.020	3.175×10^{-3}	2.489×10^{3}	0.754×10^{3}	1.659
Lexan	1.586	0.840	0.020	3.175×10^{-3}	1.199×10^{3}	1.193×10^{3}	1.260
Fibre glass reinforced polyester	1.540	0.870	0.076	6.350×10^{-3}	1.399×10^{3}	1.465×10^{3}	3.61
Polyvinyl fluoride (tedlar)	1.460	0.920	0.207	1.016×10^{-3}	1.379×10^{3}	1.256×10^{3}	0.049

Thermal capacity = Thickness x Density x Specific heat

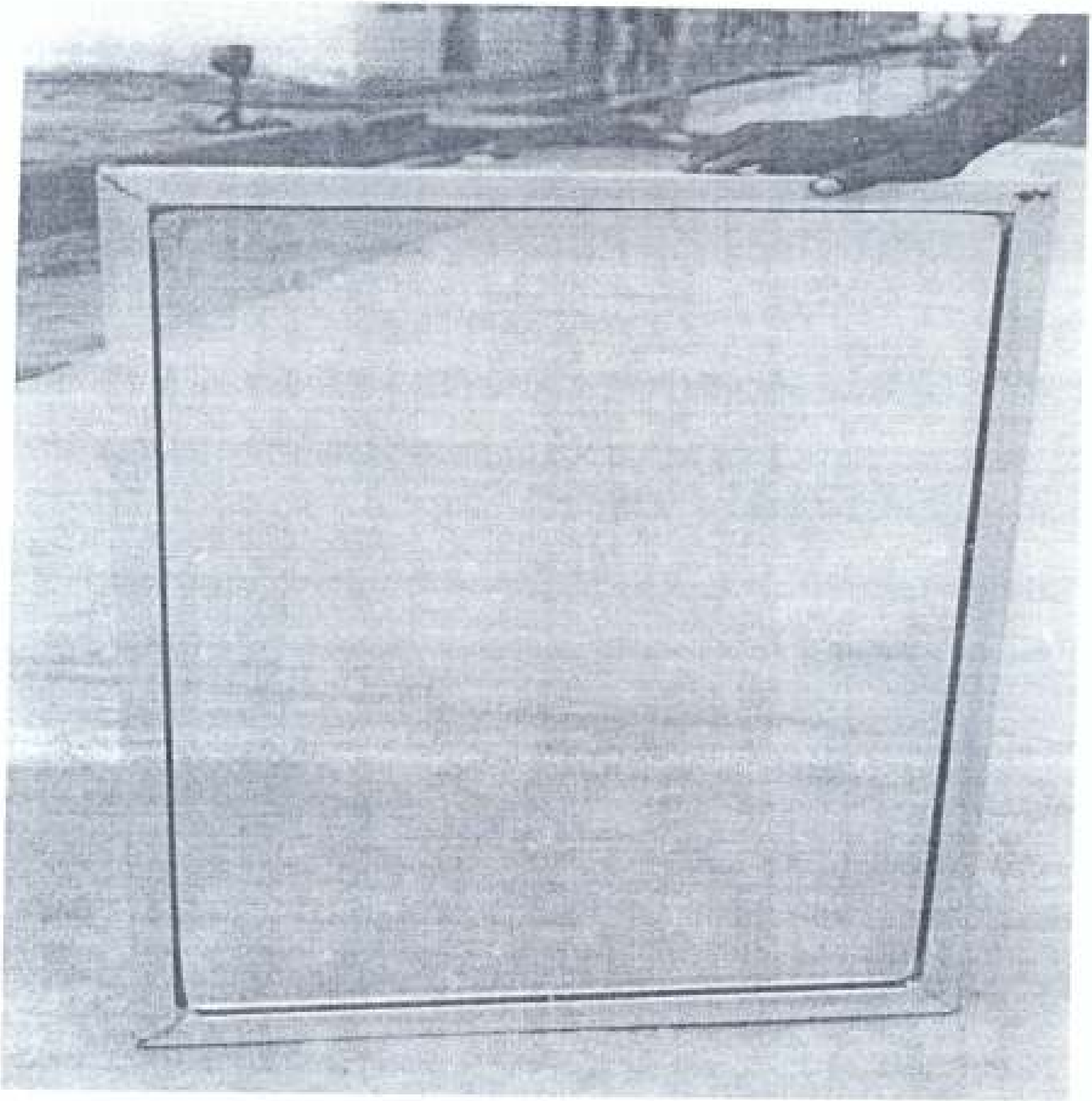


Fig 3.10 The double glazing cover

3.13.1. Framing of the upper and the lower glass cover g_1 and g_2

Four pieces of aluminium frame were cut from a long stripe of aluminum frame. Each of the pieces was chamfered at 45° at both end so as to form right-angle with the adjoining pieces. These pieces were aligned on a horizontal plane and screwed at every corner to form a rectangular frame of 90 cm x 60 cm

On the edge of glass-cover g_1 and glass-cover g_2 which were of 85 cm x 55 cm and 80 cm x 50 cm (4 mm) respectively rubber seal was fitted. The two glasses were fitted into the frame structure by removing one side of the frame, sliding the two glass sheet one at a time along the groove on the frame prevent flow of air through the groove. It minimizes transmission of shocks from the frame to the glass and also serves as damper. The clearance between the edges of the glass and the interior of the frame allowed for thermal expansion of the glass. The double-glazing lid cover is shown in the Fig (3.10).

- g_1 was purposely made wider than g_2 so to avoid risk of shattering of g_2.

3.14 Inner box (Cooking Chamber)

The inner box was made of 1mm plane aluminum sheet. The base was flat and has 70 mm x 40 cm in dimension. It's sidewalls have the shape of an inverted, truncated rectangular based pyramid. A cross section of it is shown in Fig 3.11

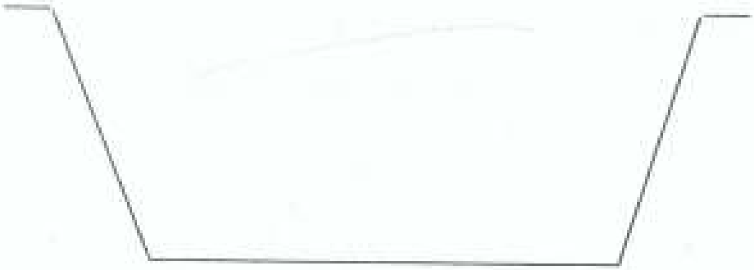


Fig. 3.11: Cross section of the inner box (absorber plate)

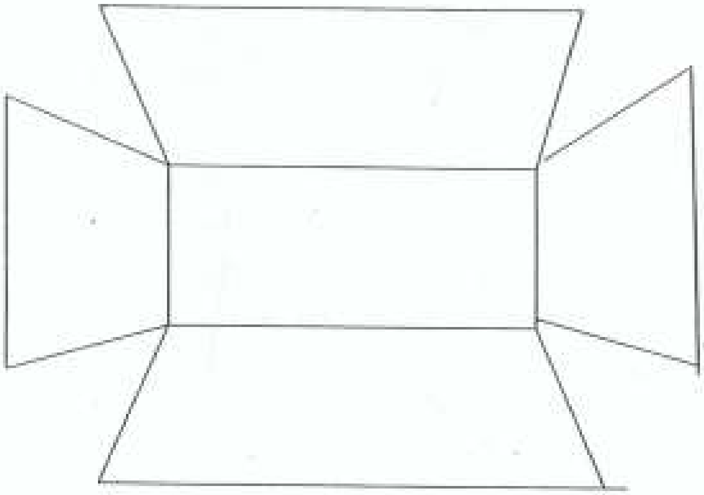


Fig 3.12: The inner absorber plate plan

The inner box was cut from the plain aluminium sheet as shown in Figure 3.12a clearance of 2 mm was allowed for the purpose of joining of the side walls by riveting.

An overlap of 4 mm was maintained at the joint so as to make it airtight. The inner box was painted matt-black. Bending the plate was avoided so as to make the absorber plate a perfect plane for thermal contact with the base of the pot.

The properties of metal used for absorbers plate are shown in the table below.

TABLE 3.3 PROPERTIES OF METALS USED FOR ABSORBER PLATES.

