Heat Transfer Enhancement to Cooking Vessel in Hot Box Solar Cooker by Utilising the Energy Intercepted by Lid

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ABSTRACT--*Lid of cooking vessel intercepts maximum energy but it is not effectively transferred to food material because of thermal contact resistance due to uncertain contact between lid and cooking vessel. In order to utilise effectively the energy intercepted by lid in cooking food, two designs of lid have been developed. In first design, a circular ring of aluminium strip has been welded to the lid's inner side such that the ring is penetrating into the pot contents (water here). In second design, a frustum of cone shaped lid has been used in which the surface of lid is in direct contact with pot contents (water here). Temperature of water in the pot in which first lid is fitted, leads by 8-9 ˚C over pot with normal lid when the water temperature in this pot reaches 90 ˚C. This is a significant improvement. Temperature of water in the pot in which frustum of cone shaped lid is fitted, leads by 3-4 ˚C over pot with normal lid when the water temperature in this pot reaches 90 ˚C.*

Keywords : *Box type solar cooker, Ringed lid, Frustum of cone shaped lid, Normal lid.*

INTRODUCTION

Solar cooking is specially a boon for the rural regions where firewood and cow dung are the main sources of energy for domestic use. Food cooked in the sun is specially tasty and healthy because of mild heat influx. There are no hot spots to burn the food. Cooking in the sun is cleaner also.

Over the past fifty years various designs of solar cookers have been developed. Box type cookers are being used for domestic applications where temperature around 100 °C can be obtained on sunny days and pulses, rice, vegetables etc. can be readily cooked in 2-3 hours. Concentrated type cookers can provide much higher temperatures and thus can cook all types of foods but they require greater attention and have not found favour with domestic users.

Solar cookers have attracted the attention of many researchers so far. Different types of solar cookers have been developed and tested all over the world. There has been a considerable interest recently in the design, development and testing of various types of solar cookers.

Several researchers have performed work on different designs of solar cookers and their performance improvement. The studies on solar cookers can be broadly classified into the following categories [1] –

a. Design, fabrication and testing of new types of solar cookers.
b. Methods of boasting solar energy onto the cooker aperature using booster mirrors.
c. Energy storage type of cookers for use indoors and also during off sun shine periods.
d. Tests on different types of cooking vessels.
e. Modeling and simulation techniques.

LITERATURE REVIEW

Pejack (2003) has discussed the mechanism of heat flow in cooking vessel [2]. Das et al. (1994) have presented mathematical model for solar box cookers loaded with one, two or four vessels with the basic objective of examining relative importance of various heat transfer rates. They also studied the effect of base plate thickness, cooker size etc. [3, 4]. Karmakar (1988) carried out experimental studies with a vessel placed on electrically heated hot plate to study the conduction to the vessel bottom and from sides, and for vessel covers under solar irradiance, and report a marginal effect of black paint on the vessel cover [4].

Mullick et al. (1987) outlined a test procedure for the solar box cooker. They have developed methods of evaluating the performance of box type solar cookers using two figures of merit [5]. Funk (2000) presented the international standard testing procedures for evaluation of solar cooker [6].

Malhotra et al. (1983) optimised cooking chamber volume of solar ovens for a fixed glazing area [7]. Nahar and Gupta (1991) studied the energy conservation potential for solar cookers in arid zones of India. They examined different solar cookers and evaluate their potential impact on energy savings [8]. Nahar et al. (1994) designed, developed and tested the performance for a large size solar cooker for animal feed [9]. Nahar (1998) designed, fabricated and tested the performance of a novel solar cooker with width to length ratio of 4 that does not require any tracking [10]. Other studies involve hot box cooker with tilted absorber

(Nahar, 1990) [11], double reflector hot box cooker with transparent insulation materials between two glazings (Nahar, 2001) [12], hot box storage type cooker (Nahar, 2003) [13], etc.

Gaur et al. (1999) studied the performance of a box type solar cooker with modified utensil having a concave lid which was about 2-7% more efficient than the utensil with normal lid [14].

Amer (2003) introduced and extensively investigated the performance of a novel design of solar cooker in which the absorber was exposed to solar radiation from the top and the bottom sides and a set of plane diffuse reflectors was used to direct the radiation onto the lower side of the absorber plate [15].

