Design Investigations on Solar Cooking Devices for Rural India

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ABSTRACT

This article discusses the usefulness of Second Law analysis (exergy analysis) for comparing and optimizing the performance of solar collectors. Here, the exergetic formulas for both the parabolic and flat plate collectors are deduced and a parametric study is made using hourly solar radiation. The exergy output is optimized with respect to the collector temperature and different parameters are calculated. It is found that most of the parameters such as exergy output, exergetic and thermal efficiencies, stagnation temperature, increases with a rise in solar intensity for both the collectors. However initially, the value of exergetic efficiency varies in accordance with the solar intensity but declines further with an increase in solar intensity for parabolic collector.

Keywords: Parabolic disc collector; Exergy analysis; Concentration ratio; Stagnation temperature; Optimum collector temperature; ambient temperature.

Nomenclature

A	surface area(m^2)
C	concentration ratio
Cp	specific heat (W/K)
Ex	exergy (W)
FR	heat removal factor
F′	efficiency factor
Is	solar intensity (W/m^2)
m	mass of fluid(g)
Q	heat gain (W)
T	temperature
U	overall heat transfer coefficient (W/K/m^2)

Greek letters

α	absorptivity
ε	emissivity
η	efficiency
ϱ	reflectivity
σ	Stefan's constant

Subscripts

a/A	ambient/absorber
e	exergetic
i	initial
$m\rightarrow\infty$	for large mass
f	final
R	reflector
st	stagnation
T	thermal
u	useful

INTRODUCTION

The traditional methods of cooking involve burning of wood in an open fire, sometimes included by a horse shoe shaped alcove made of clay or bricks to act as a wind shield. In some cases three stones are placed around the fire to act as supports for any cooking vessel. These methods are very inefficient as only 5% to 10% of the energy in the wood fuel is utilized in the cooking process. Thus it was felt that there was need to improve the cook stoves. This leads to introduction of improved chulhas, wood fired mud stoves. In our country energy consumed for cooking shares a major portion of the total energy consumed. In villages, 95% of the consumption goes only to cooking. Variety of fuel like coal kerosene, cooking gas, firewood dung cakes and agricultural wastes are used. The energy crisis is affecting everyone. The solution to this problem is the harnessing of solar energy for cooking purposes. This article discusses the usefulness of Second Law analysis (exergy analysis) for comparing and optimizing the performance of solar collectors. In this communication the exergetic formulas for both the parabolic and flat plate collectors are deduced and parametric study is made using hourly solar radiation. The exergy output is optimized with respect to the collector temperature and different parameters are calculated. It is found that most of the parameters such as exergy output, exergetic and thermal efficiencies, stagnation temperature, increases with a rise in solar intensity for both the collectors. However initially, the value of exergetic efficiency varies in accordance with the solar intensity but declines further with an increase in solar intensity for parabolic collector. This is due to fact that the radiation losses increases with an increase in collection temperature. Exergetic optimization of flat plate collectors is carried out to evaluate the performance of a flat plate collector depending on parameters like mass flow rate and outlet fluid temperature. The optimal mass flow rate for maximum exergy efficiency are computed and it is observed that decreasing the flow rate below the optimal value increases the temperature of the fluid but there is a decrease in exergy and energy efficiency. On the other hand, increasing the flow rate over the optimal value increases the energy efficiency, but it decreases in exergy efficiency and fluid temperature.

A SHORT HISTORY OF SOLAR COOKERS

The first solar cookers were described by Mouchot (1) who had been commissioned by the French Colonial troops in Africa. He used a parabolic concentrator to focus solar radiation onto a cooking pot, which was suspended from a stand.

In the United States, C.G. Abbot (1) built several cooking ovens using cylindrical parabolic reflectors to concentrate solar radiation onto a blackened tube protected by a glass enclosure. A small solar cooker designed by Abbot was exhibited at the Smithsonian Institution Museum in Washington. In this cooker, cylindrical parabolic reflectors automatically tracked the sun by means of a clockwork mechanism. However, the cost of this system was too high for a commercial market to develop.

During the early 1930s, solar cooking experiments were continued by Mourin (1) primarily for the French colonies. Unfortunately these experiments resulted in no significant use of solar cookers. M.L. Ghai (2) of the National Physical Laboratory of India attempted to solve the solar cooking problem by using a parabolic reflector, with a pot supported at the focus. The Devidayal Industries manufactured this device for a limited time with the intent of commercializing it, but the cost was too high to be attractive. The results of tests of cookers have been described by Mathur and Khanna (3), National Physical Laboratory of India, New Delhi, who state "Since tradition in cooking method plays a very major part, it is doubtful if much could be done yet in changing traditional methods and efforts made to introduce solar cookers in villages have completely failed." Several solar devices were exhibited at the UNESCO Conference on wind power and solar energy in New Delhi during October 1954 (4). Danish Solar Cooker Developed by Danchurchaid an Introduced into Upper Volta During 1977 which is seen in fig 3.6. Practically all the solar cookers had manually adjustable mirrors mounted in a frame, each mirror, individually and frequently, to reflect solar radiation to the pot, thus making it somewhat unattractive to the sophisticated housewives.

The most serious problem with the direct, concentrating collector type solar cooker was reported to be that it was outside the average housewife's everyday experience. Few housewives could become attached to the idea of sitting or standing in the yard while dinner is cooking. Even in such lands as India, where fuels and money are scarce, large-scale demonstrations of solar cookers never led to their adoption by people who would have benefited most. The reason: the equipment, the procedure, the whole cooking process was not something done by generations of ancestors. With this in mind, Farber (6) at the University of Florida designed a solar powered cooking range with 24 hour cooking capability. This device incorporated a parabolic concentrator, a heat storage unit and a range- top cooking unit inside the house. The heat transfer fluid proposed for this unit was cottonseed oil and the storage media was a phase change salt. Unfortunately, there is no way to evaluate the value of such a solar cooking system since it has not yet been built.

DESIGN PRINCIPLES AND CONSTRUCTIONAL DETAILS OF A SOLAR BOX COOKER

The solar rays penetrate through the glass covers and are absorbed by a blackened metal tray kept inside the solar box. The solar radiation entering in the box is of short wavelength. The higher wavelength radiation is not able to pass through the glass cover, i.e. radiation from absorber plate to outside the box is minimized by providing the glass cover. Two glass covers are provided to minimize the heat losses by making the box air tight, by providing a rubber strip around and between the upper lid and the box. Insulating material like glass wool, paddy husk, saw dust or any other material is filled in the space-between blackened tray and outer cover of the box. This minimizes heat loss due to conduction. When this cooker is placed in the sun, blackened surface starts absorbing sun rays and temperature inside the box starts rising. The cooking pots which area also blackened are placed inside with food material, gets heat energy and food is cooked in a certain period of time depending upon the actual temperature attained inside. The temperature attained depends upon the intensity of solar radiation and material of insulation provided. The amount of solar radiation intensity can be increased by providing mirrors. Absorber tray (blackened metallic tray) is painted black with suitable black paint which is dull in color so that it can withstand the maximum temperature attained inside the cooker as well as of water vapor coming out of the cooking utensils. The top cover contains two plain glasses with about 20 mm distance between them. Neoprene rubber sealing is provided around the contact surfaces of the glass cover and the cooker box. A small vent for vapor escape, is provided in the sealing Collector area of the solar cooker is increased by providing a plane reflecting mirror equal to the size of the box, and hinged on one side the glass frame. A mechanism (Guide for adjusting mirror) is provided to adjust the reflector at different angles with the cooker box.

The temperature inside the solar cooker with a single reflector is maintained from 70 to 110°C above the ambient temperature. This temperature is enough to cook food slowly steadily and preservation of nutrients. Depending on the factors such as season and time of the day, type of the food and depth of the food layer, cooking time ranges from 1 to 4 hours.

DESIGN PRINCIPLES AND CONSTRUCTION DETAILS OF CONCENTRATING SOLAR COOKERS

A parabolic mirror reflects solar radiation which is parallel to the axis to its focus. This property of a parabolic mirror is used in the construction of concentrating collectors in the form of a parabola with the absorber placed at its focal point.

Figure 1 shows a parabola which is described by equation

$$y = x^2/4f \qquad (1)$$

Where f = focal length (the distance of the focal point from the vertex is known as focal length).

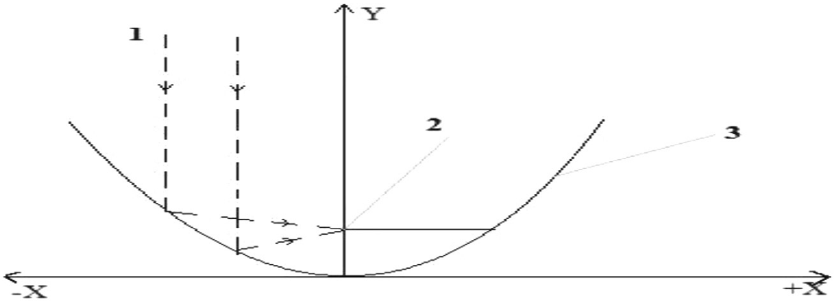

Figure 1. Schematic of a parabola [10]: (1) Incident solar radiation, (2) focus point, (3) parabolic reflector

Next, a parabola can be assumed to be made of a small circle arc. Such an arc CA shown in Figure2.