MATERIALS	DENSITY (Kg/m^3)	SPECIFIC HEAT (KJ/Kg^0C)	THERMAL CONDUCTIVITY (W/m^0C)
Aluminum	**2707**	**0.996**	**204**
Iron	**7897**	**0.452**	**73**
Steel	**7833**	**0.65**	**54**
Copper	**8954**	**0.383**	**386**
Brass	**8522**	**0.385**	**111**
Silver	**10524**	**0.234**	**419**
Tin	**7304**	**0.226**	**64**
Zinc (pure)	**7144**	**0.384**	**112**

3.15 Cooker Support

The cooker support was constructed from a long strip of 570 cm angle iron bar. Two sets pieces of the angle iron were cut, these are of dimension 90.5 cm and 60.5 cm. Both ends of each piece were cut at 45° as shown in Figure 3.13a in order to form right angles with adjoining pieces. The angle bars, set on a horizontal plane forming a right angle at every corner joint, were made at the corner by welding. This forms the cooker seating shown in Figure 3.13b

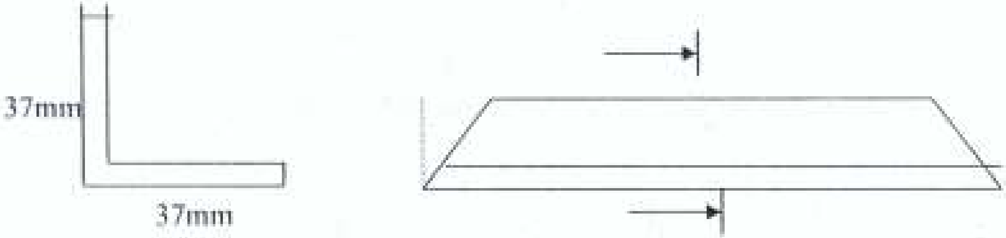


Fig.3.13a: Angle bar for cooker seating cut at both end and at 45°

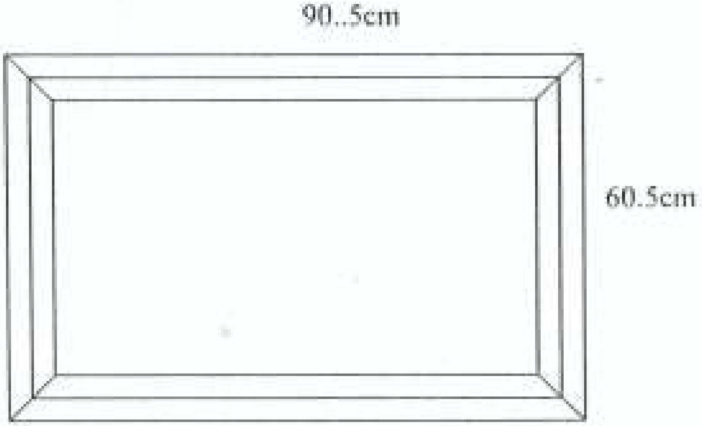


Fig. 3.13b: Cooker seating shown the welded joint

3.16 Assembling

On completing the fabrication of different components the work was organised in sequence as follows

Step 1: The metal casing (box) was set in position for insulation by putting sawdust inside forming a truncated rectangular pyramid inside the casing.

Step 2: The inner box (aluminium) was set in position and was nailed to the hard wood on the metal case.

Step 3: Angle iron bar frame was nailed to the top of the metal box, and the collector panel was set in position and was hinged to the frame.

Step 4: The insolation booster panel was set in position with the edges having pivots set side ways and the reflective surface facing the collector surface. This panel was hinged to the angle iron frame at the top of the metal box.

Step 5: The entire equipment was set on the cooker support.

This constituted a complete assembly of the solar Energy Hot-Box cooker as shown in figure 3.14.

Fig 3.14a The Solar Energy Hot-Box Cooker With a Reflector

Fig 3.14b The Solar Box Hot Cooker with the Glazing Lid Opened

Fig 3.14c The Solar Hot-Box Cooker With Three Reflectors

CHAPTER FOUR

PERFORMANCE TESTS

4.0 Thermal performance evaluation

Thermal performance of a solar energy box cooker is an important parameter of solar box cooker. It is also the standard of grading solar cookers. Therefore the measurement of thermal efficiency of solar cooker is a paramount work. There is no united method and standard for the measurement in the world presently (Ren. et al., 1997). The transient variability of the applied climatological conditions, namely insolation and ambient temperature, render steady state rating procedures inappropriate for rating solar cookers as is done for most solar devices.

Thermal performances of solar cookers include mainly two parts;

- Thermal efficiency and its measurement.
- The principle and method of measurement.

The performance of the solar cooker was thus evaluated by carrying out series of thermal test under No - load condition and sensible heat tests with reflectors in place.

4.1. No Load Test

The main objective of this test was to determine the stagnation temperature and the thermal response of the interior of the cooker to variation in the global irradiance in a day.

4.1.1 Experimental Procedure

- K-type thermocouples were used to measure the temperature of the absorber plate (T_{ab}), the stagnant air within cooking chamber (T_s), the inner glass surface (T_{c2}), the outer glass surface (T_{c1}) and the ambient temperature (T_{amb}).
- The thermocouples were glued to the respective surfaces.
- The thermocouples leads were connected to the temperature channels of a digital multimeter one after the other. Temperature readings were taken at interval of 30 minutes.
- Instantaneous measurements of Global Insolation were taken using a Pyranometer. The readings were obtained at the same interval of 30 minutes in W/m^2.
- A digital anemometer, with an accuracy of ±0.005 m/s was used to record wind speed (V) in m/s at the same time intervals.
- The plane-mirror reflectors were set to face the sun always and were adjusted to ensure that area of reflected rays covered the entire glazing surface.

4.1.2 Results and Discussion

Details of the test are given in Table 4.4 and Figures 4.7 and 4.8 for the test with reflectors in place. A maximum absorber plate temperature of $141^{O}C$ was recorded with reflector in place at solar radiation values between 769.67 W/m^2 and 1079 W/m^2 between 11:00 a.m and 12:30 p.m local time.

However, the cumulative contribution due to the reflector before the solar noon would have also boosted the overall contribution by the reflector even at solar noon. The sun is displaced considerably from the zenith at solar noon and thus solar radiation is not normal to the horizontal and consequently, the reflector contribution would be expected to be appreciable at solar noon for some months. The absorber plate temperature measured was expectedly consistently higher than other temperature in the cooker. This is desirable as the anticipated major mode of heat transfer to the cooking vessel is by conduction from the absorber plate. Cooking chamber air temperature was also expectedly high between 29°C and 137°C for most of the test period. However, for peak insolation values of between 767.67 W/m^2 and 1079 W/m^2, the peak plate temperature without reflectors is 108°C compared to 141°C when the reflectors are in place. This explained the performance and the anticipated advantage of the plane reflectors in the design.

4.2 Sensible Water Boiling and Heat Tests

The objective of these tests was to determine the time to boil a given quantity of water and the effect of weather condition on the boiling.

4.2.1 Experimental Procedure

Thermocouple (k-type) were used to measure the temperature of the absorber plate (T_{ab}), the stagnant air within the cooking chamber (T_s), the outer glass surface (T_{c1}), the inner glass surface (T_{c2}), the ambient temperature (T_a), the water temperature in the pots outside the cooking chamber and inside the chamber (T_{w1}) and (T_{w2}) were monitored.

- The thermocouple leads were connected to the thermocouple channel of the digital meter read –out.
- Instantaneous measurement of global irradiance (G) was obtained using a pyranometer and the reading taken at interval of 10 minutes.
- Anemometer was used to measure the wind speed.
- The cooker was located at an open place, within the premises of the Department of Physics, FUTA, with full access to direct solar radiation such that it is free from shadow.
- The plane mirror reflectors were set to face the sun when in use and were adjusted at regular interval to ensure that area of reflected rays covered the entire glass surface.
- 1.5 kg of water was put into the two pots one outside and the other one inside the cooking chamber.

4.2.2 Results and Discussions.

Details of a typical test data for the sensible heat test for the solar cooker with and without the reflectors in place are given in Tables 4.1, 4.2, 4.3 and 4.4 for a tests under taken from 18th to 22nd April respectively. During the tests, insolation was fairly high with intermittent wind and cloud cover around 1:30 pm and 4:00 pm and thus with little variability in the solar irradiance as can be seen from Figures 4.3 and 4.4.

The variation of the water temperature with time for the two cases with and without the plane mirrors in place are shown in Figures 4.1 and 4.2 respectively while the overall cooker performance (for all the measured temperatures) for both cases of the cooker with and without reflectors are shown in Figures 4.3 and 4.4 respectively. The two test results are representative of a series of sensible heat tests under taken.

A control test was carried out on the 18th of April 2004, a pot with 1.5 kg of water was placed outside on ground and another pot with the same amount of water was placed inside the cooking chamber, the test was carried out between the hours of 11.30 am and 12.30 pm, the results shows a temperature rise from 26 °C to 39 °C in the pot outside and a temperature rise of 26°C to 96°C in the pot inside the cooking chamber. The two pots were of aluminum sheet and were painted matt black. It took 15 minutes to boil the same quantity of water with electric cooker and 13 minutes using kerosene stove.

In some of the heat test conducted the water temperature failed to reach 100 °C, but could only attain a maximum temperature of 96°C and this is due to the inclement weather characterized by cloud over cast and poor insolation. Contrary to expectations, it was confirmed from the readings that the highest temperature obtained for the cooker during the test does not conform to the highest insolation during the periods. The reasons for this may be due to wind, which convects heat away from the cookers window.