Kumar (2004) presented a thermal analysis to evaluate the natural convective heat transfer coefficient for trapezoidal enclosure of box type solar cooker by conducting several indoor simulated experiments [16]. Kumar (2005) also presented a simple test procedure for estimation of design parameters for thermal performance evaluation of box type solar cooker by performing a series of out-door experiments [17].

Rao and Subramanyam (2003, 2005) demonstrated experimentally that a cooking vessel kept on supports (lugs) and also a cylindrical cooking vessel with central annular cavity perform much better when compared to a conventional cylindrical vessel on the floor of the cooker [18, 19]. Reddy and Rao (2006, 2007) have presented a mathematical model and experimental verification for heat transfer analysis of a cooking vessel on lugs and cooking vessel with central cylindrical cavity in a box type solar cooker with thermic fluid [20, 21]. Reddy and Rao (2008) compared the performance of the cooking vessel with depressed lid on lugs with that of the conventional vessel on lugs and found that the average improvement of performance of the vessel with depressed lid is 8.4% better than the conventional cylindrical vessel [1].

Harmim et al. (2008) have demonstrated experimentally that cooking time can be reduced considerably by using finned cooking vessel [22].

Harmim et al. (2010) have developed a box type solar cooker with finned absorber plate [23].

Karwa and Varshney (2010) have presented results of an experimental study to see the relative strength of different modes of heat transfer in a conventional hot box solar cooker. They found that the contribution of radiation heat transfer is marginal but conduction and convective modes of heat transfer are practically equally strong [24].

Thus several researchers have performed work on the different designs of solar cookers and their performance improvement since the late 19th century to the beginning of the 21st century.

OBJECTIVES

From the literature review it can be seen that much efforts have not been made in conventional hot box solar cooker for improvements in heat penetration through the cooking vessel and into the food material to be cooked. There is still need to understand the mechanism of heat flow to cooking vessel and to seek new solutions in hot box solar cooker for enhancing the performance.

The main hindrances in heat penetration into pot contents (food) are:

(1) The thermal contact resistance between bottom surface of cooking vessel and absorber tray and

(2) The thermal contact resistance between lid and vessel's side surface.

Lid of cooking vessel intercepts maximum energy but it is not effectively transferred to food material because of thermal contact resistance due to uncertain contact between lid and vessel. Hence the objectives of present experimental study to be carried out as per BIS 13429:2000 [25] is to make some efforts to utilise effectively the energy intercepted by lid in cooking food.

EXPERIMENTAL METHODOLOGY

Experimental Setup

Solar cooker

The box type solar cooker used in the study is shown in Fig. 3.1. As per claim of supplier, solar cooker has been fabricated to meet the standards prescribed by BIS for solar cookers. It is approved by Agro Industries Corporation Limited and Rajasthan Renewable Energy Corporation Limited (Formerly REDA).

The cooker consists of a 0.6 m X 0.6 m X 0.22 m box made of GI sheet with a mat black painted trapezoidal tray of (43 cm X 43 cm at bottom, 50 cm X 50 cm at top and 10 cm height) made of 28 SWG thick GI sheet. Four cooking vessels/ pots can be kept inside it. Aluminium pots with mat black painted on outside of size 190 mm diameter and 60 mm height have been used in the study.

The total absorber area is 0.382 m^2; the bottom surface of the tray is 0.185 m^2 in area.

The cover plate is double glazed. Spacing between inner and outer glazings (4 mm thick each) is about 15 mm. The glazing area is L_g X W = 498 mm X 498 mm. Provision on the side is made to keep the cover plate at inclined position for loading and unloading of the cooking pots.

A plane mirror (reflector) is hinged at the side of box to increase the solar irradiation on glazing. Mirrors are free from bubbles and waviness. The reflecting area of mirror is 506 mm X 506 mm which is greater than the glazing area. Provision on the sides is made to keep the mirror in any inclined position. There is a provision to keep the mirror in any inclined position.