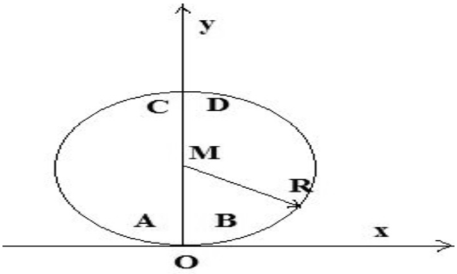

Figure 2. Parabola extended Arc

The arc is approximated by part of the circle with Radius R. The equation of the arc follows the equation of the circle

$$x^2 + (y-R)^2 = R^2 \qquad (2)$$

or

$$y = \pm [R [1-x^2/R^2]^{1/2} + R$$

For segments with a very small surface area i.e. $x^2/R^2 < 1$ one can write the following equation

$$[1-x^2/R^2]^{1/2} = 1-[x^2/2R^2] \tag{3}$$

Hence

$$y = \pm[R - x^2/2R]+R \tag{4}$$

The above equation mentioned holds good for both the arc segments AB and CD. Next, considering only the lower arc segment AB (Figure 2) one gets

$$y = x^2/2R \tag{5}$$

Comparing equation (5) and equation (1), it is clear that equation (5) also describes a parabola with $f = R/2$. This shows that a mirror segment, which satisfies the condition $x^2/R^2 < I$, can be used to make a parabolic concentrator.

The maximum possible absorber temperature is a function of concentration ratio of concentrators. It is given by

$$T_A = T_S\,[C/C_{max}]^{1/2} \tag{6}$$

Where

T_A = Absorber temperature
T_S = Outer surface of the sun = 5762°K
C = Concentration ratio
C_{max} = Maximum possible concentration ratio

From Figure 3 one can see that, a concentrator with a concentration ratio of about 20, should absorb radiation to give more than 700°K temperature which is almost true for a community size solar cooker. Our domestic solar cooker has a concentration ratio of about 1 while the maximum surface temperature reached during experiments was 140°C which is much less than 695°K.

Energy Losses in a Concentrating Collector. In concentrating collectors, there are various sources of solar or thermal radiation losses. These are identified as:

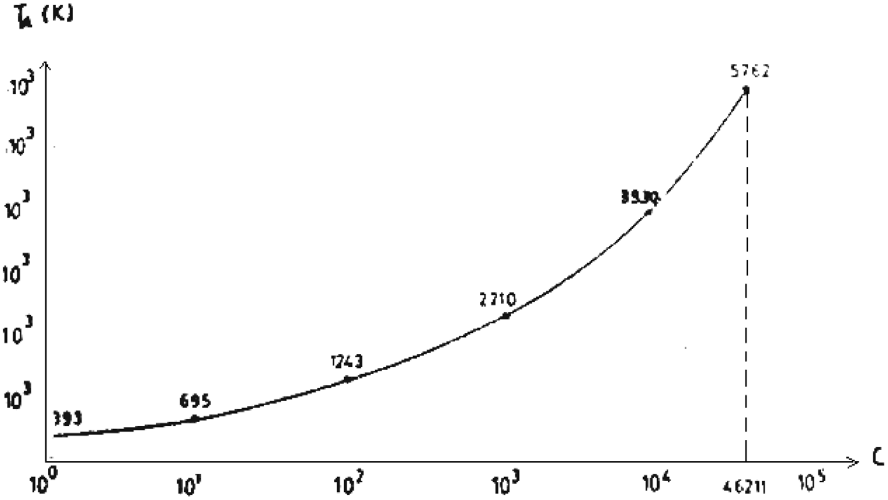

Figure 3. Graph showing relation between Concentration ratio and temperature obtained

1. Incomplete reflection the mirror surface.
2. Optical imperfections in the mirror surfaces because of limitations in the fabrication techniques.
3. Orientation error. The mirror may not be exactly oriented along the solar axis or the absorber is not exactly in the focal point or line of the mirror.
4. Reflection on the absorbing surface.
5. Radiation from the absorber in the long wave region.
6. Convection from the absorber.

Incomplete Reflection of the Mirror Surface. The energy losses due to incomplete reflection can therefore be represented by the expression:

$$Q_R = (1-\varrho)\, G_{Di}\, A_R \tag{7}$$

Where

ϱ = Reflectivity of mirror
G_{Di} = Direct radiation on an inclined mirror surface (w/m^2)
AR = Aperture area of the mirror (m^2).

Mirror surfaces made of acrylic with aluminium film have a reflectivity of 0.8 and losses between 7-24%.

Inaccuracies on the Mirror Surfaces. The mirror surfaces are very often not exactly shaped and has corrugations (not visible by the naked eye). There are also some deviations from exact geometrical contour. These factor result in further blurring of the sun's image.

Tracking Arrangement Inaccuracies. A defective alignment of the collector system towards the sun can be caused by the tolerance limits of the tracking system or by unsteady or inaccurate tracking. The larger the concentration ratio, the more exact the orientation should be because the absorber gets smaller and smaller.

Reflectivity and Emissivity of the Absorber

For concentrating collectors in which the absorber temperature reaches a maximum value, the absorber can be coated selectively. The reflectivity of the (ϱA) is absorber is $\varrho A = (1-\alpha)$. The emissivity is a measure of radiation emitted by the absorber in the long wave region. Most of the selective surfaces have a very small value of ε in this spectral region. As a result of reflection on the absorber, the encountered energy losses can be represented.

Convection from the Absorber

Since the absorber is warmer than the surrounding air, it loses energy by convection:

$$Qi = U_A A_A (t_p - t_a) \qquad (8)$$

U_A = Heat loss coefficient w/m^2 °K
A_A = Absorber area (m^2)
t_p = Absorber temperature (°C)
t_a = Ambient temperature (°C)

DESIGN REQUIREMENTS FOR SOLAR COOKERS

It was important to identify to the principal requirements for the successful use of solar cooker in the less developed areas of the world. They may be summarized as follows: (a) the unit must cook foods effectively; it must therefore provide energy at a sufficient rate and temperature to properly cook desired quantities and type of food. (b) It must be sturdy enough to withstand rough handling, wind and other hazards. (c) It must be socially acceptable and fit in with the cooking and eating habits of the people, i.e. provide for cooking to be done in the shade and if possible at times when the sun is not shining. (d) It must be capable of manufacture locally, and to deliver a cooking unit at a sufficiently low cost to be afforded by the lower income households.

The need for solar cooker development and application has been amply cited the reviewed literature. As pointed out previously, they are the result of the scarcity of the cooking fuels, principally wood, their high cost, their wasteful use and the resulting deforestation. Although cooking requires only relatively small portion of the world's total energy consumption, the aggregate individual and family impact of substantial cooking fuel replacement in less developed countries could be great. Major benefits would be derived from the use of dried animal wastes for fertilizer rather than fuel, conservation of trees and other ground cover, and the reduced outlay of the limited funds for fuel purchase.

Before summarizing the state of solar cooker development, solar cookers will be briefly described according to the type of cooker. Basically they may be considered as (a) simple direct solar cooking devices where the cooking takes place at the point of solar concentration or collection, and (b) advanced solar cookers in which the thermal energy from the solar collector is transferred to a remote area by means of some heat transfer fluid and/or the solar cooker system incorporates some type of energy storage.

DESIGN INVESTIGATION ON SOLAR COOKERS

Various designs of solar cooker have been developed in our country (see Figures 4-6). Basically there are three designs of solar cookers:

1. Flat plate box type solar cooker with or without reflector
2. Multi reflector type solar oven and
3. Parabolic disc concentrator type solar cooker.

The flat box type design is the simplest of all designs. Maximum no load temperature with a single reflector reaches up to 160°C. In a multi-reflector oven, four square triangular or rectangular reflectors are

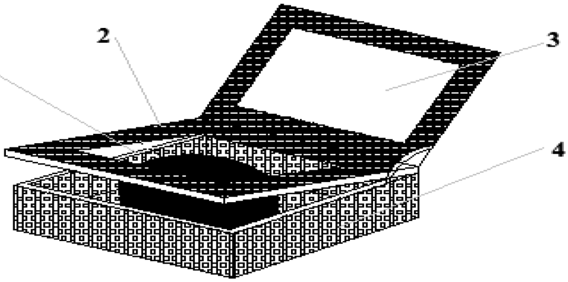

Figure 4. Box type solar cooker: (1) Cooking vessel, (2) window frame, (3) reflector, (4) box

mounted on the oven body. They all reflect the solar radiations into the cooking zone in which cooking utensils are placed. The temperature obtained is of the order of 200°C. In the compound cone reflector type solar cooker, temperatures of the order of 450°C can be obtained in which solar radiations are concentrated into a focal point.

