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SS Bhandari
Assistant Professor, Department of Mechanical Engineering, G. B. Pant University of Agriculture and Technology Pantnagar, U. S. Nagar, Uttarakhand, India

Deepak Pal
M. Tech student, Department of Mechanical Engineering, G. B. Pant University of Agriculture and Technology Pantnagar, U. S. Nagar, Uttarakhand, India

Govind Verma
Assistant Professor, Department of Information Technology, G. B. Pant University of Agriculture and Technology Pantnagar, U. S. Nagar, Uttarakhand, India

Corresponding Author:
SS Bhandari
Assistant Professor, Department of Mechanical Engineering, G. B. Pant University of Agriculture and Technology Pantnagar, U. S. Nagar, Uttarakhand, India

Heat transfer mechanism to the cooking vessel in a box type solar cooker

SS Bhandari, Deepak Pal and Govind Verma

Abstract
The present study investigates the mechanisms of heat transfer to a cooking vessel within a solar box cooker (SBC), with particular emphasis on assessing the effect of elevating the vessel using support lugs on overall thermal performance. Two identical solar cookers were utilized to conduct a comparative analysis. In one configuration, the water-filled cooking pot was placed directly on the absorber plate, whereas in the second, the cooking vessel was positioned at the top of aluminium lugs with varying heights. Experimental results demonstrated that, for an equivalent duration, the water temperature exhibited a greater rise when the vessel was in direct contact with the absorber plate, compared to when it was elevated. These findings indicate that elevating the vessel does not enhance heat transfer efficiency; rather, it marginally diminishes it. The primary modes of heat transfer to the cooking vessel were identified as conduction from the absorber plate to the vessel base, followed by convective heat transfer from the vessel base to the water. Consequently, it is concluded that the use of support lugs does not positively impact the thermal efficiency of box-type solar cookers. In contrast, the incorporation of booster mirrors markedly improves cooker performance by augmenting the thermal input to the cooking vessel.

Keywords: Cooking vessel on lugs, solar energy, solar cooker, heat energy

Introduction
According to the 2019 report by the International Energy Agency (IEA), approximately 2.3 billion people worldwide still lack access to clean cooking fuels. The majority of this population resides in Sub-Saharan Africa as well as parts of Central and Southeast Asia. The continued reliance on traditional, non-commercial fuels such as firewood, charcoal, coal, cow dung, and kerosene contributes to both greenhouse gas emissions and indoor air pollution. Exposure to such pollutants is a significant factor in the development of non-communicable diseases, including stroke, ischemic heart disease, chronic obstructive pulmonary disease (COPD), and lung cancer. Women and children, who are typically tasked with cooking and gathering firewood, face the highest exposure levels and therefore bear the heaviest health burden. To address these risks, promoting the adoption of clean cooking technologies is essential. These alternatives include the use of solar energy, electricity, biogas, liquefied petroleum gas (LPG), natural gas, alcohol-based fuels, and advanced biomass stoves that align with the World Health Organization (WHO) emission guidelines (WHO report, 2016). Among these, solar cookers present a viable and sustainable solution, particularly in rural areas. They have emerged as a promising technology for meeting domestic cooking energy needs due to their potential for wide adoption. The performance of basic box-type solar cookers (SBCs) depends on several variables, which can be categorized into three main areas: climatic conditions, design features, and operational practices. Climatic factors include solar radiation, ambient air temperature, and wind speed. Design characteristics involve the type of black coating on the cooking tray, the number and quality of transparent glazing layers, the insulation of the cooker, and the use of reflectors or boosters. Operational aspects pertain to the type and quantity of food being cooked, as well as the nature and number of cooking vessels used. Box-type solar cookers offer several advantages over conventional cooking methods. They allow food to cook slowly, helping to preserve its nutritional content. Because the heat is evenly distributed and moderate, there's no need for constant stirring, and the food rarely burns. Solar energy, being renewable and free, also eliminates fuel costs and reduces environmental pollution. Additionally, the use of solar cookers can ease the physical burden of collecting firewood or other biomass fuels. In India, cooking accounts for a substantial share of total energy consumption, especially in