The solar radiation falls upon the glazing directly and indirectly after reflection from mirror. The maximum projected area of glazing is known as aperture area. The maximum projected area of mirror is known as reflector area. The sum of aperture area and reflector area is termed as intercept area. The ratio of intercept area to the aperture area is known as concentration ratio.

Joint between glazing and absorber tray is sealed by polyurethane foam. The space between the absorber tray and outer sheet of box is filled with glass wool insulation on all sides and bottom. Thermal resistance R ($=\delta/k$) of about 40 mm thick glass wool (thermal conductivity = 0.06 $Wm^{-1}K^{-1}$ at 380 K) is about 0.66 m^2KW^{-1}. However BIS recommends a minimum value of 0.96 m^2KW^{-1} at 100 ˚C.

Experimental Devices

The experimental study has been made by recording temperature rise of the water in the vessel with a calibrated HTC digital K type thermocouple (Ni Cr / Ni Al Alloy). The temperature probe of the thermocouple has been placed in the cooking vessels with measuring tip of the thermocouple submerged in the water. Thermocouple wires have been sealed using epoxy resin to make the vessel vapour tight. The ambient temperature has also been measured by the thermocouple.

The solar Irradiance on the horizontal plane has been measured using a Tenmars solar power meter TM-206 (solarimeter) calibrated against a precision pyranometer available in IIT Jodhpur.

SCHEMES OF EXPERIMENT

The heat to the conventional cooking vessel and its contents (water in the present study) flows by conduction through the bottom of the vessel from heated absorber tray, though there exists a thermal contact resistance between the bottom of the vessel and absorber tray surface. Heat flows by convection from the heated absorber tray to vessel's side walls. Heat also flows from the heated cover/ lid of vessel to the contents of the vessel by conduction through the side walls of the vessel though there is a thermal contact resistance because of uncertain contact between the lid and vessel's side surface. The contribution of radiative heat transfer to cooking vessel is not direct but the absorber tray and vessel's lid are heated by radiation.

Lid of cooking vessel intercepts maximum energy but it is not effectively transferred to food material because of thermal contact resistance due to uncertain contact between lid and cooking vessel. In order to study the contribution of heat transfer by the lid of the vessel into the food material to be cooked in hot box solar cooker, two configurations (schemes) have been designed which have been described in Table 1. Present experimental study is based on these two schemes. In the first scheme a special design of lid as shown in Fig. 2 has been used in which a circular ring of aluminium strip has been welded to the lid's inner side such that the ring is penetrating into the pot contents (water here) in order to utilise effectively the energy intercepted by lid in cooking food. In the second scheme a frustum of cone shaped lid as shown in Fig. 3 has been used in which the surface of lid is in direct contact with pot contents (water here) in order to utilise effectively the energy intercepted by lid.

EXPERIMENTAL PROCEDURE

The experimental study has been made by recording temperature rise of the water in the vessel with a thermocouple. The temperature probe of the thermocouple has been placed in the cooking vessels with measuring tip of the thermocouple submerged in the water above 10 mm from pot bottom. Thermocouple wires have been sealed using epoxy resin to make the vessel vapour tight. The ambient temperature has also been measured by the thermocouple.

The solar Irradiance on the horizontal plane has been measured using a solarimeter. The tests were conducted in still air (wind velocity less than 1.0 m/s).

All components and instruments were checked for proper functioning. The pots were placed in the cooker as shown in the Fig. 1. Cooking pots have been filled with 1000 cc of water, which works out to be_about 8.8 litres of water per m^2 of the glass area. This is in the range suggested by BIS for standard conditions for load of 8 kg of water / m^2 of aperture area. Equal quantity of water at ambient temperature has been used in the cooking pots as they are of the same size in the tests.

The tests were started in the morning between 9 AM and 10 AM IST. Solar Irradiance and temperatures have been measured at 20 min interval in the beginning. This interval was reduced to 10 min after the water temperature reached about 75-80 ˚C. The upper limit of the water temperature for the time period analysed cannot be taken as 100˚C (the boiling point at atmospheric pressure) because the rate of variation of water temperature approaches zero as the water temperature approaches 100˚C. Therefore, the upper limit of sensible heating (T_{w2}) has been fixed in the temperature range 90˚C – 95˚C (Mullick et al., 1987). The data recording was continued until the water temperature reached about 95°C as per suggestion of BIS.