The test shows that the absorber plate and the design of the inside of the cooker play an important role in their performance. The collector absorber for the cooker is made of aluminum with a thermal conductivity of 204 W/m°C. The higher the thermal conductivity the ability of the collector absorber to attain a higher temperature and maintain it, if insolation is provided.

The design of the absorber collector sides is at an angle 75°C to the base. This increase s the surface area and gives it more aperture opening. Tilting the inner angle improve the performance of the cooker.

The rate at which a black body radiates energy depends on its emissivity, temperature, absorptivity and surface area.

Another point for consideration in design the solar cooker is the type of insulating materials used. The sawdust insulation used has a thermal conductivity of 0.11 W/m^2 °C. This reduces the loss of heat.

Throughout the duration of the test, the temperature of the glass covers 1 and 2 are always maintained between 35°C to a maximum of 75°C. The glass cover is made from ordinary plain glass with a thickness of 4 mm and thermal conductivity of 1.05 W/m^2 °C. This explains why the absorber in the cooker attains higher temperature up to 141°C.

TABLE 4.1 SENSIBLE HEAT TEST ON COOKER WITH REFLECTORS IN PLACE (18/04/04)

Time	*Tw_1 (°C)*	*Tw_2 (°C)*	*Ts (°C)*	*Tc_1(°C)*	*Tc_2(°C)*	*Tab (°C)*	*Tamb (°C)*	*G_T (W/m^2)*	*V m/s*	*RH %*
11:30am	26	26	57	35	46	65	28	603.85	1.499	70.2
11:40am	33	46	63	38	60	70	30	629.79	1.624	69
11:50am	35	55	66	39	64	80	31	708.49	1.741	69.6
12:00pm	35	73	72	40	69	94	31	619.55	0.978	67
12:10pm	37	85	72	42	69	96	30	754.98	2.523	66.7
12:20pm	40	93	73	51	70	96	32	696.87	3.134	66.8
12:30pm	42	96	79	52	75	108	32	872.63	2.459	64.3
								Av = 698.02	A_V=2.03	

Where -:T_{w1} - water temperature in the first pot,

T_{w2} - water temperature in the second pot,

T_{c1} - outer glass cover ,

T_{c2} - inner glass cover,

T_{ab} - absorber temperature

T_{amb} – ambient temperature

V – wind speed

RH - relative humidity

G_T - global irradiance

T_s - space temperature

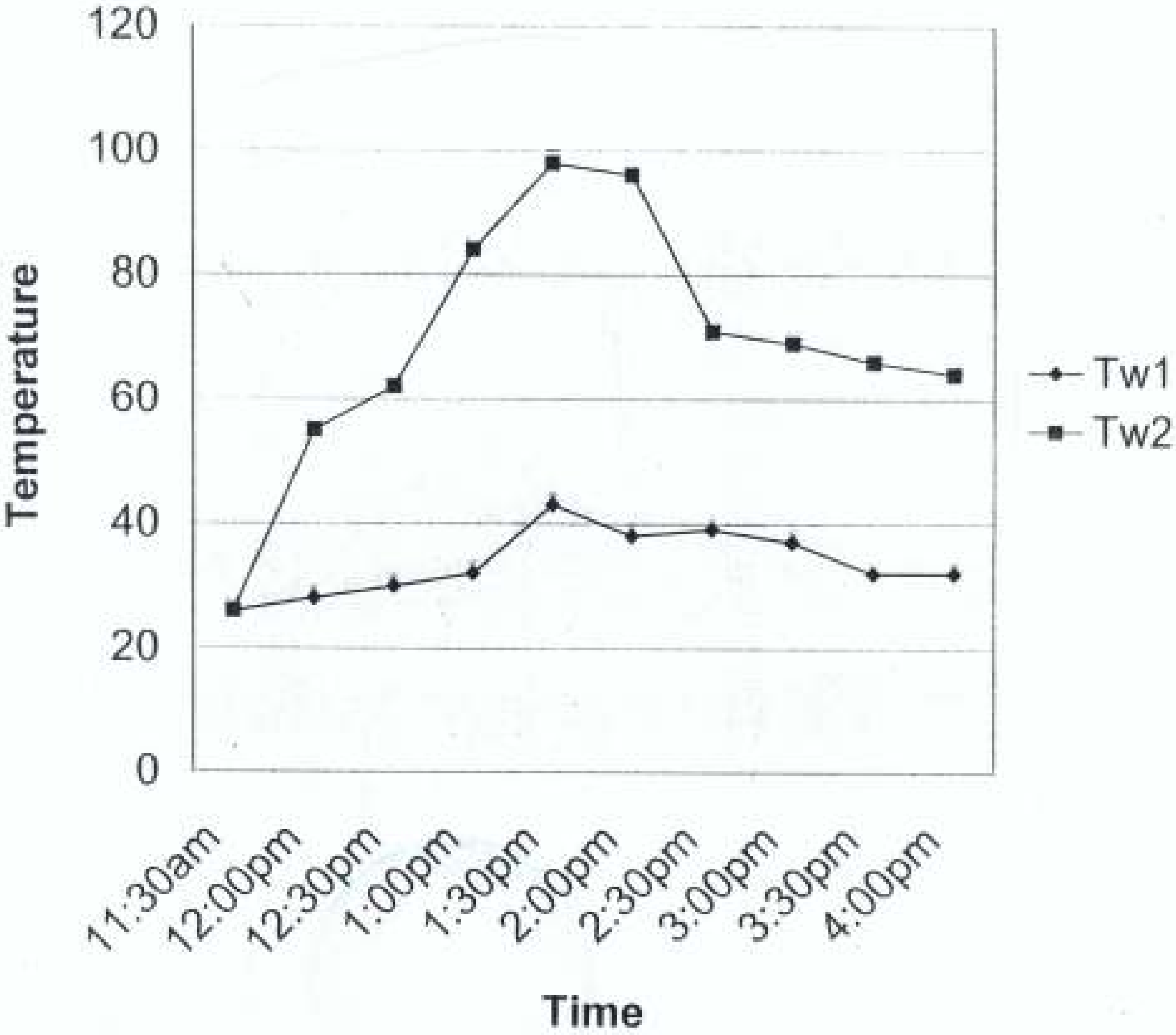


Fig. 4.1: Diurnal variation of water temperature with 1.5 kg of water in two pots (19/04/04)

Where -:T_{w1} - water temperature in the first pot

T_{w2} - water temperature in the second pot

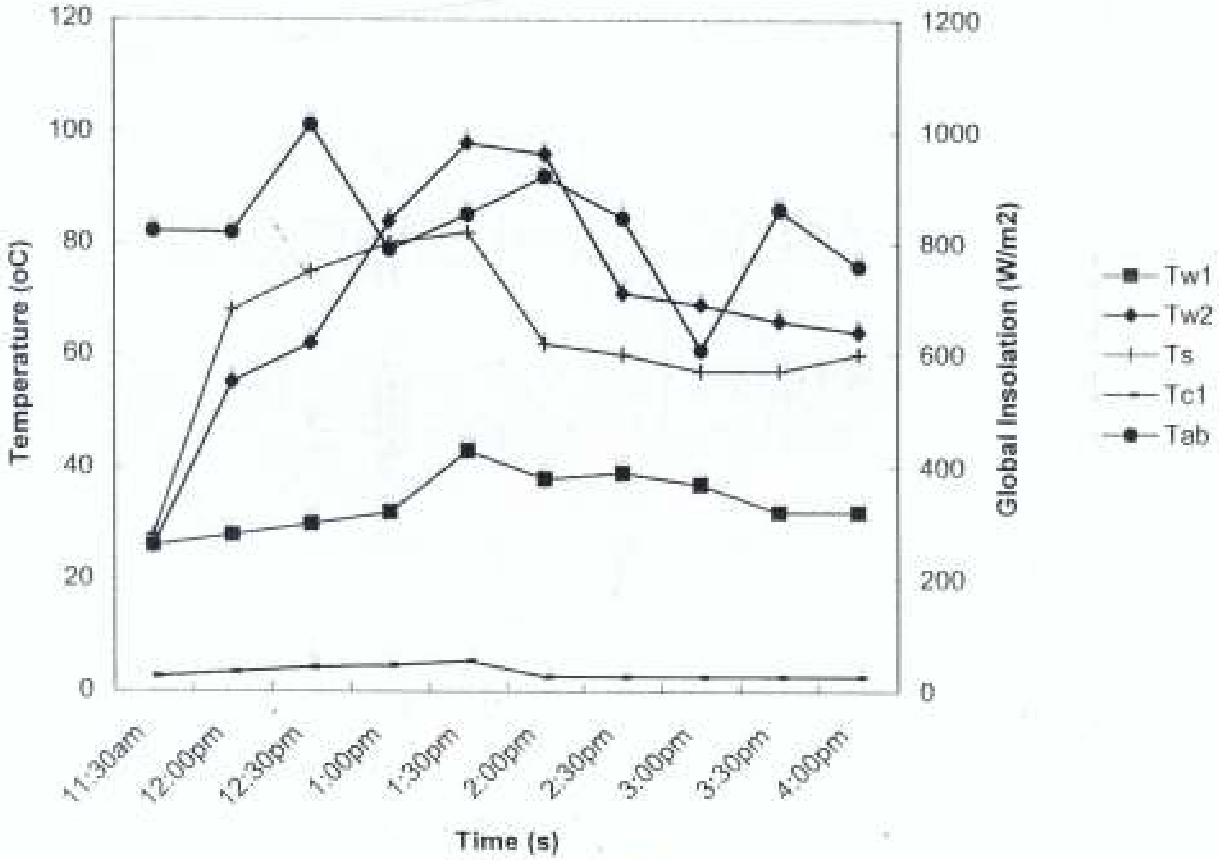


Fig 4.2: Variation of Tw1, Tw2, Ts, Tc1 and Tab with Time for a sensible heat with reflectors in place (19/04/04).