Since the oil embargo of 1973 world attention has turned to the problem of diminishing fossil fuel supplies and to the search for alternative energy resources. Among the renewable energy resources which are being considered one of the most popular and perhaps the most promising is solar energy. Long before 1973 it was coming apparent that the less developed countries (LDCs) would be facing energy problem quite different problem from those which would be faced by the developed countries in the 1970s. With a low technological based and immature economic development, the LDCs depend heavily upon man or animal power for mechanical energy and upon forest and agriculture products for thermal energy. Therefore, as these countries began the process of developing, and as their population and standard of living began to increase serious energy shortages developed. During this period a number of concerned organizations and individuals began to consider the problem of increased energy requirements for these countries and started experimenting with the use of solar energy as a means of supplying their energy needs. These efforts generally have not been successful on a significant scale because of technical, economic, social or political reasons. However, they have served to identify and prioritize the most serious energy problems facing the LDCs. However, during the past few years it has been amply demonstrated that solar energy can provide both the thermal energy required for cooking and the mechanical energy necessary to pump the water needed for irrigation.

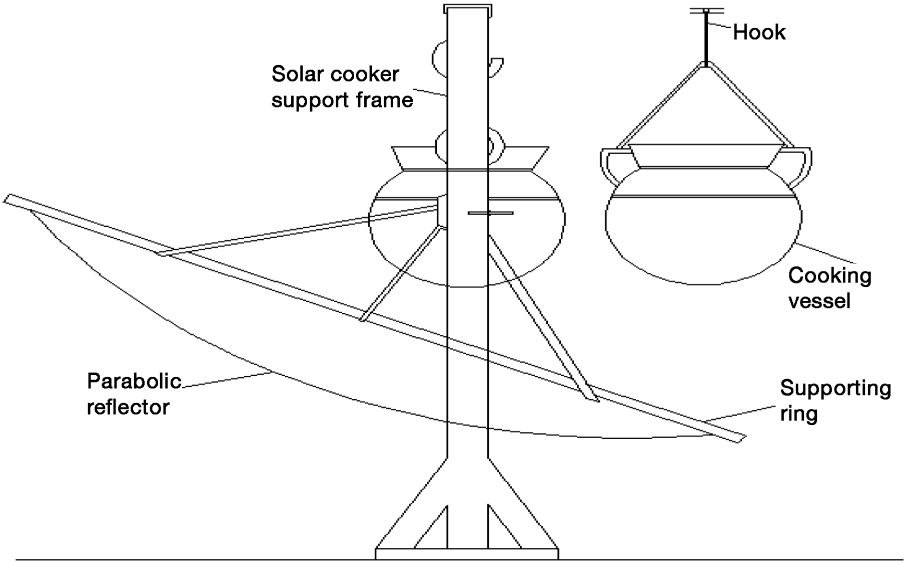

Figure 5. Sketch of Danish Solar Cooker Developed by Danchurchaid and introduced into Upper Volta During 1977

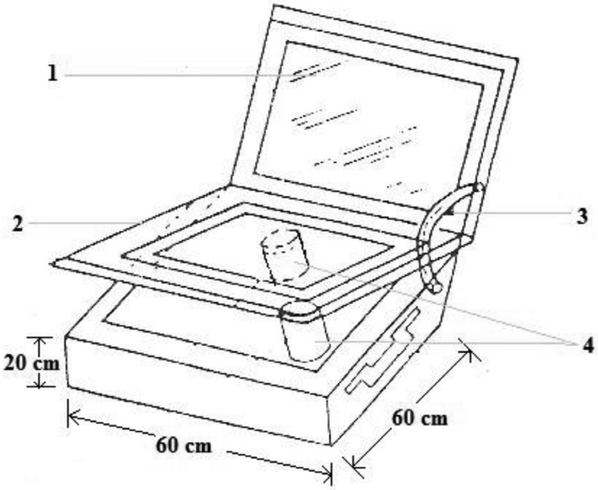

Figure 6. Details of a box type solar cooker: (1) reflection mirror, (2) glass cover, (3) guide for adjusting reflecting mirror, (4) cooking pot.

Direct Solar Cookers

Direct solar cookers may be classified as (a) concentrating parabolic and spherical dish or trough collectors where the heat at the focus of the collector directly heats either a vessel containing the food or the food itself and (b) ovens or food warmers which are insulated boxes with transparent covers in which solar energy is collected by direct radiation or by radiation from some type of reflected surface.

Parabolic Concentrator Cookers

The most familiar type of solar cooker is the parabolic dish collector which heats food either directly or in a bowl or pan placed at the focus of the collector. These collectors have been the subject of continuous investigation throughout the past 100 years. Figure 7 is a diagram of a parabolic dish solar cooker which was taken at the laboratory of l'office de l'Energie Solaire, ONERSOL, in Niamey, Niger. Typical elements of this cooker are (a) a "U" frame which supports the parabolic concentrator and food support. A vertical-axis support is located at the bottom of the "U" frame so that the entire assembly is free to rotate in a bearing to follow the sun in its east-west motion, (b) a horizontal bar which connects the top of the open end of the "U" frame and supports a platform or a grill on which the food or food containing vessel is placed. This bar provides a horizontal axis about which the concentrating reflector pivots so that the food support is always at the focal point of the concentrator. This axis permits the cooker to be adjusted in the azimuth plane, (c) the parabolic concentrator which collects the solar radiation and concentrates it onto the cooking platform, and (d) a positioning or holding device which permits the azimuth position of the collector to be maintained without further attention by the operator.

In Figure 8 the azimuth holding device consists of two flat plates attached to the triangular shaped pivot arms which connect to the horizontal axis supporting the cooking platform. Holes in these flat plate permits a pin to engaged the vertical arms of the "U" support and hold the azimuth position of the concentrator. To cook with this device the operators stand behind the collector and turns the entire assembly until it faces the direction of the sun.

Ovens and Food Warmers

Solar ovens or food warmers typically use some concentrating of solar radiation in an insulated chamber with a transparent cover (glass)

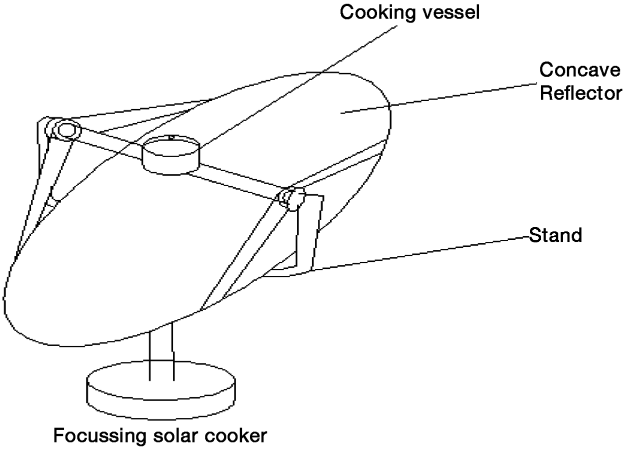

Figure 7. Parabolic solar cooker

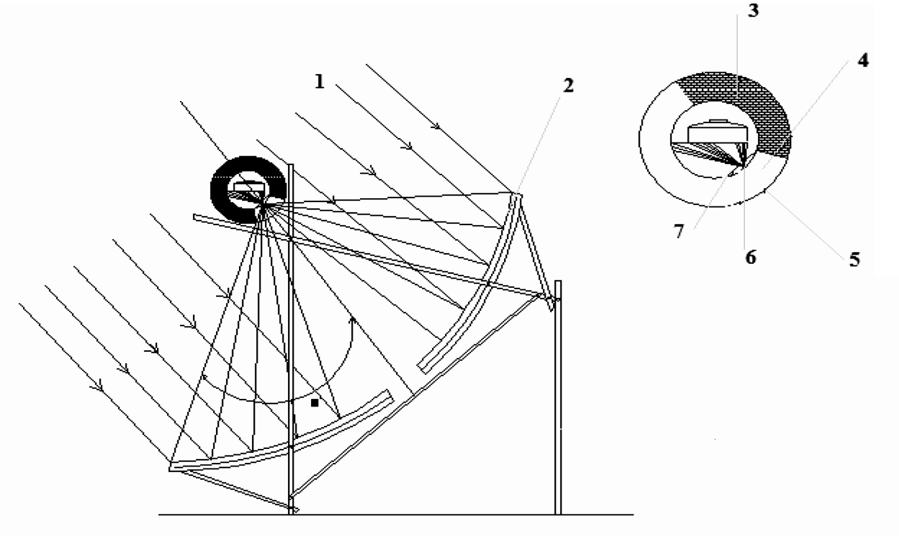

Figure 8. Schematic of a Solar Oven Designed by Prata: (1) incident radiation, (2) concentric reflector, (3) glass wool, (4) slit, (5) plastic cover, (6) focus, (7) glass

for trapping the heat ("green house effect"). Telkes (8) has summarized some of the potential advantages of solar ovens as: (a) capability for baking or roasting, (b) requires less focusing and orientation than the parabolic/spherical concentrating collector, (c) cooking pots and pan are protected from the wind, (d) severable pots or pans can be used at the same time, (e) heat can be stored permitting the preparation of food in partly cloudy whether, and (f) food can be kept warm after sunset.