The tilt of the reflector was varied every 30 minutes so that the reflected radiation does not fall outside the glazing and covers the glazing completely. The cooker was also tracked every 30 min.

A direct comparison of temperature rise of a known quantity of water in conventional pot directly kept on absorber tray with temperature rise of same quantity of water in an identical pot with modified lid design has been made.

In the schemes both pots have been kept centrally in the solar cooker as shown in Fig. 1. For scheme 1, aluminium pots with mat black painted on outside of size 180 mm diameter and 65 mm height have been used. For scheme 2 aluminium pots with mat black painted on outside of size 190 mm diameter and 60 mm height have been used in the study. The thickness of the frustum of cone shaped lid used in the study was 1.37 mm while the thickness of normal lid used for comparison in the study was 0.94 mm.

To reduce effects of uncertainty and errors, the experiments have been repeated two or three times.

The tests were conducted at Government Polytechnic College, Jodhpur. Jodhpur is located at 26.25˚N latitude, 73.03˚E longitude and 235 m elevation of sea level.

EXPEIMENTAL DATA

Ideally the experiment must be conducted in a clear weather but sometimes there were intermittent clouds and the diffuse radiation was observed to be 20-30%. The solar radiation exceeded 600 W/m^2 (which is the recommendation of all standards including BIS most of the time) after 10 am except during the short periods of cloudy conditions on some days of experiment. The tests were conducted in still air (wind velocity less than 1.0 m/s). The ambient temperature T_a varied from a 30 ^{o}C in the morning to a maximum of 42 ˚C in the afternoon. The opening area (L x W) of hot box solar cooker varies by about 10% because of the adjustment of the tilt of the mirror.

Table 1 **Schemes used in experimental study**

Scheme No.	Details
1	Aluminium pot 1 kept on absorber tray conventionally and a circular ring of aluminium strip welded to the lid of aluminium pot 2 such that ring is penetrating into the pot contents (water here); both pots kept directly on absorber tray side by side as shown in Fig. 1.
2	Aluminium pot 1 kept on absorber tray conventionally and aluminium pot 2 with frustum of cone shaped lid such that lid is penetrating into the pot contents (water here); both pots kept directly on absorber tray side by side as shown in Fig. 1.

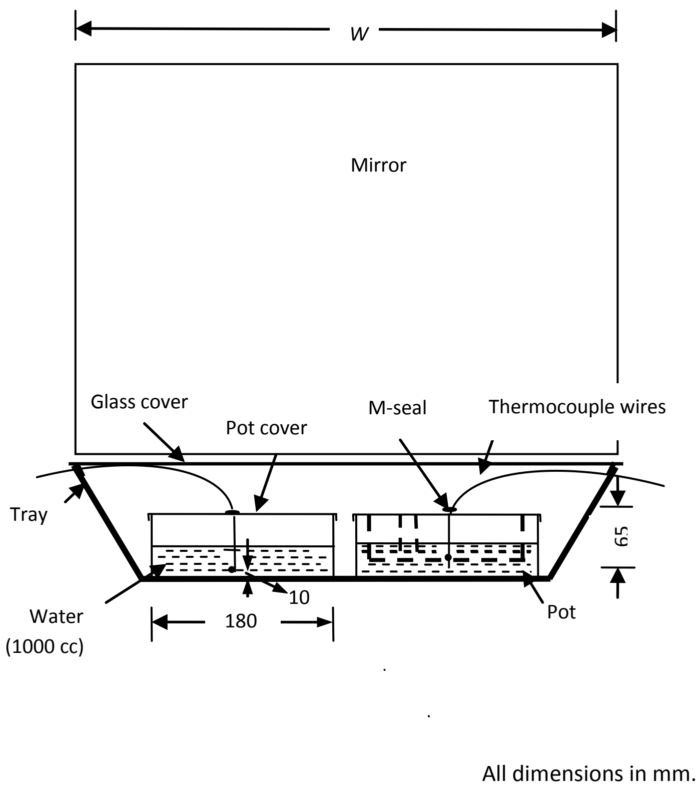

Fig. 1 **Pots kept side by side on the tray.**

Fig. 2 **Special design of lid used in the study in which a circular ring of aluminium strip welded to the inner side of lid of aluminium pot**

Fig. 3 **A design of lid used in study - frustum of cone shaped lid**

RESULT AND DISCUSSION

It can be seen from Fig. 4 that temperature of water in the pot 2 in which lid with circular ring is fitted, leads by 8-9 ˚C when the water temperature in this pot reaches 90 ˚C. This is a significant amount. This proves a high value of thermal contact resistance due to uncertain contact between lid and cooking vessel.