Where -:T_{w1} - water temperature in the first pot

T_{w2} - water temperature in the second pot

T_s - cooker space temperature

T_c - collector temperature

T_{ab} - absorber plate temperature

TABLE 4.2 SENSIBLE HEAT TEST ON COOKER WITH REFLECTORS IN PLACE (19/04/04)

Time	*(T_{w1} °C)*	*T_{w2} (°C)*	*T_s (°C)*	*T_{c1}(°C)*	*(T_{c2} °C)*	*T_{ab} (°C)*	*T_{amb} (°C)*	*($G_T W/m^2$)*	*V m/s*	*RH %*
11:30am	26	26	28	26	26	26	29	822.21	0.482	68.7
12:00pm	28	55	68	35	57	91	29	819.55	2.361	68.4
12:30pm	30	62	75	43	70	89	31	1012.63	3.541	68.1
1:00pm	32	84	80	46	75	105	33	789.09	2.178	67.4
1:30pm	43	98	82	54	79	100	33	851.74	0.742	66.9
2:00pm	38	96	62	27	58	74	32	920.68	0.483	65.6
2:30pm	39	71	60	26	54	70	31	845.64	1.536	63.6
3:00pm	37	69	57	26	53	69	29	608.06	2.521	63.4
3:30pm	32	66	57	27	55	69	30	860.04	3.201	62.7
4:00pm	32	64	60	26	58	82	30	759.18	1.63	63.5
		Mass f water =1.5kg								
		Number of pot = 1								
		Mass of pot =0.86kg								

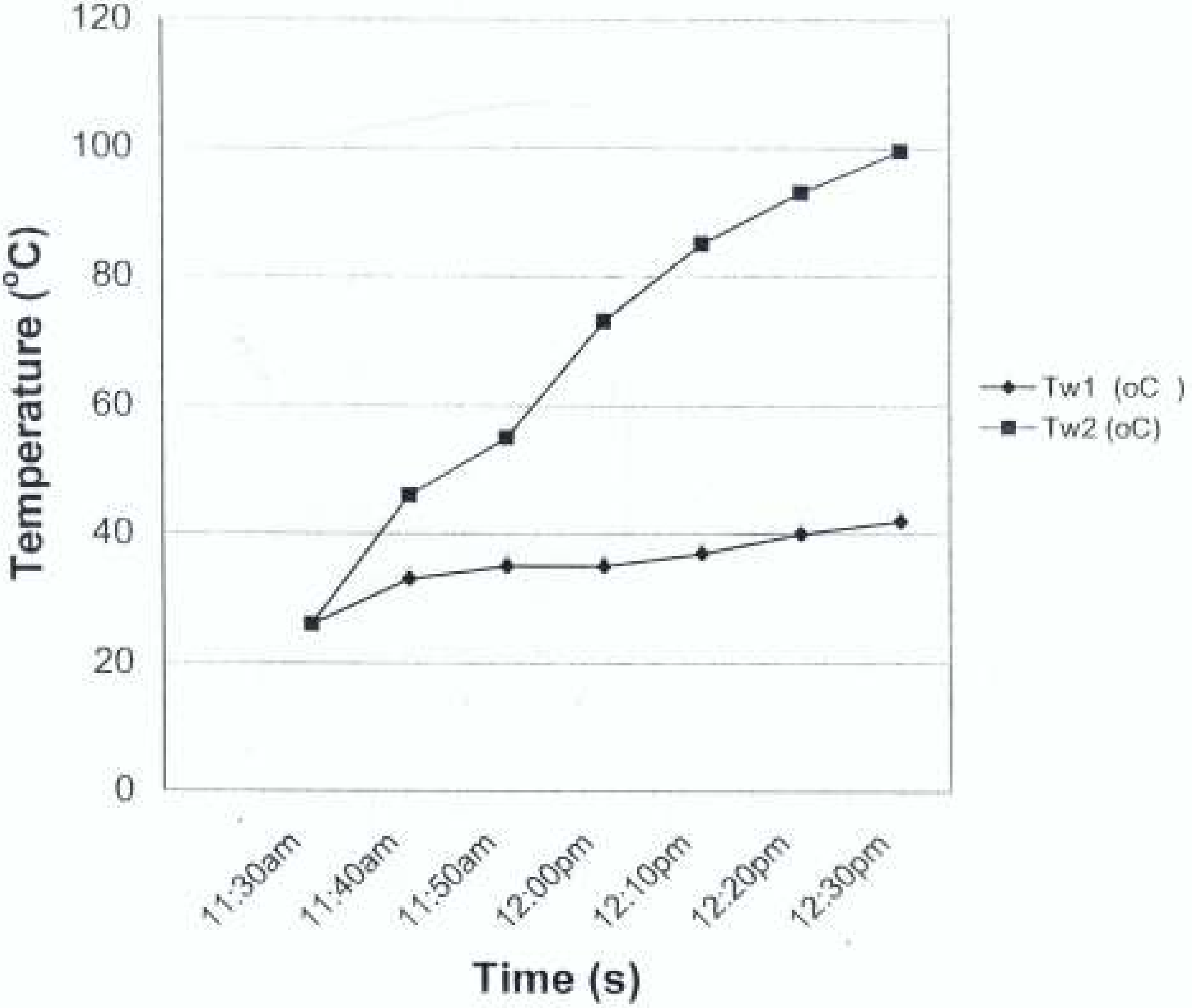


Fig. 4.3: Diurnal Variation of Water Temperature with 1.5kg of Water.(18/04/04)

Where -:

T_{w1} - water temperature in the first pot

T_{w2} - water temperature in the second pot

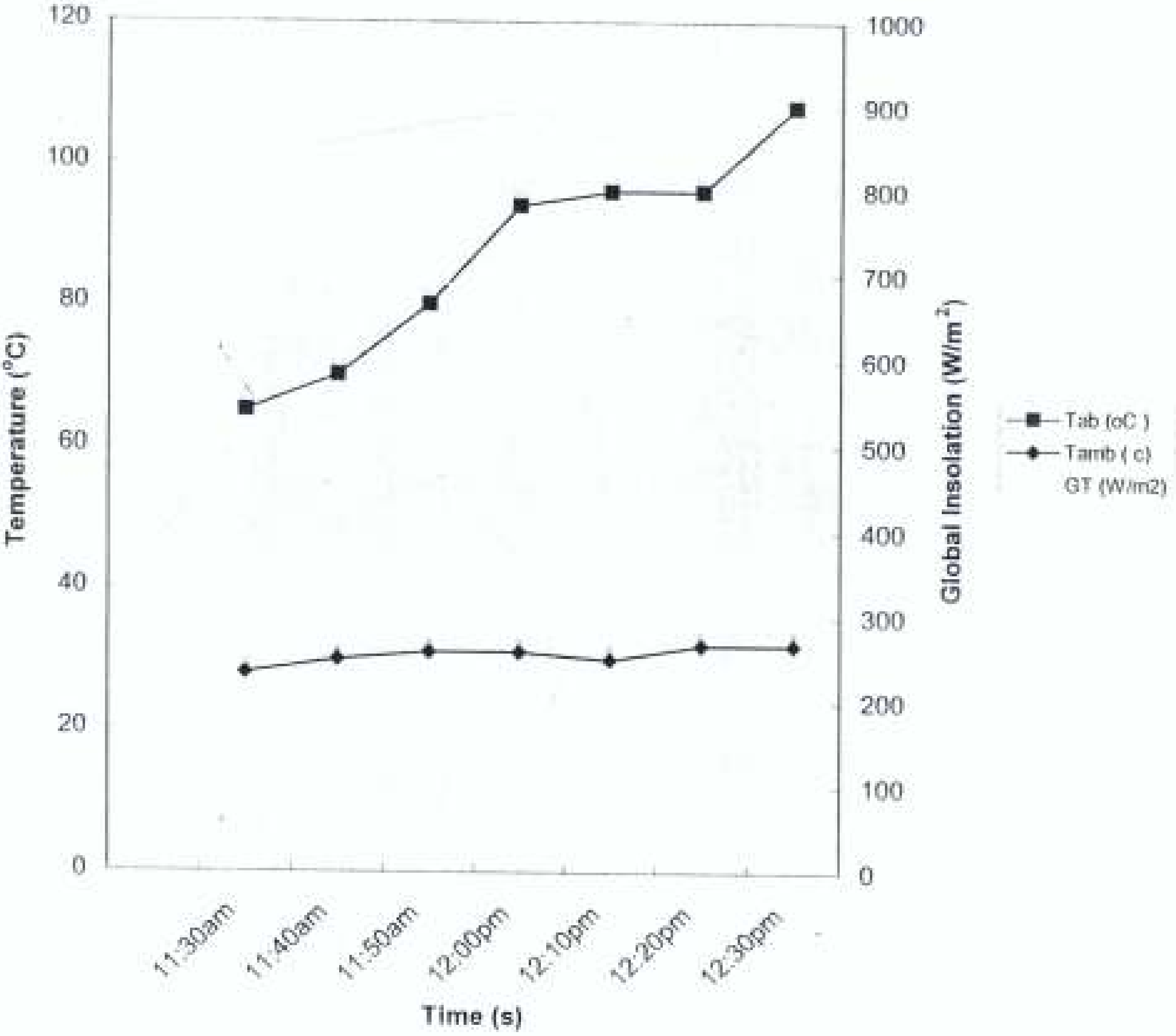


Fig. 4.4; Diurnal variation of Cooker Plate Temperature and The Global Insolation. (18/04/04)

Where -: T_{ab} - absorber plate temperature

T_{amb} - ambient temperature

G_T - global irradiance

TABLE 4.3 SENSIBLE HEAT TEST ON COOKER WITHOUT REFLECTORS IN PLACE (23 April, 2004).

Time	*Tw_2 (°C)*	*Ts (°C)*	*Tc_1 (°C)*	*Tc_2 (°C)*	*Tamb (°C)*	*Tab (°C)*	*G_T (W/m^2)*	*Vm/s*	*RH%*
10:00am	29	29	29	29	29	29	358.45	1.263	69.9
10:30am	38	68	34	57	29	65	412.05	0.978	68.2
11:00am	45	74	37	69	30	71	502.99	0.456	66.3
11:30am	56	81	41	77	31	81	798.11	2.521	66.3
12:00pm	66	88	45	78	32	91	694.04	2.293	63.1
12:30pm	74	92	50	84	33	94	757.7	0.793	63
1:00pm	81	95	51	86	30	114	872.53	0.956	60
1:30pm	87	98	52	87	30	115	1073.59	1.342	59.3
2:00pm	90	99	59	90	29	125	1001.55	1.234	57.8
2:30pm	89	92	49	81	28	115	416.53	0.845	58.4
3:00pm	90	86	38	74	29	91	797.6	1.203	57.6
3:30pm	87	83	41	70	30	88	669.47	1.241	56
4:00pm	82	80	36	65	30	87	458.21	2.56	58.3

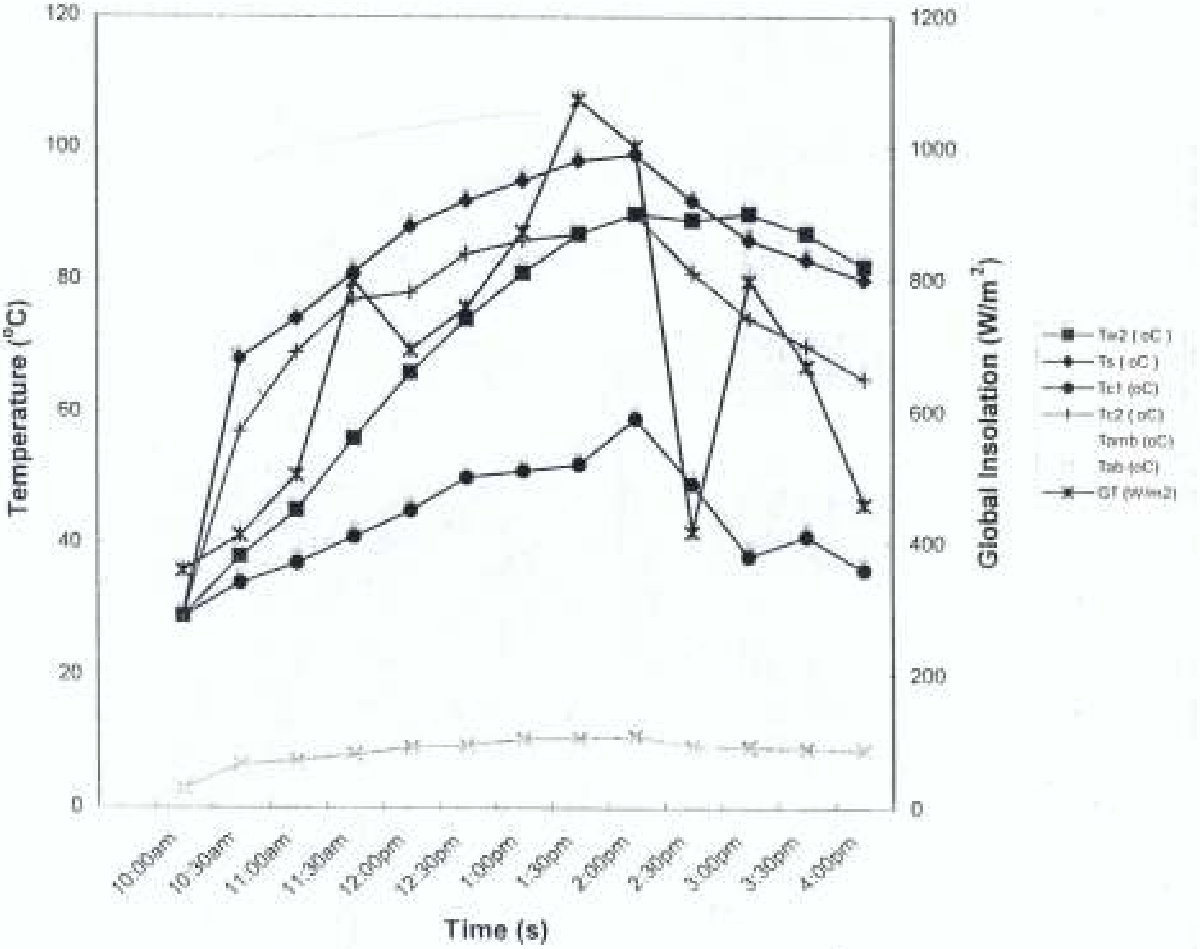


Fig. 4.5: Variation of T_{w2}, Ts, T_{c1}, T_{c2}, T_{amb} and T_{ab} with Time and Global Insolation Without Reflectors in place. (23/04/04)