The temperature of a solar oven can be increased by adding additional solar concentration from some type of concentrating collector. An example of this concept is shown by the schematic in Figure 8 by Prata (5). Figure 9 shows the schematic drawing of an experimental solar oven, designed by Telkes.

Figure 10 shows a solar food warmer developed by Brace Research Institute. The warmer consists only of glass covers over a food warming area. The walls and bottom of the warming area painted black to increase solar absorptivity. Concentration by reflective surfaces generally is not used in warmers since temperature requirements are relatively low.

ADVANCED SOLAR COOKERS

To overcome the problems of cooking in the direct sunshine and of the cooking only when the sun is shining two advanced solar cooking concepts were surveyed. The first involved the use of a heat transfer system to permit cooking to be done in a shelter. The second

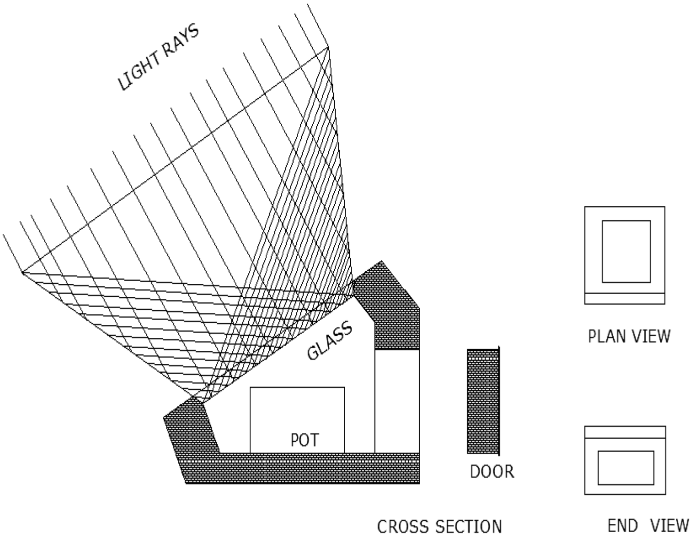

Figure 9. Schematic of a Solar Oven Designed by Telkes

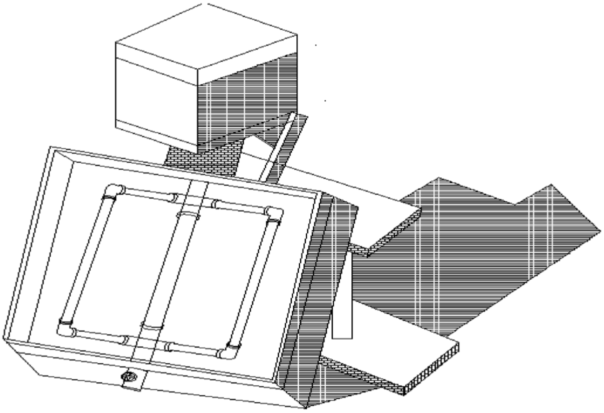

Figure 10. Perspective View of Solar Steam Food Warmer Developed by Brace Research Institute

involved the use of some type of energy storage system which would permit the cooking to be done in the evening or at the other times when the sun is not shining.

Heat Transfer Systems

Various type of heat transfer systems have been proposed for bringing the heat generated in the solar collector into a sheltered area where the heat can be used for cooking as previously discussed, heat transfer systems forms the basis for most solar thermal systems used to operate mechanical devices. For example, in the water pumping system the hot water from the flat plate collector is transferred to the evaporator where the collected heat is used to vaporize inorganic liquid in a similar manner, flat plate collector have been used to heat water to produce steam which in turn heat a remote hot plate. Unfortunately the maximum temperature obtainable with a flat plate collector is of the order of 140°c and as the working fluid temperature approaches this temperature the efficiency of the system becomes so low as to be useless. One example of such a system is illustrated in Figure11.

The heat transfer pipe leads from the top of sloping structure. The collector consists of a series of longitudinal pipes which runs the length of the collector and are connected in parallel by headers at the top and bottom. Water is permitted to fill about three quarters of the length of the tubes and is sealed off by means of a valve. The system is then allowed to reach thermal equilibrium which is about 140°C at 3.5 atmosphere absolute pressure. By opening a valve leading to the hot plate the steam is allowed to condense on the hot plate releasing
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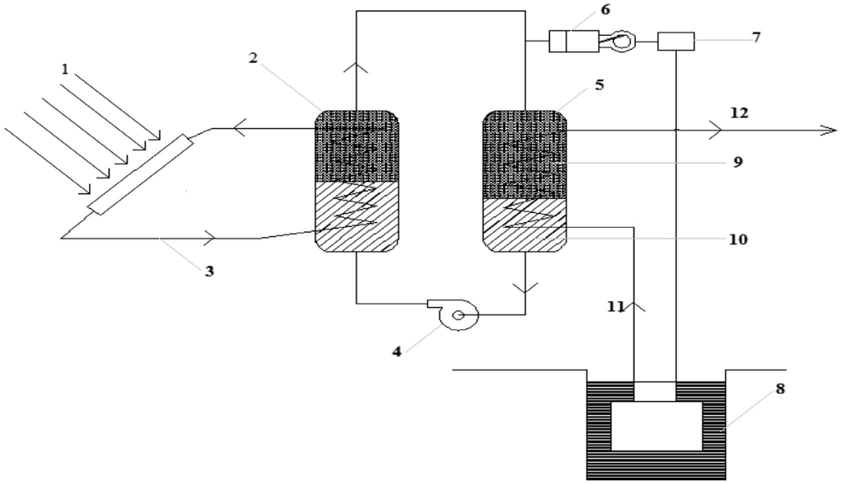

Figure 11. Schematic of a typical SOFTRETES Solar Water Pumping System: (1) incident radiation, (2) boiler, (3) collector water outlet, (4) circulating pump, (5) condenser, (6) expander, (7) hydraulic pump, (8) water reservoir, (9) organic vapor, (10) organic liquid, (11) cooling water in, (12) hot water out.

the heat of vaporization to the plate. The problem associated with this collector are (a) the relatively low hot plate temperature which would be suitable only for light stewing or water heating chores (b) the low efficiency of the system and (c) steam under pressure present potential safety hazards in the village environment.

To increase the temperature of the cooking unit, concentrating solar collectors, usually parabolic or cylindrical trough, have been proposed to heat oil which is circulated through a pipe or tube type receiver (heat exchanger) located at the focal line of the trough. The heated oil is then used to transfer the collected heat to a hot plate or stove located in the dwelling or other sheltered area. Oil is proposed instead of water in these heat transfer system because it will remain a liquid at atmosphere pressure at the temperature provided by the trough collector (175-200°C). Figures 12-15 are the artist concept of two heat transfer solar cooking systems proposed by Stam and Swet (9). Because line-focus, linear trough collector are used in this concept some type of one0axis tracking is required in order to keep the concentrated energy focused on the heat transfer pipe. In Figure 12 this is provided through a weighted pulley arrangement in which the downwards movement of a driving weight is cause to coincide with the speed of flowing sand in an hour-glass. Through this pulley action the rotation of the trough follows the east-west motion of the sun at 15°per hour. Figures (13-14) show a concept which uses an "automatic" tracking system. A bimetal "heliotrope" in the axis of the trough, reacts to direct heat from the sun to rotate the trough until a "sun-shade," attached to the trough, moves between the "heliotrope" and the sun, casting its shadow on the "heliotrope."

An artist's rendering of the solar cooking heat transfer/storage system proposed by Farber (6). This system differs from the previous two in that a two separate heat transfer loops are used. One loop receives and energy from the collector and transfer it to a thermal storage medium (phase change material). The second loop receives heat from the storage medium and transfers it to the cooking area.

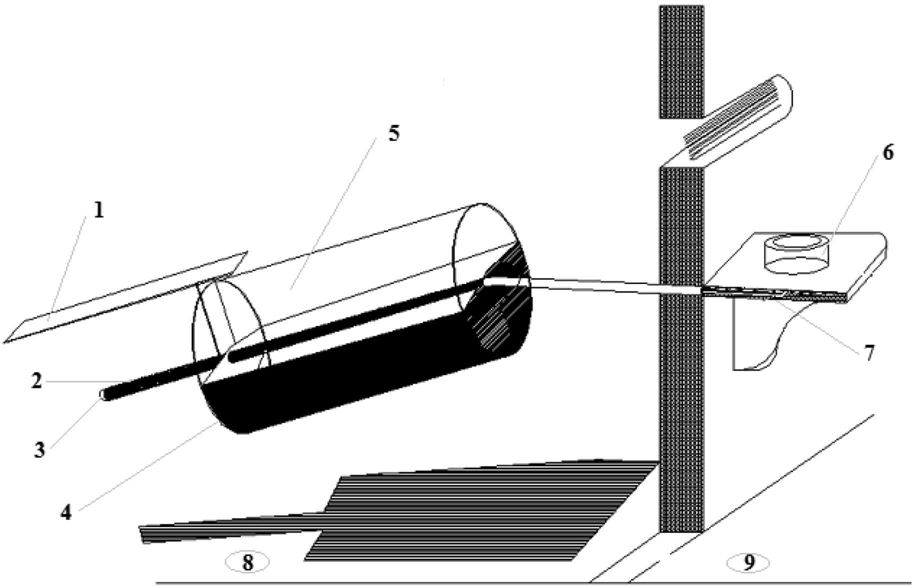

Figure 12. Artist Concept of an "Automatic" Tracking Solar Cooking System Proposed by Swet: (1) feedback sun shade, (2) bimetal thermal heliotrope, (3) clear plastic shield, (4) ridged lightweight foam plastic, (5) parabolic cylinder mirror aluminized mylar surface, (6) utensil or thermal storage mass, (7) hot plate, (8) outdoors, (9) indoors

Energy Storage Systems

Several methods are available for storing the energy required for cooking. Among these are sensible heat, latent heat of fusion and chemical energy.