It can be seen from Fig. 5 that temperature of water in the pot 2 in which frustum of cone shaped lid is fitted, leads by 3-4 ˚C when the water temperature in this pot reaches 90 ˚C.

The design of frustum of cone shaped lid can be criticized because of reduction in volume of cooking vessel hence puts a limit of space for cooking food in the cooking vessel. There is some cleaning problem also with the frustum of cone shaped lid.

In case of large size pot or multiple pots in solar cooker, amount of energy intercepted by pot lid / lids is higher and energy absorbed by absorber tray is reduced. So utilisation of the energy intercepted by lid in cooking food is very important in case of large size pot or multiple pots (2-4) in the solar cooker.

Since contribution of heat transfer from the lid to the food has been found significant, different designs of pot/ pot-lid can be developed. A special design of lid can be used in which a circular ring of aluminium strip is welded to the lid's inner side such that the ring is penetrating into the pot contents in order to utilise effectively the energy intercepted by lid in cooking food. For uniform heating of food concentric circular rings or spiral shaped ring may be used. A pot with reduced lid–pot side gap should be developed such as half opening lid. A frustum of cone shaped lid can be used but it will put a limit of space for food in the cooking vessel. Utilisation of the energy intercepted by lid in cooking food is very important in case of large size pot or multiple pots (2-4) in the solar cooker.

To reduce effects of uncertainty and errors, the experiments have been repeated two or three times. Repeatability of the results has been verified.

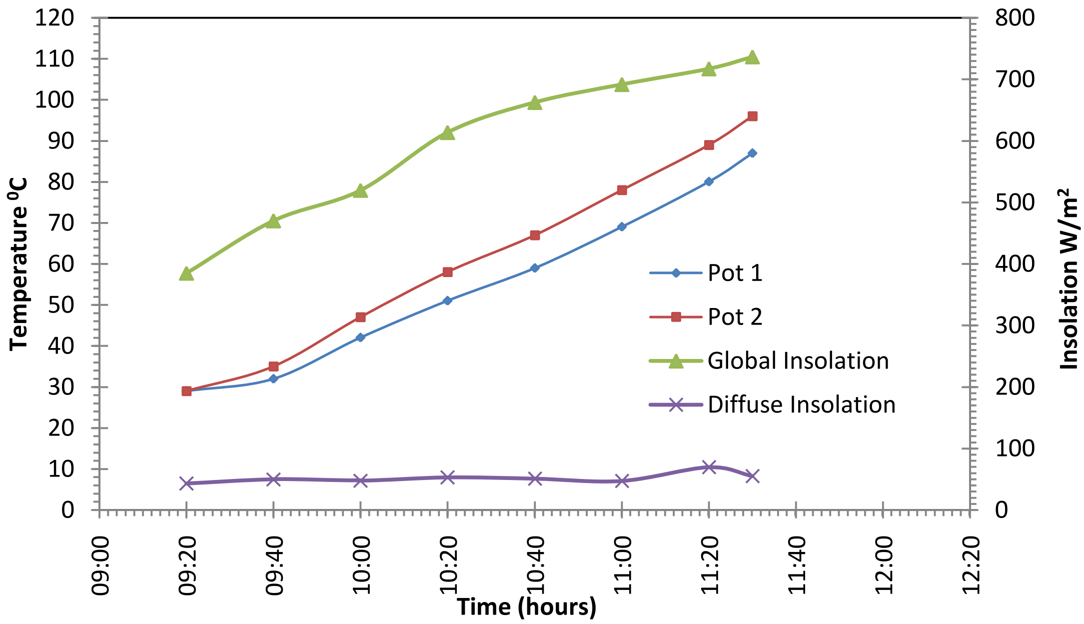

Fig. 4 **Scheme 1: Aluminium pot 1 kept on absorber tray and a circular ring of aluminium strip welded to the lid of aluminium pot 2 such that ring is penetrating into the pot contents (water here) ; both pots kept directly on absorber tray, side by side as shown in Fig. 1.**