Where -: T_{w2} - water temperature in the second pot

T_s - Cooker space temperature

T_{c1} - outer glass cover

T_{c2} - inner glass cover

T_{amb} – ambient temperature

T_{ab} - absorber plate temperature

G_T - global irradiance

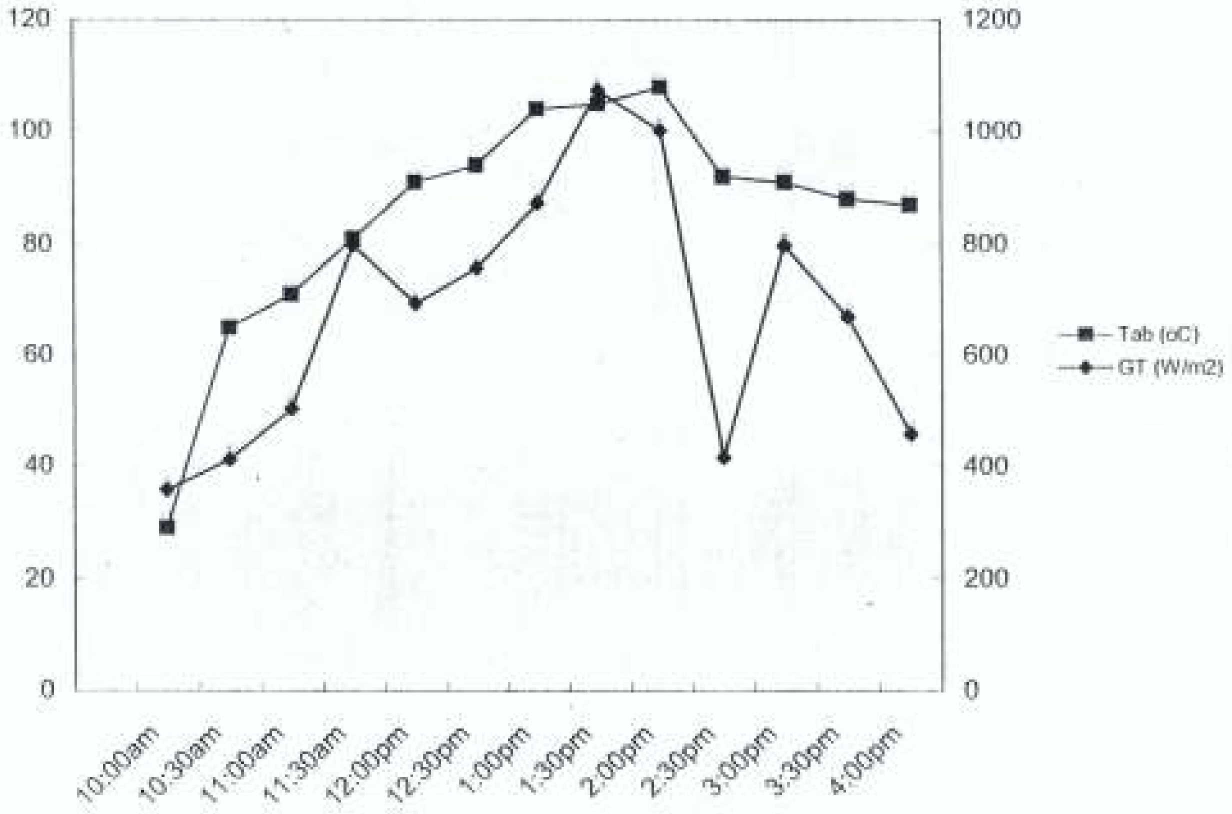


Fig 4.6: Diurnal Variation of Cooker Plate Temperature without reflectors (23/04/04)

Where -: T_{ab} - absorber plate temperature

G_T - global irradiance

TABLE 4.4 NO LOAD TEST WITH REFLECTORS IN PLACE (21 April, 2004)

Time	*Ts* (^{o}C)	T_{c1} (^{o}C)	T_{c2} (^{o}C)	T_{amb} (^{o}C)	T_{ab} (^{o}C)	G_T (W/m^2)	*V m/s*	*RH %*
9:30am	29	28	28	29	29	382.77	0.235	75
10:00am	63	32	59	29	81	462.78	0.844	71.4
10:30am	81	38	66	30	106	946.57	0.961	67.2
11:00am	89	40	75	29	120	1079	2.502	65.6
11:30am	97	43	74	30	128	882.74	1.324	65.2
12:00pm	92	39	72	32	132	823.15	1.226	62.6
12:30pm	96	46	70	33	141	769.67	0.804	64.2
1:00pm	93	31	62	30	210	821.32	0.849	61
1:30pm	86	35	64	31	102	891.81	1.532	61.9
2:00pm	87	32	57	32	98	604.23	1.375	62.3
2:30pm	79	31	54	30	93	544.13	0.965	55.5
3:00pm	76	28	50	30	89	189.53	0.795	56.3
3:30pm	72	28	47	29	80	364.16	2.228	56
4:00pm	65	29	47	29	76	252.62	2.551	53.1

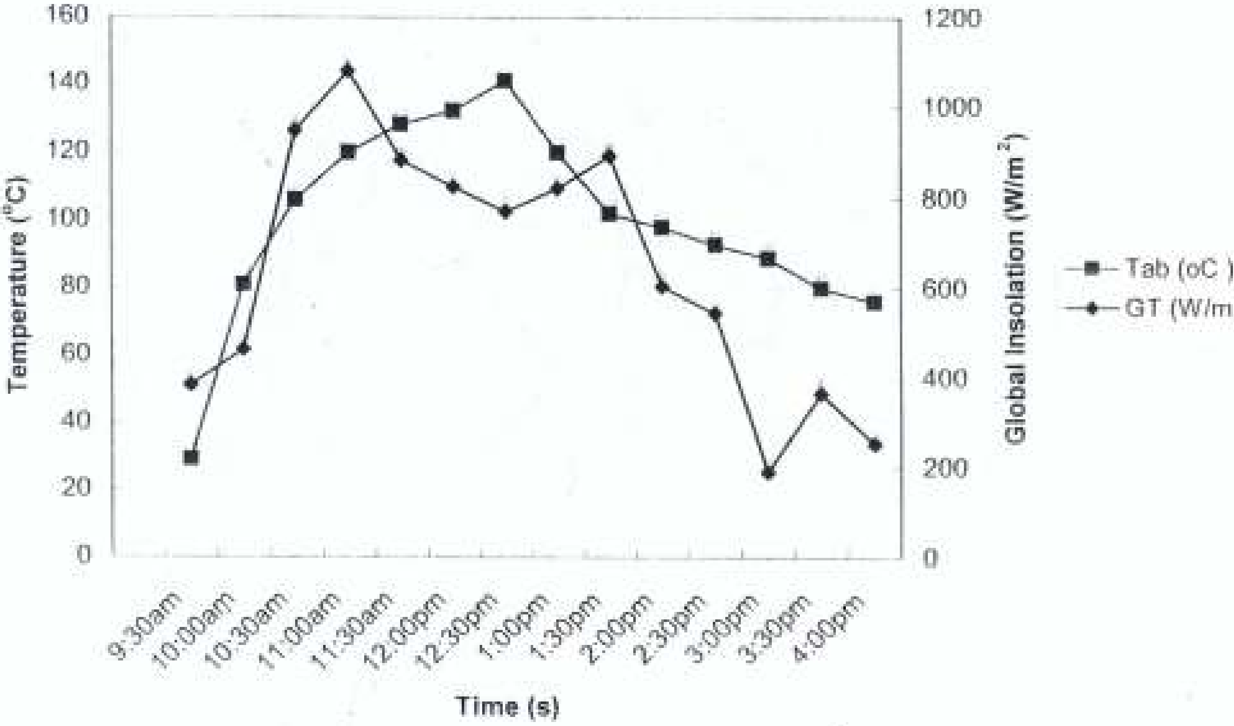


Fig 4.7: Diurnal variation of Cooker plate Temperature without load. (21/04/04)