Sensible Heat

Sensible heat refers to the heat capacity of a material and is expressed as the heat in calories required to raise one gram of the material one degree Celsius. The reverse situation is also true in that the same numbers of the calories of heat are released when one gram of the material is lowered one degree Celsius. Of the commonly available materials water has the highest heat capacity; one calories per degree Celsius (1 cal gm-1°C-1). Unfortunately, since the boiling point of water is only 100°C, water cannot be used to provide sensible heat for cooking above this temperature without using pressurized vessels which would present technical and safety problems in a primitive or non-technical environment. Considering readily available materials which can be conveniently stored and used at temperature of about 150°-200°C, oils and rocks appear to be the most promising. Available oils in the LCD's of Africa are vegetable oils such as peanut and cottonseed. The heat capacity of these oils is about 0.48 cal gm-°C-1 and rock is about 0.2 cal gm-°C-1. The most economical storage system might be expected to be a combination of rock and oil in which the major portion is a rock bed through which oil circulates and serves as the heat transfer medium. A rock bed of properly sized stones provides a large surface area and the tortuous path of the oil through the bed ensures rapid heat exchange. Assuming a bed of 70 percent by volume of rocks and 30 percent oil the heat capacity would be about 0.28 cal gm-°C-1.

Latent Heat of fusion

The latent heat of fusion of a material is the amount of heat required to melt a specific amount of the material at its melting point temperature. Many investigators have attempted to design systems to utilize the heat of fusion of various materials in order to economize on the amount of material required to store a given amount of heat energy. For example, the melting point of the mixed salt NaNO2-NaOH is 240°C. The heat of fusion of this salt is about 58 cal/gram, which is the amount of heat required to melt one gram of NaNO2-NaOH at 240°C. There, in freezing one gram of this material 58 calories would be released at 240°C.

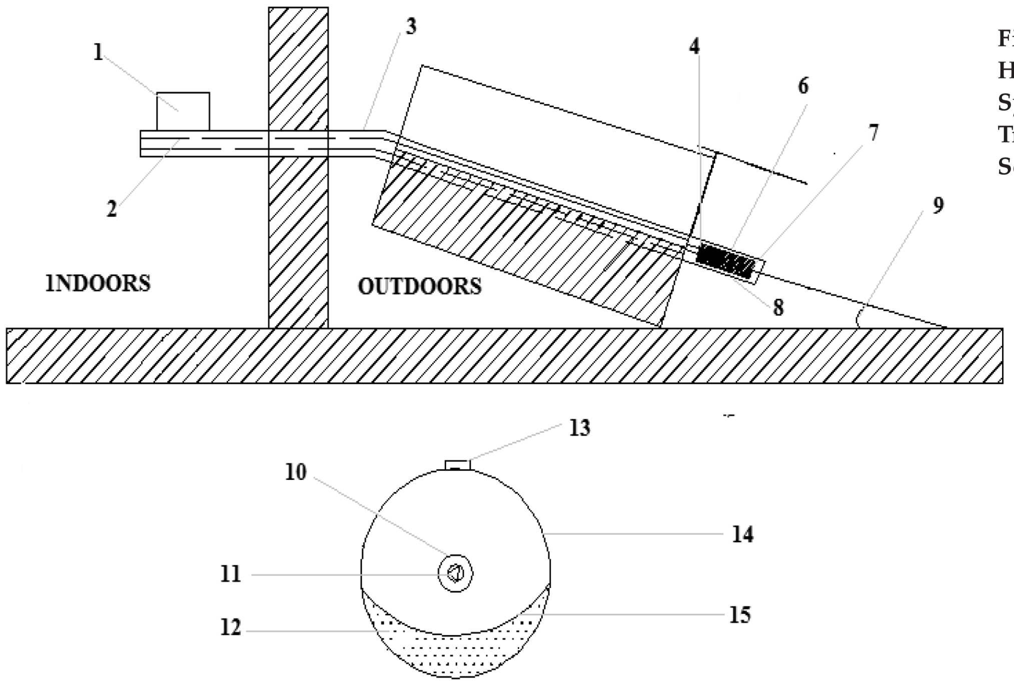

Figure 13. Artist Rendition of Heat Transfer Solar Cooking System Using Automatic Tracking Proposed by Swet. See legend below.

1 Thermal storage mass
2 Hot plate
3 Insulation
4 Summer sun
6 Bimetal thermal heliotrope
7 Winter sun
8 Clear plastic shield
9 Local latitude

10 Evacuated transparent shield
11 Ni plated steel heat pipe filled with Dowtherm heat transfer fluid
12 Rigid lightweight foam plastic
13 Balance weight as required for mass symmetry
14 Circular plastic wind and dust screen
15 Parabolic cylinder mirror aluminized mylar surface

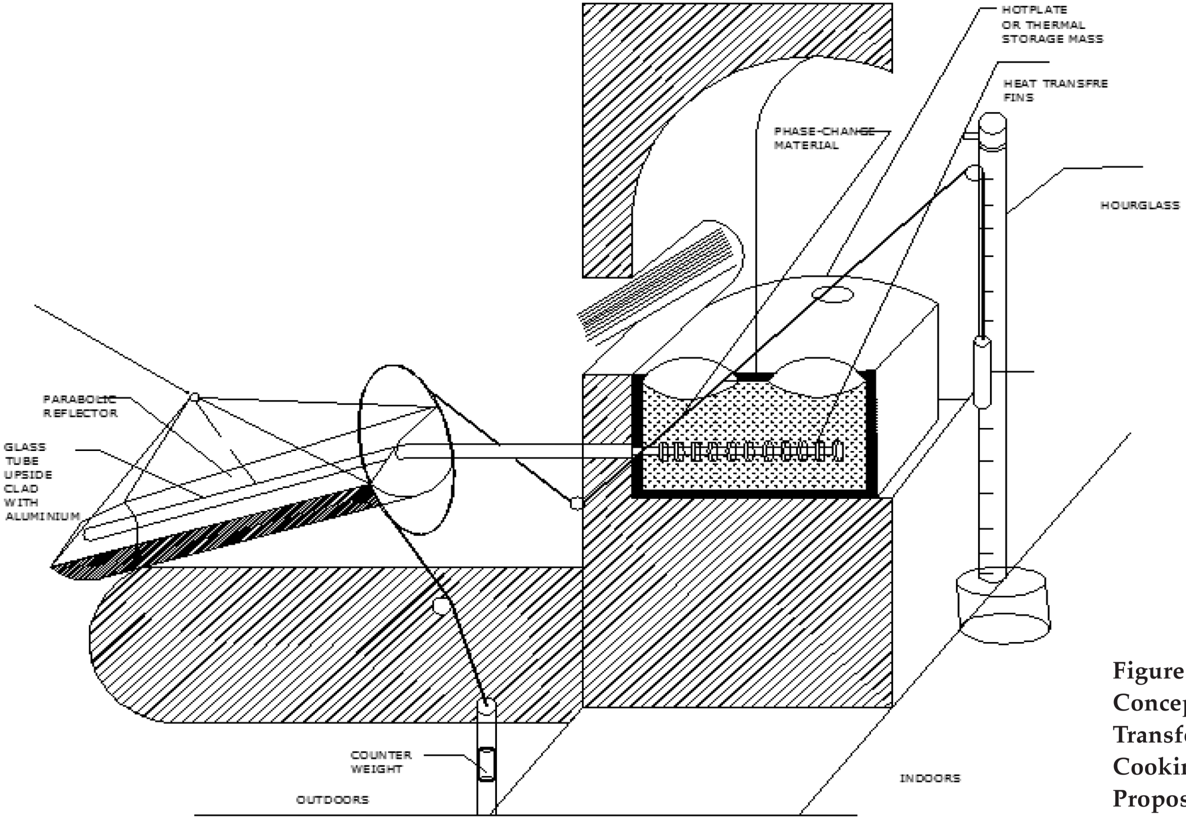

Figure 14. Artist Concept of a Heat Transfer Solar Cooking System Proposed by Stam.

As pointed out in the previous section, the sensible heat for typical oil is about 0.48 cal gm-1°C-1. Therefore in order to obtain the same amount of thermal energy in oil to be used at 240°C with 1° temperature drop, about 120 grams or 120 times as much oil by weight would be required as NaNO2-NaOH. An alternate storage method would be to raise the temperature of one gram of oil 120°C above 240°C or to 360°C in which the same amount of energy would be available above 240°C. (This latter case is not practical in the case of oil since most of oils are chemically unstable when used above about 600°F).