rural regions where fuels such as firewood, dung cakes, coal, LPG, and agricultural residues are commonly used. This heavy reliance on polluting fuels underscores the need for alternative, cleaner cooking methods. Solar energy presents a sustainable option in this context. Efforts to improve solar box cooker efficiency have led to numerous design innovations. For example, thermal efficiency has been enhanced through the addition of thermal energy storage systems or by incorporating extended fins into the cooking vessels. Historical attempts to use solar energy for cooking go back over two centuries. In 1776, De Saussure built the first solar hot box in Switzerland, featuring a blackened wooden interior and two glass panes separated by an air gap, which could reach temperatures close to 90 °C. In 1837, John Herschel developed a solar cooker in England using a black container insulated with sand and double glazing, achieving cooking temperatures up to 116 °C. Later developments include Maria's 1959 design with inclined mirrored reflectors and Tiwari and Yadav's 1986 bottom-loading model that reduced heat loss. Mullick *et al*. (1987) [3] were notable for introducing a standard method to assess the thermal performance of box-type cookers. In the early 2000s, Subramanyam and Narasimha Rao explored the effects of supporting cooking vessels on lugs, finding that elevated vessels benefited from improved airflow and heat transfer. They later studied vessels with central annular cavities on lugs, which further enhanced heat distribution and cooking efficiency. Reddy and Narasimha Rao (2006) [8] developed a mathematical model to simulate a double-glazed SBC, comparing a traditional vessel placed on the base with another featuring a central annular cavity placed on lugs. Both held one liter of water. The simulations indicated that the modified vessel reached higher temperatures, showcasing its superior heat transfer capability.

However, not all studies reported positive outcomes. Rao and Subramanyam (2003) [9] observed heat transfer improvement using lugs, while Arif *et al*. (2021) [11] reported reduced thermal efficiency when vessels were elevated, as lower temperatures were recorded compared to vessels placed directly on the absorber plate. Besides these other design enhancements have also been proposed. Vengadesan and Senthil (2021) [12] added inward-facing aluminum fins of different lengths (25 mm, 35 mm, and 45 mm) to the vessel lid, boosting convective heat transfer and improving cooking rates. Their modified cooker achieved a thermal efficiency of about 56.03% and a heat transfer coefficient of 58.54 W/m² °C. Nayak *et al*. (2018) [13] introduced fins around the vessel's exterior, increasing the cooker's performance but reducing space for additional vessels inside. Cuce and Cuce (2013) [14] instead placed extended fins on the absorber plate, achieving improved thermal performance with a peak temperature of 63 °C and efficiency of 30%. Saxena *et al*. (2011) [15] improved convection by shaping the vessel bottom into lug-like curves, reaching a cooking power output of around 78 W. The previous literature studies of modification of cooking vessel and effect of lugs are summarized on Table 1. These various design strategies have led to noticeable improvements in the thermal efficiency of solar cookers, though they are not without challenges. In light of these previous findings, the current experimental study aims to further explore heat transfer mechanisms within box-type solar cookers. conducted at the Solar Energy Laboratory in Pantnagar (latitude 29°24'N, longitude 79°27'E), the study used two identical solar box cookers meeting the Bureau of Indian Standards (BIS) specifications. The objective was to examine the thermal behavior of water inside the cooking vessels under two configurations: in one cooker, the vessel was placed directly on the absorber plate; in the other, it was elevated using integrated lugs. Temperature readings over time were recorded and analyzed to compare the heat transfer efficiency between the two experimental setups.

2. Description of box-type solar cooker

The experimental setup shown in Fig.1 is used for evaluating the thermal performance of a box-type solar cooker. It consists of the following instruments and equipment: (a) Two identical box-type solar cookers were employed to ensure consistency and facilitate comparative analysis (b) A pyranometer was used to measure the intensity of solar radiation incident on the cooker surface. (c) Thermocouple wires were installed to record temperature variations at different points within the cooker. (d) A milli voltmeter was connected to the thermocouples to measure the voltage corresponding to temperature changes. (e) Aluminium lugs, used as vessel supports, were of varying heights (ranging from 2 mm to 9 mm) with a uniform diameter of 6.3 mm.