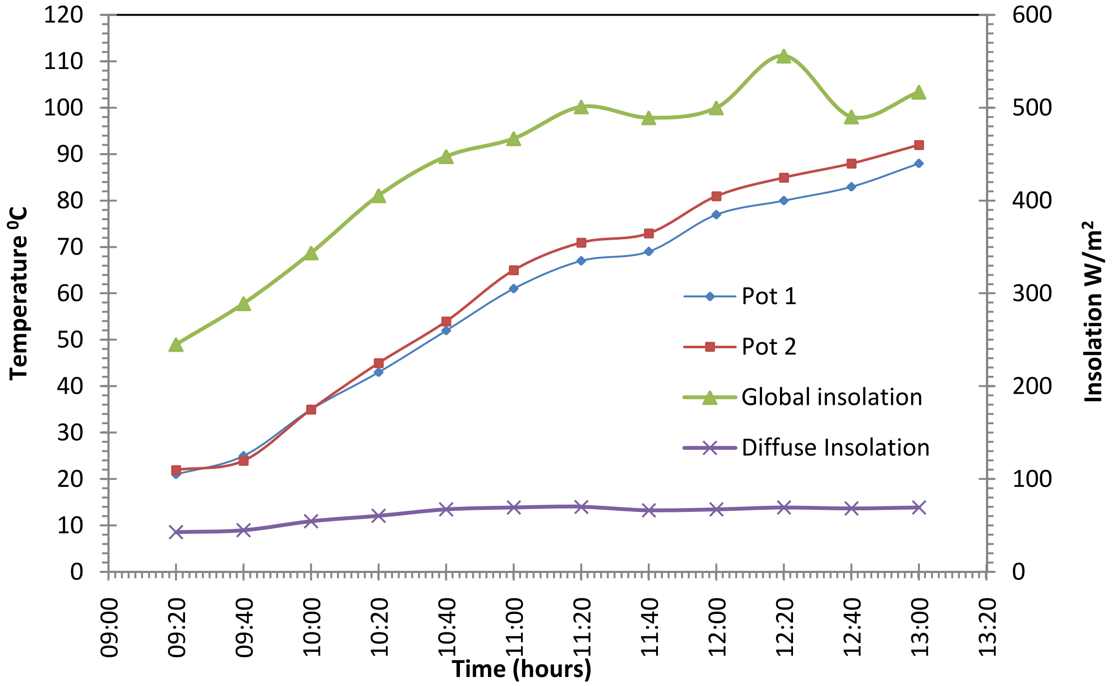

Fig. 5 **Scheme 2: Aluminium pot 1 kept on absorber tray and aluminium pot 2 with frustum of cone shaped lid such that lid is penetrating into the pot contents (water here); both pots kept directly on absorber tray side by side as shown in Fig. 1.**

CONCLUSIONS

In order to utilise effectively the energy intercepted by lid in cooking food, two special designs of lid have been studied. In first design a circular ring of aluminium strip has been welded to the lid's inner side such that the ring is penetrating into the pot contents (water here). In second design a frustum of cone shaped lid has been used in which surface of lid is in direct contact with pot contents (water here).

Since contribution of heat transfer from the lid to the food has been found significant, different designs of pot/ pot-lid can be developed. A special design of lid can be used in which a circular ring of aluminium strip is welded to the lid's inner side such that the ring is penetrating into the pot contents in order to utilise effectively the energy intercepted by lid in cooking food. For uniform heating of food concentric circular rings or spiral shaped ring may be used. A pot with reduced lid–pot side gap can also be developed such as half opening lid. A frustum of cone shaped lid can be used but it will restrict space for food in the cooking vessel. Utilisation of the energy intercepted by lid in cooking food is very important in case of large size pot or multiple pots (2-4) in the solar cooker.

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