The typical for a heat of fusion storage system use a series of pipes or a coil of tubes in a tank filled with the salt (or other material) with the desired heat of fusion. Concentrated solar energy is used to heat oil (or other heat transfer fluid) to a temperature above the melting temperature of the salt. This hot fluid passes through the tubes or pipes in the tank and melts the surrounding salt. The melting salt will remain at its melting temperature until all of the salt becomes liquid. Beyond this the temperature of the liquid salt will increase according to its heat capacity (storing sensible heat) until it approaches the temperature of the oil in the tubes. To recover the stored energy, oil to heat the cooking unit is circulated through tubes submerged in the melted salt. As the salt freezes on the outside of the tube walls the heat of fusion is transferred to the oil at the melting temperature of salt. Theoretically it would be possible to maintain the temperature of oil going to the cooking unit at the melting temperature of the salt until all the salt become solid. Unfortunately, this has not being realized in practice because of the thermal resistance which is presented by the frozen layer of the salt on the tubes. That is, heat cannot be transferred from the still liquid salt through the frozen salt layer and into the tubes containing the oil at a high enough rate to maintain the oil at the melting temperature of the salt; the temperature required for cooking. Even with these difficulties heat of fusion storage concepts continue to attract attention and research in this area will continue.

A survey [30] was made of all simple compounds with melting points between 130°C and 200°C. The thermal storage capacity for each compound was tabulated in terms of the number of kilograms and liters of liquid required to provide the heat required for cooking a meal for a family of six. Of the materials surveyed, Al2Cl6 had the highest heat of fusion of about 90,000 cal/liter. On this basis about 14 liters of liquid Al2Cl6 would be required to cook a meal for a family of six persons, assuming 100 percent efficiency or 28 liters on the same basis that 40 gallons of the rock and oil were required. Although this is the only about one fifth of the volume of heat storage material compared with the sensible heat storage system it still represent a technology yet to be realized and probably not suitable for suitable for village use.

A recent effort to develop a high temperature heat of fusion thermal storage system was reported by the Honeywell [10]. The experiment employed a cube-shaped tank, approximately eight feet on a side, which contained the heat storage medium; 99% NaNO3 and 1% NaOH. Tubes at the bottom of the tank carried the charging steam used to melt the salt, and tubes at the top of the tank carried feedwater for steam generation. In order to remove the salt which solidified on the heat removal tubes at the top of the tank, mechanical scraper were developed. Laboratory scale experiments revealed difficulties with the scraping system and the system's ability to recover heat, and the program was cancelled without further development.

Chemical Energy

Chemical energy can be realized by using a system of reversible chemical reactions in which energy can be absorbed or released according to the reaction taking place. Solar energy in the form of heat can be used to drive the reactions in one direction and the heat is recovered when the reaction is reversed. Chemical storage has the advantage that energy is not lost during the time period of storage as in the case of thermal storage. An example of a chemical system utilizing heat of solution of acid is under investigation by VITA. This concept is based on the fact that heat is generated when concentrated acid, in this case sulphuric acid, is mixed with water. Preliminary calculations based on the energy needed to cook for a family of six would require a two chamber, 21 liters stainless steel reaction vessel to hold the two liquids. Assume that both liquids are mixed in one chamber; when this chamber is exposed to direct solar radiation water would be distilled from the acid solution in one chamber into the other chamber. Heat energy for cooking would be released when the container is inverted mixing the acid and water. This concept is only in the experimental stage and many technical obstacles must be, not the least of which is necessity to use sulphuric acid, a highly toxic and dangerous substance, as the base material. In addition the 6 gallon, 2 chamber stainless chamber probably would be prohibitively expensive; and filled with 27 kilograms of liquid would be difficult to manipulate and dangerous to handle. Most other processes which involved heat of solution, such as sodium hydroxide in water, are equally dangerous, expensive and of excessive weight and bulk. Although interesting in concept, chemical storage, at present state of technology, does not appear suitable for Indian village use.

PERFORMANCE EVALUATION OF CONCENTRATING SOLAR COOKERS

Energy Efficiency of Solar Cooker

Energy efficiency of a Solar Cooker can be defined as the ratio of energy output (only the increase of the water energy due to temperature growth) to the energy input (the energy of solar radiation). The energy input to the SC can be calculated as follows:

$$E_i = IA_a \tag{9}$$

And, energy output of the SC was obtained in watts as follows:

$$E_0 = \frac{m_w c_{pw}\left(T_{wf} - T_{wi}\right)}{\Delta t} \tag{10}$$

Thus the instantaneous energy efficiency of the SPC was calculated as follows:

$$\eta = \frac{E_0}{E_i} = \frac{\dfrac{m_w c_{pw}\left(T_{wf} - T_{wi}\right)}{t}}{IA_a} \tag{11}$$

Exergy Efficiency of Solar Cooker

Exergy efficiency of any process is a ratio of the exergy transfer rate associated with the output to the exergy transfer rate associated with the driving input (Kotas, 1990). The following expression for the available energy flux, which has the widest acceptability, was used to calculate the exergy of solar radiation (exergy input to the solar cookers).

$$E_{xi} = I\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T}\right)\right]A \tag{12}$$

And the exergy output may be calculated by using

$$E_{xo} = \frac{m_w c_{pw}\left[\left(T_{wf} - T_{wi}\right) - T_a \ln\frac{T_{wf}}{T_{wi}}\right]}{\Delta t} \tag{13}$$

The instantaneous exergy efficiency can be defined as the ratio of the increased water exergy to the exergy of the solar radiation:

$$\Psi = \frac{E_{xo}}{E_{xi}} = \frac{\dfrac{m_w c_{pw}\left[\left(T_{wf} - T_{wi}\right) - T_a \ln\frac{T_{wf}}{T_{wi}}\right]}{\Delta t}}{I\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T}\right)\right]A} \tag{14}$$

Thermodynamic Optimization of the Performance of Parabolic Collector

The common way to increase the performance of a solar collector is to optimize the thermal efficiency of collector, which is define as the ratio of ‘useful energy output’ to that of ‘incident solar energy’ during the same time period. The performance of solar collectors can also be evaluated from the analysis of exergy which is very effective tool to improve the performance (Dincer, 2002). The amount of exergy delivered by solar collectors is mainly affected by thermal irreversibility between the sun and the collector. Higher the temperature difference between the sun and the collector, higher will be the irreversibility. In another way, if the irreversibility associated with a process is small then the work produced (exergy) by device is more. The performance of a system can be improved by minimizing the irreversibility associated with it.

The exergy collected by a solar collector can also be increased by increasing the collector area. Since, collector is an expensive component of any solar thermal system which leads to more investment in the form of capital cost. The second law analysis is more informative in regard to the optimum operating zone, quantifying the inefficiencies, their relative magnitudes and locations. So we optimize the exergy output from the collector from the second law point view. Second law analysis for optimization of flat plate solar air heaters has been performed by

Altfeld et al., 1988 where net exergy flow was maximized by minimizing exergy losses by absorption of radiation at absorber temperature level. Based on this analysis, optimal designs of the absorbers and flow ducts were determined. Having developed the optimal designs for air heaters, Altfeld et al. 1988 conducted sensitivity analysis to study the influence of varying operational conditions on the optimal results. Hepbasli, 2008 comprehensively reviewed and evaluated performance of a wide range of renewable energy resources and had defined exergy efficiency of solar flat plate collector. Luminosu et al., 2005 conducted exergy analysis of a flat plate collector with the assumption that the global solar radiation is equal to the solar flux and inlet fluid temperature is equal to ambient temperature. Optimal operation mode of flat plate collector was determined by maximizing exergy efficiency of the collector with respect to various parameters. Exergy analysis has been applied by various authors (Öztürk, 2004; Petela, 2005, Rosen, 1999) to judge a system and have shown how exergy analysis provides illuminating and meaningful assessment of solar thermal processes and can assist in improving and optimizing designs.