Where -: T_{ab} - absorber plate temperature

G_T - global irradiance

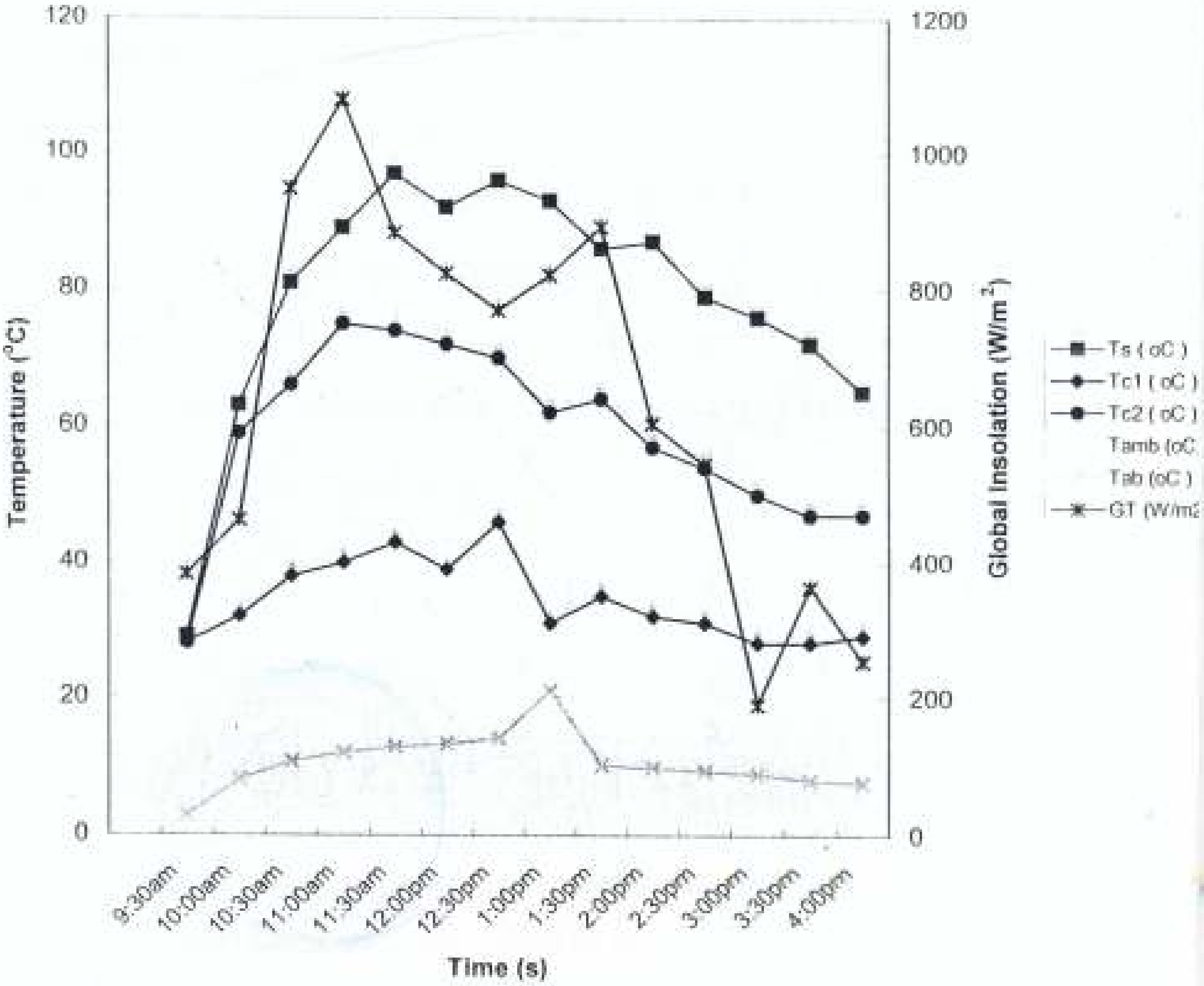


Fig 4.8: Variation of T_s, T_{c1}, T_{c2}, T_{amb} and T_{ab} with Time and Global Insolation for a No Load Test. (21/04/04)

Where -: T_s – cooker space temperature

T_{c1} - outer glass cover temperature

T_{c2} - inner glass cover temperature

T_{amb} – ambient temperature

T_{ab} - absorber plate temperature, G_T – global irradiance

4.3. PERFORMANCE RATING OF SOLAR BOX COOKER

Thermal performance of solar cooker is an important parameter. Solar cookers have been generally rated thermally according to no-load stagnation absorber plate temperatures; sensible water boiling tests and cooking tests. The above tests depend on climatic parameters, such as insolation ambient temperature, and wind speed and thus do not lend themselves easily to standardization.

The performance of the cooker is considered in terms of its thermal efficiency. This is the ratio of sensible heat delivered by the cooker to heat available at the collector surface within a specified time. This is given as

$$\eta = \frac{\left[(MC)_c + (MC)_W\right]\Delta T}{GA_1} \qquad 4.1$$

$$\eta = \frac{\left(M_w C_w + M_c C_c\right) \times \left(t_2 - t_1\right)}{GA_1} \qquad 4.2$$

Where -:

M_w = Mass of water - 1.5 kg

C_w = Specific heat capacity of water - 4200 J/kg K

M_c = Mass of container – 0.86 kg

C_c = Specific heat capacity of container – 980 J/kg K

G = Global irradiance – 698.02 W/m^2

A_1 = Aperture area of the cooker - .0.8 x 0.5 in(m^2)

t_2 = final temperature - 96°C

t_1 = initial temperature - 28°C

Table 4.5: The work sheet for water heating measurement

S/NO	ITEMS	SYMBOL	UNITS	READING
1	Weight of H_20	M	kg	1.5kg
2	Average ambient temperature	T	K	28^0C
3	Initial temperature of water	T_1	K	28^0C
4	Final temperature of water	T_2	K	100^0C
5	Accumulative direct solar radiation	H	kJ/m^2	
6	Aperture area of solar cooker	A_c	m^2	
7	Average beam radiation intensity	I_b	W/m^2	
8	Measure time	T	S	3600s
9	Average wind speed	V	m/s	
10	Efficiency	η	%	

In Table 4.1 for the cooker with reflectors in place the global irradiance G_T = 698.02 W/m^2, temperature change ΔT = 66 °C, specific capacities of water and aluminium are 4200 J/kg K and 980J/kg K respectively, time interval = 60mins. The thermal efficiency is thus calculated using equation 4.2.

$$\eta = \frac{(0.85kgx980kg'') + (2kgx4200J/kg^\circ C)x68^\circ C}{698.02x0.8x0.5x3600s}$$

$= 0.482559$

48.26%

For the cooker without reflectors the value of the variable one obtained from the sensible heat test data on table 4.3 are as follows, average global irradiance G_T= 677.91 W/m^2, time interval 65mins, the thermal efficiency calculated is

$$\eta = \frac{(0.85x980) + (1.5x4200)x66.5}{677.91x0.8x0.5x65x60}$$
$$= 0.4485$$
$$= 44.85\%$$

In Table 4.1, the average global irradiation, G = 698.02 W/m^2, time interval t = 60 mins, and temperature change $\Delta T = 66^0C$, Cw and Cc are 4,200 J/Kg^{0}C and 980 J/Kg^{0}C

$$\eta = \frac{(M_w C_w)\Delta T}{GA_t}$$
$$= \frac{1.5x4200x66}{698.02x0.8x0.5x3600} \qquad 4.4$$
$$= 0.426055$$
$$= 42.62\%$$

The thermal efficiency of the cooker with and without reflectors in place are 48.26% and 44.26%, while the thermal efficiency of water heating is 42.62%. It is seen from these experimental results that by incorporating the plane reflectors on the cooker, the boiling time for 1.5 kg of water is reduced from 65minutes to 60minutes. Expect when there was cloud cover, consequently, the thermal efficiency of the cooker without reflectors is less than when the reflectors were all in place.

$$P_s = \frac{(M_w C_w)(t_2 - t_1)}{T} \qquad 4.5$$

$$\frac{1.5x4200x66}{3600}$$
$$= 115.5W$$

Ps = Actual effective power of solar cooker during measuring period

The specific power (KW)

P =700 x η x A_c

T = measuring period (S)

4.4 Energy Efficiency

To perform energy analysis of the solar box cooker, the quantities of input and output of energy must be evaluated. The overall energy balance of the solar cooker can be written as:

Energy Input = Energy Output + Energy Loss

Energy input to the solar box cooker is the total solar energy incident upon the plane of the solar cooker per unit time per unit area. Thus, energy input to the solar box cooker can be calculated as follows:

$$E_i = I_t A_{sc} \qquad 4.6$$

Where E_i is the energy input in the solar box cooker in W, I_t is the total solar irradiance in W/m^2 and A_{sc} is the surface area of the cooker

Energy output of the solar cooker is thus

$$E_o = M_w C_w \frac{T_{w2} - T_{w1}}{\Delta t} \qquad 4.7$$

Eo = energy output in W; M_w = mass of water in kg; C_w = specific heat capacity of water in J/kg/k, T_{w2} and T_{w1} are final and initial temperature of water in K and t is the time in second.

Energy efficiency (η_1%) of the solar cooker can be defined as the ratio of energy output to the energy input of the solar cooker. It is thus calculated from the equation below.

$$\eta = \frac{E_o}{E_i} \qquad 4.8$$

$\eta = 0.41372\%$

$= 41.37\%$

Where -: $M_w = 1.5$ kg

$C_w = 4200\ \mathrm{J/kg^{O}C}$

$T_{w2} = 94^{O}C$

$T_{w1} = 28^{O}C$

$\Delta t = 3600\ \mathrm{s}$

$I_t = 698.2\ \mathrm{W/m^2}$

$A_{sc} = (0.8 \times 0.5)\ \mathrm{m}$.

4.5 Cooker Testing

Generally cookers are thermally rated according to:

1) stagnation plate temperature
2) Time required for cooking different food products.
3) Time required bringing a known amount of water to the boiling point.

Solar cookers depend on the climatic parameters. Research has been made for evaluating the hot box type solar cooker which is independent on the climatic parameters. In this case two Figure of merits F_1 and F_2 are determined by conducting the stagnation temperature test (without load) and by sensibly heating known amount of water. The first Figure of merit, F_1, which is defined as follows:

Heat loss factor (U_{LS}) at stagnation temperature (T_{PS}) is given as:

$$\eta_0 I_S = U_{LS}\left(T_{PS} - T_a\right) \qquad 4.13$$

Where η_0 is the optical efficiency

I_S – Solar Insolation

T_a – ambient temperature

T_{PS} – stagnation temperature

The first figure of merit F_1 is given as:

$$F_1 = \frac{\eta_o}{U_{LS}} = \frac{T_{PS} - T_a}{I_S} \qquad 4.14$$

The determination of second figure of merit F_2 involves the measurement of temperature of known amount of water heated during the course of day. It is desired that the water temperature should reach the boiling point as quickly as possible to reduce boiling time. The time interval dt required for a known thermal capacity of water $(MC)_w$ to increase its temperature by dT_w is given as

$$dt = \frac{(MC)_W \, dT_W}{Q_U} \qquad 4.15$$

Q_u – rate of useful heat gain by water and

$$Q_U = AF^I \left[\eta_O H - U_L (T_W - T_a)\right] \qquad 4.16$$

A – is the aperture area

F^I – the heat exchange efficiency factor

H_1 – is the solar radiation

Integrating equation 4.11 for the time interval t during which mean solar radiation is H_1 and water temperature rises from T_{w1} to T_{w2} and rearranging the term we have

$$F^I U_L = \frac{(MC)_W}{A_1} \, ln \left[\frac{1 - \frac{U_L}{\eta_O}\left(\frac{T_{W2} - T_a}{H_1}\right)}{1. \frac{U_L}{\eta_O}\left(\frac{T_{W1} - T_a}{H_1}\right)} \right] \qquad 4.17$$

F^I and U_L are almost independent of the climatic parameters. Thus, the time interval t required to increase the known amount of water temperature from T_{w1} to T_{w2} will depend on climatic parameters.