Thermodynamic Analysis of Parabolic Collector

The basic Hottel-Whillier equation for the actual useful heat gain (Q_u) of concentrating solar collector system, considering the radiation losses is:

$$Q_u = F_R A_A \left[C\left(\rho_R \alpha_A\right) I_s - U_L \left(T - T_a\right) - \varepsilon\sigma\left(T^4 - T_a{}^4\right)\right] \tag{15}$$

The maximum work output is:

$$W_{\max} = Q_u \left(1 - \frac{T_a}{T}\right) \tag{16}$$

The output exergy (E_0) of the collector at temperature T is:

$$E_0 = Q_u \left(1 - \frac{T_a}{T}\right) \tag{17}$$

Substituting Eq. (1) into Eq. (3) we have:

$$E_0 = F_R A_A \left[C\left(\rho_R \alpha_A\right) I_s - U_L \left(T - T_a\right) - \varepsilon\sigma\left(T^4 - T_a{}^4\right)\right]\left(1 - \frac{T_a}{T}\right) \tag{18}$$

The exergy delivering rate is given by:

$$E_0 = W_{\max} = \frac{mC_p}{t}\left[\left(T_f - T_i\right) - T_a \ln\frac{T_f}{T_i}\right] \tag{19}$$

where T_f and T_i are the final and initial temperatures of the water respectively. The actual useful heat gain by the working fluid is:

$$Q_u = \frac{mC_p}{t}\left(T_f - T_i\right) \tag{20}$$

From Eqs. (1), (5) and (6) we have:

$$\begin{aligned} E_0 = {} & F_R A_A\left[C\left(\rho_R \alpha_A\right) I_s - U_L\left(T - T_a\right) - \varepsilon\sigma\left(T^4 - T_a^4\right)\right] - \\ & \frac{mC_p T_a}{t}\ln\left(1 + \frac{F_R A_A t}{mC_p T_i}\left[C\left(\rho_R \alpha_A\right) I_s - U_L\left(T - T_a\right) - \varepsilon\sigma\left(T^4 - T_a^{\,4}\right)\right]\right) \end{aligned} \tag{21}$$

RESULTS AND DISCUSSIONS

To have a numerical appreciation of the results we have prepared a numerical program in MATLAB for solving the three equations (19, 20 and 21) given above and using the following design parameters of the concentrating collector and flat plate collector:

Area of the absorber/receiver of the concentrating collector

$(A_A) = 0.05 m^2$

Area of the reflector/aperture for concentrating collector

$(A_R) = 1.53\ m^2$

Concentration ratio of the concentrating collector

(C) = 31.36

Overall heat loss coefficient from the absorber for concentrating collector

$(U_L) = 8\ W/m^2\ K$

Reflectivity of the reflecting surface

$(\rho_R) = 0.90$

Absorptivity of the absorber

$(\alpha_A) = 0.90$

Emissivity of the absorber

$(\varepsilon) = 0.90$

Stefan-Boltzmann constant

$(\sigma) = 5.67\times10^{-8}$ Wm^{-2} K^{-4}

Efficiency factor of the absorber

$(F')= 0.90$

Area of the absorber/receiver of the flat plate collector

$(A_A) = 0.2304$ m^2

Overall heat loss coefficient from the absorber for flat plate collector

$(U_L) = 3.8$ W/m^2 K

The concentration ratio of the collector (C) is 31.36 and mass of the fluid (m) in the pot is 1 kg to 3 kg. The hourly solar radiation (I_s) in W/m^2 and corresponding ambient temperature (T_a) used in this study are taken from the experimental data. We have studied the effect of the solar radiation and time of day on the stagnation temperature, exergy output, optimum fluid inlet temperature, exergy efficiency and thermal efficiency of the solar collectors during the both summer and winter climatic conditions.

Figure 15 shows the variation of stagnation temperature with the time of day. The stagnation temperature is maximum at 12:30 a.m. because solar radiation is maximum at that time for both type of solar cooker in summer and winter.

The hourly solar intensity and its effect on the various performance parameters of the parabolic concentrating disc type solar collector (SPC) and flat plate collector are given in Figures 16-18 for a typical set of operating conditions. Figures 16-18 show the variation of optimum temperature, optimum temperature at large mass, maximum exergy output with the time of day. As the graphs shows all the parameters are increasing function of solar intensity. On the other hand, for low solar intensity the exergy efficiency first increases and then decreases. Since, the collection temperature and the quality of energy increase with the concentration ratio and hence, the exergy loss also increases, thereby we get the results shown in Figs 16-18. It is also observed that all the parameters increase as the incident solar radiation increases. But for a given mass and solar intensity, if the concentration ratio is increased beyond a limit, the heat loss also increases thereby decreasing the output and the performance of the collector.

The effects of the time of day on the main performance parameters such as exergy output, exergy efficiency are shown in Figures 19 and 20 for a fixed value of concentration ratio (C = 31.36). It is seen from graphs that all the parameters such as the stagnation temperature, optimum temperature and exergy output at large mass increases as the solar intensity increases and vice-versa. It is seen from these figures that the maximum exergy output and exergy efficiency, at large mass are also increasing functions of the solar intensity. Also it is observed that the mass and concentration ratio is the critical parameters. The concentration ratio is increased, the stagnation temperature, energy quality (exergy) and the collection efficiency increases. But for a given mass and solar intensity, if the concentration ratio is increased beyond a limit, the heat loss also increases thereby decreasing the output and the performance of the collector and hence, we get the results shown in Figures 15–19 for a given set of operating parameters.

COMPARATIVE ANALYSIS OF DIFFERENT SOLAR COOKER USING PUGH MATRIX

Given some design criteria, the Pugh matrix is used to compare and contrast a number of design concepts for selecting the best concept. The box type solar cooker is selected as a "base line." This baseline is scored as S against all of the criteria. Storage type solar cooker and Parabolic Concentrator Solar Cooker are then compared against solar box type cooker. If design concept is:

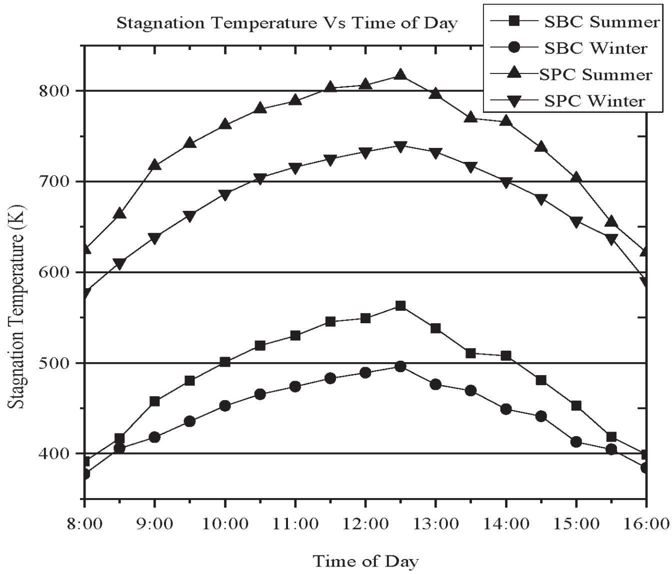

Figure 15. Variation of stagnation temperature with Time of Day

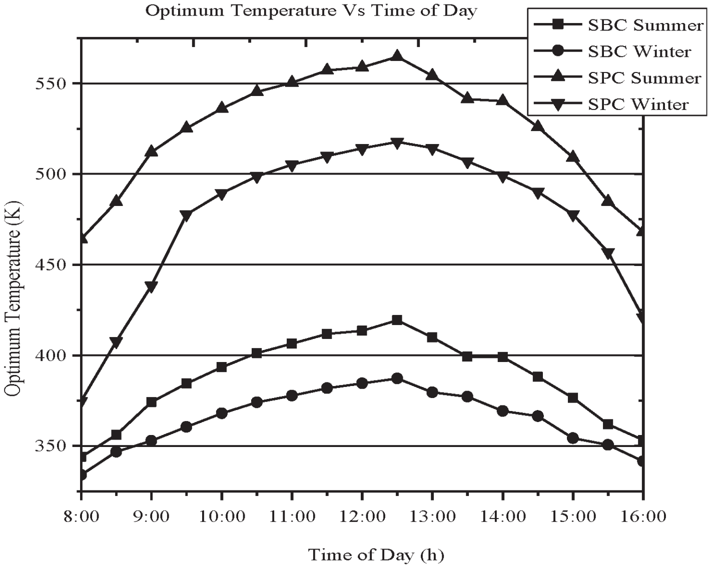

Figure 16. Variation of Optimum Temperature with Time of Day

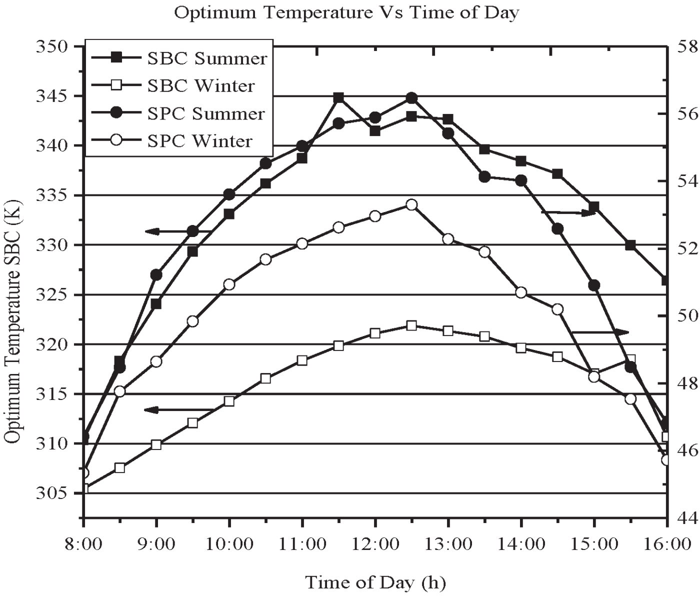

Figure 17. Optimum Temperature at constant mass with Time of Day

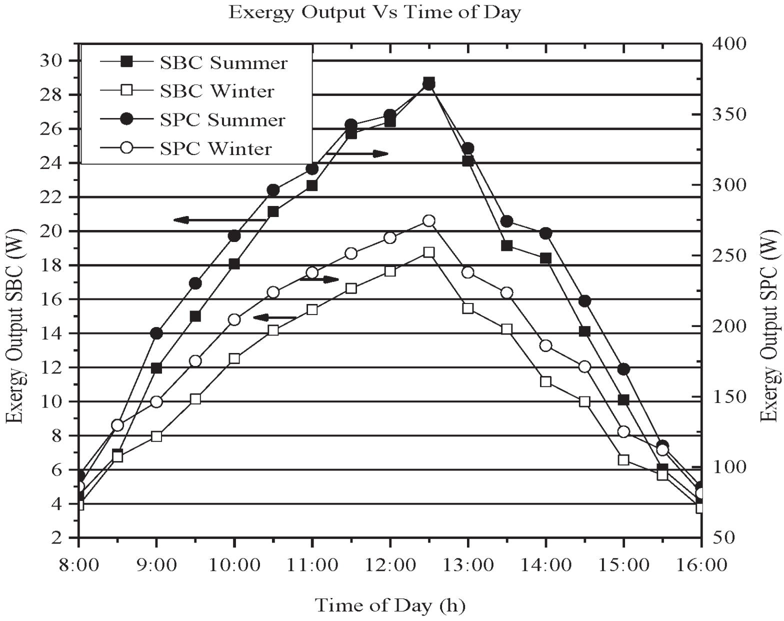

Figure 18. Exergy output at optimum temperature with Time of Day

- better than the baseline a "+" is entered in the appropriate cell
- worse than the baseline a "–" is entered in the appropriate cell
- the same than the baseline a "S" is entered in the appropriate cell

Figure 21 indicates that the total score of parabolic concentrator cooker is "5" maximum than the other solar cookers which conclude that the thermal performance of it is more than the others.

Figure 22 indicates that the total score of Box Type Solar cooker is "0 " which conclude that it is cheaper than the others. The parabolic concentrator cooker is a close second scoring "-1" which indicates that it is cheaper than Box Type Solar Cooker with Heat Storage Material.

Figure 23 indicates that the total score of parabolic concentrator cooker is "1" which concludes that it is more reliable than the others.

Figure 24 shows that the total score of Box Type Solar Cooker is "0" which is maximum than the others. So box type solar cooker is easy to manufacture.

Figure 25 shows that the total score of Box Type Solar Cooker with Heat Storage Material is "2" which is maximum than the others.

CONCLUSION

The present study analyses the performance of different type of solar cookers and with storage systems by using data for concentration ratios and hourly solar radiation. It is inferred that most of the performance parameters, such as, the exergy output, exergetic efficiency, stagnations temperature, inlet temperature and ambient temperature etc. increases in proportion to the solar intensity increase. Thus the present analysis can be used as an important tool for the design and performance criteria of concentrating collectors and other types of solar collectors as well. In this study evaluation various storage type solar cooker and Parabolic Concentrator Solar Cooker are compared against solar box type cooker in order to investigate the possibilities of various options available for meeting cooking energy needs. The findings of thermal efficiency and controlled cooking tests of Box Type Solar Cooker with Heat Storage Material is maximum than the others. This exercise in India is necessary to estimate future energy demand, to predict consumer response to policy decisions that promote or discourage certain cooking fuels and to make informed decisions regarding various possible fuel paths.

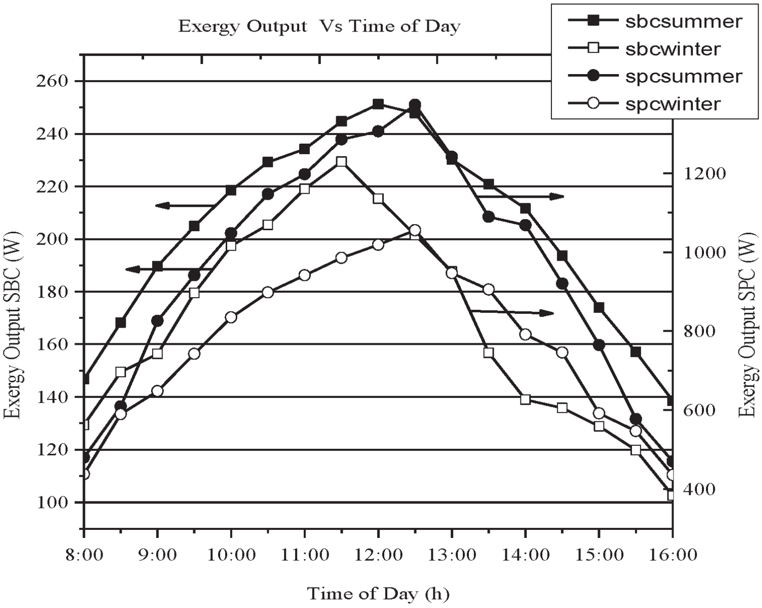

Figure 19. Exergy output at optimum temperature at constant mass with Time of Day

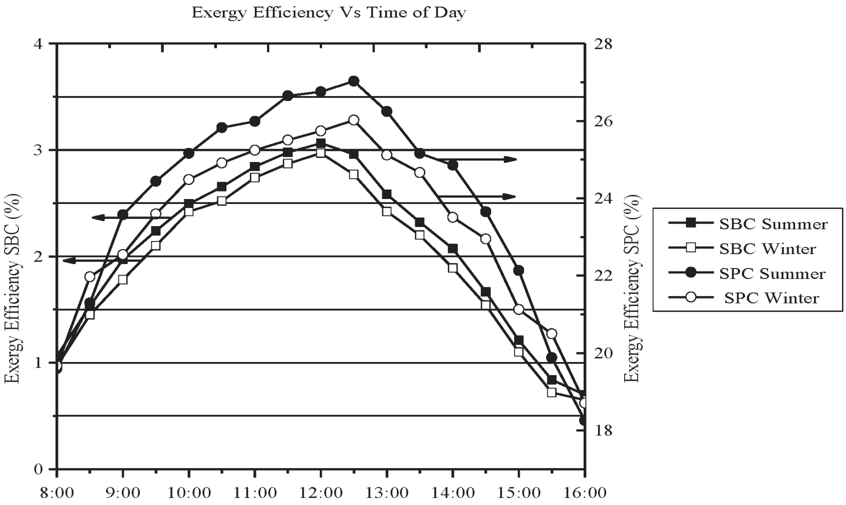

Figure 20. Exergy efficiency with Time of Day

		Design Concepts		
	Pugh Concept Selection Matrix *DESIGN CRITERIA*	Box Type Solar Cooker	Box Type Solar Cooker With Heat Storage Material	Parabolic Concentrator Solar Cooker
Solar/Thermal Performance	*Cooking Power*	S	+	+
	Energy Efficiency	S	-	+
	Exergy Efficiency	S	+	+
	Stagnation Temperature	S	+	+
	Optimum Temperature	S	+	+
	Total +	0	4	5
	Total -	0	1	0
	Total Score	0	3	5

Figure 21. Pugh matrix for solar/thermal performance

		Design Concepts		
	Pugh Concept Selection Matrix *Design Criteria*	Box Type Solar Cooker	Box Type Solar Cooker With Heat Storage Material	Parabolic Concentrator Solar Cooker
Cost	*Manufacturing Cost*	S	-	-
	Maintenance Cost	S	-	S
	Operating Cost	S	S	S
	Total +	0	0	0
	Total -	0	-2	-1
	Total Score	0	-2	-1

Figure 22. Pugh matrix for cost analysis

		Design Concepts		
	Pugh Concept Selection Matrix	Box Type Solar Cooker	Box Type Solar Cooker With Heat Storage Material	Parabolic Concentrator Solar Cooker
Reliability/Durability	Life	S	-	S
	Reliability	S	S	S
	cooking Time	S	-	+
	Preservation Of Nutrients	S	-	S
	Total +	0	0	1
	Total -	0	-3	0
	Total Score	0	-3	1

Figure 23. Pugh matrix for Reliability/Durability

		Design Concepts		
	Pugh Concept Selection Matrix	Box Type Solar Cooker	Box Type Solar Cooker With Heat Storage Material	Parabolic Concentrator Solar Cooker
Ease of Manufacturing	Design	S	-	-
	Assembling	S	-	-
	Size	S	-	S
	Insulating material	S	S	+
	Placement Of Cooking Pot	S	+	-
	Glazing	S	S	+
	Tracking system	S	S	-
	Total +	0	1	2
	Total -	0	-3	-4
	Total Score	0	-2	-2

Figure 24. Pugh matrix for ease of manufacturing

		Design Concepts		
	Pugh Concept Selection Matrix *Design Criteria*	Box Type Solar Cooker	Box Type Solar Cooker With Heat Storage Material	Parabolic Concentrator Solar Cooker
Ease of Use	*Day*	S	S	S
	Night	S	+	S
	Portability	S	-	S
	Ease of handling	S	+	-
	Inside House	S	+	-
	Total +	0	3	0
	Total -	0	-1	-2
	Total Score	0	2	-2

Figure 25. Pugh matrix for ease use

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