The second figure of merit F_2 is given by

$$F_2 = F_1\left(F'U_L\right) = \frac{\eta_O}{U_{LS}}\left(F'U_L\right) = F'\eta_O \qquad 4.18$$

Here, it has been assumed that heat loss U_L is approximately the same as heat loss at stagnation temperature. Therefore the second figure of merit F_2 can be given as

$$F_2 = F_1\frac{(MC)_W}{A_r}\, ln\left[\frac{1-\frac{1}{F_1}\left(\frac{T_{W2}-T_a}{H_1}\right)}{1-\frac{1}{F_1}\left[\frac{T_{W2}-T_a}{H_1}\right]}\right] \qquad 4.19$$

For the cooker with reflectors in place, at stagnation plate temperature, absorber temperature Tab = 141°C, ambient temperature Tamb = 31°C, global insolation H =769.67 W/m^2, the first and second figure of merits were calculated as F_1 = 0.1429 m^{2}K/W, F_2 = 0.2834 m^{2}K/W, for the cooker without reflectors at absorber temperature Tab = 104 °C, ambient temperature Tamb = 31 °C and global insolation H = 872.52, the corresponding first and second figure of merits were calculated as F_1 = 0.0837 m^{2}K/W and F_2 = 0.3015 m^{2}K/W. F_1 is the ratio of the optical efficiency of the heat loss factor at stagnation determine from No Load stagnation tests. The higher the value of F_1 the better the performance of the cooker. F_2 is the controlling factor in the sensible heating of the load and is obtained from the full load water boiling tests. F_2 is a dimensionless parameter independent of climatic condition.

4.6 Factors Affecting the Efficiency of the Solar Cooker

The performance of a solar cooker is measured by its thermal efficiency. The factors which could enhance or reduce the efficiency of the cooker include the following:-

- **Surface of the Cooking Pot: -** The cooking pot must be painted dull black to absorb a high percentage of the reflected solar radiation.
- **Time of Cooking: -** For effective utilization of the sun energy for cooking, it is best to set up the cooking device during period of bright sunshine. The best time of cooking for our location at Akure of clear days ranges from 9:30a.m to 4:30p.m. Outside this range, the intensity of the sun would reduce and cooking time would be prolonged.
- **Season of the Year: -** During the wet season, the efficiency of the cooker is considerably low. It is either no sunshine at all or very low sunshine.
- **Collector Type: -** The desired temperature range of the material to be heated is the most important factor in choosing the correct type of collector. An uncovered absorber is certainly not suitable for producing process heat. The amount of radiation on that spot, exposure to storm, and the amount of space must all be carefully considered when planning a solar cooker.
- **Effect of Cloud: -** Efficiency of Solar Cooker is usually reduced by cloud, Thin layers of cloud and scattered cloud reflecting sunlight, increase the diffused solar irradiation falling on the cooker, thick layers of cloud reduce diffuse solar irradiation. Also if there is cloud between the sun and the point of observation, then the bean solar irradiation is weakened or eliminated.
- **Dust in the atmosphere:** -During harmattan period in December/January, the dust-laden wind reduces the efficiency of the performance of the cooker even

with considerable sunshine because of the scattering of the sun radiation in the atmosphere (Exell, 2000).

- **Geographical Location:** - The latitude of the location could significantly affect the design of a solar cooker. For locations near the equator, a simple solar box cooker is desirable.

4.7 Economic Analysis of the Cooker

The objective of economic analysis can be viewed as the determination of the least cost method of meeting the energy need, considering both solar and non-solar alternatives.

In 1977, Beckman outlined the concept of solar savings. Solar savings are the difference between the cost of conventional system and a solar system which is simplified in the equation.

Solar savings = cost of conventional energy – cost of solar energy.

It is estimated that about #20,000.00 will cover the cost of producing a solar box cooker. Solar cooker does not degrade easily and the lifespan can be upward of 2 years but not more than 4 years for aluminum sheet when used as a reflector and up to 10 years for glass mirror if properly kept from dust, moisture, dew or rain. The initial cost might be considered high for rural dwellers but it would have paid for itself by the end of the third year considering savings on other fuel. An average of four member family will require 4 liters of kerosene for four days for three meals a day. This will cost between #240 - #300. In a year, a total about #32, 000.00 - #35, 000.00 must have been spent on kerosene alone apart from both the initial cost and maintenance cost of stove. This if put together will give a rough estimate of about #37, 000.00, which is about two times the cost of producing a solar box cooker. Although solar box cooker can not be used at all times, expecially during the rainy season. Solar box cooker therefore cannot serve as exclusive means for cooking, but will rather supplement other means, thereby saving cost on kerosene.

4.8 Cooker costs

The costs of this box type solar cooker like those of any other manufactured items, is dependent on the size of the cooker. The costs are summarized in Table 4.6

TABLE 4.6 Cost of materials

MATERIALS	**ITEMS**	**COSTS ₦**
G18 metal sheet	1	3500.00
Angle Iron Bar (20x20x 4)cm	3	1x 3000.00
Aluminum Foil (Sheet)	1	2,000.00
Mirror (2" x 3")	3	1,500.00
Plane Glass (2" x 3")	2	1,000.00
Aluminum Frame	1	3,000.00
Paints (matt black)	3	3,000.00
Wood Planks (70x10x5)cm	2	1,500.00
Misleaneous Expenses		1,000.00
Nails	-	300.00
Gum	-	
Glue	-	
Transportation	-	1,500.00
TOTAL		**20,500.00**

The cooker have a potential useful lifetime that depends on the model (how much "ruggedness" is built into them), on the care of the user, and on the material used for the reflector.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.0 Conclusion

A box type solar cooker have been designed and constructed at the Federal University of Technology, Akure, Nigeria using locally available materials. This work has demonstrated the probable shift of the dependence of a section of the citizenry on fossil fuel.

Solar radiation can be effectively and efficiently utilized for cooking in our environment if proper design is used and certain procedures followed. A major factor for effective use is the proper selection of time of cooking.

The temperature of the glass cover 1 and 2 was always maintained between 35°C and 75°C and the absorber attain a temperature of 110°C. A maximum absorber plate temperature of 141°C was recorded with reflector in place at solar radiation values of 769.67 W/m^2 - 1079 W/m^2 between 11.00 am and 12.30 pm local time respectively. Cooking chamber air temperature was also expectedly high between 29°C and 137°C for most of the test period. For peak insolation value between 761.67 W/m^2 and 1079 W/m^2 the peak plate temperature without reflectors was 125°C and 141°C when the reflectors were in place. This explains the advantage of the booster reflectors in the design.

The sensible heating test shows that it took 60 minutes to boil 1.5 kg of water in the cooker when all the three reflectors were in place. The thermal efficiency of water heating with and without reflectors and the energy efficiency of the solar cooker were 48.2%, 44.85% and 41.37% respectively.

The performance of the cooker was also measured by computing the first figure of merit (F_1) and second figure of merit (F_2) for the sensible heating test, the first and second figure of merits were calculated as 0.1429 m^2K/W, 0.2834 m^2K/W respectively. For the cooker without reflectors at absorber temperature, 104 °C, ambient temperature, 31 °C and global insolation, 872.52 W/m^2, the corresponding first and second figure of merits were calculated as F_1 = 0.0837 m^2K/W and F_2 = 0.3015 m^2K/W. The incorporation of additional two plane reflectors considerably improved the performance of the cooker and resulted in higher stagnation plate temperature, shorter boiling time and higher figure of merit. With the performance tests evaluation, the solar box cooker could only be use as a back – up cooker or a pre – cooker because of its limitation.

5.1 Recommendations

(1) Users should accept the cooker as complementary equipment but not a complete substitute for other cooking systems, because of its limitation. It cannot be used at night or early morning when there is no sunshine, it can also not be used during rainfall.

(2) For further studies the performance of the solar box cooker could be stimulated under varying weather conditions and varying controlling parameters.

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