The structural components of the solar cookers were as follows

1. The inner cooking tray, made from galvanized aluminium sheet, measured 38 × 38 cm² at the base and had a depth of 8 cm.
2. A double-glass cover served as the transparent lid, with an aperture area of 47 × 47 cm² to allow maximum sunlight entry while minimizing heat loss.
3. The outer box was constructed from fiber material with dimensions of 53 × 53 × 16 cm³ and insulated using glass wool to reduce thermal losses.
4. A booster mirror of size 48 × 48 cm² was integrated to reflect additional sunlight into the cooking chamber, thereby improving efficiency.
5. Aluminium cooking vessels of two different capacities were used to assess the cooker's performance with varying loads.

Table 1: Literature studies on performance of solar cooker using modified utensils

Authors Published Year/References	Brief title	Location of study/Type of vessel used	Results highlights
Gaur *et al*. (1999) [16]	Performance study of SBC with modified utensil	Lucknow (India) Modified Utensil with concave shaped lid	The stagnation temperature of water with modified utensil was 3-7 °C more than plain lid. The time for attaining boiling temperature reduces by 10-13% in concave shaped lid in comparison to plain lid.
Narasimha Rao and Subramanyam (2003) [9]	Performance study of SBC with cooking vessel on lugs	NIT Warangal (India) Cooking vessel placed on mild steel lugs of 7 mm height and 10 mm diameter	Cooking vessel supported on lugs achieves maximum boiling temperature earlier than conventional vessel. Reduction in cooking time with vessel on lugs support.
Narasimha Rao and Subramanyam (2005) [10]	Performance study of SBC by cooking vessel with central annular cavity supported on lugs	NIT Warangal (India) Cooking vessel placed on mild steel lugs of 7 mm height and 10 mm diameter	Cooking vessel with central annular cavity supported on lugs achieves maximum boiling temperature 25 min earlier than conventional vessel placed directly on absorber plate.
Reddy and Narasimha Rao (2007) [8]	Mathematical modeling and experimental study of SBC by cooking vessel with central annular cavity supported on lugs	NIT Warangal (India)	Cooking vessel with central annular cavity supported on lugs achieves maximum boiling temperature earlier than conventional vessel. Performance improvement of 5.9% with modified cooking vessel.
Harmim *et al*. (2008) [17, 18]	Experimental study of double exposure SBC with finned cooking vessel	Adrar, Algeria. Rectangular shaped Finned cooking vessel Material-Aluminium	Finned cooking vessel attained boiling temperature of water nearly 14 min earlier than the conventional cooking vessel. Power increases by 7.49 W with modified vessel.
Saxena *et al*. (2011) [15]	Thermodynamic review of SBC	Moradabad U. P (India) Modified cooking vessel with curvature lugs of radius 2.5 mm	Cooking time reduction by 20 min in comparison to conventional vessel. Cooking power of modified cooking vessel increases by 13%.
Sethi *et al*. (2014) [20]	Experimental study of inclined SBC with parallelepiped cooking vessel	Ludhiana, Punjab (India)	Boiling time reduces by 37% and cooking power increases by 40% with parallelepiped cooking vessel.
Geddam *et al*. (2015) [19]	Thermal performance study of SBC with finned cooking vessel and PCM	Tiruchirappalli (India) Finned cooking vessel with PCM filled in annular space between the vessel Material-Aluminium	6 minutes difference in attaining boiling temperature between conventional and finned vessel respectively. Food can be kept hot up to 3-4 h during off-sunshine hours.
Nayak *et al*. (2016) [13]	Performance study of SBC with finned cooking vessel	Sarang, Odisha (India) Aluminium cooking pot	The maximum temperature in unfinned and finned cooking pot is 93 °C and 102 °C in clear weather. Time difference between attaining boiling temperature in finned and conventional vessel is 1 h.
Watkins *et al*.(2017) [22]	Performance study of insulated PV supported solar electric cooker	Uganda (Africa) Insulated cylindrical pot with immersion heater	Plate maximum temperature of 502 °C for the 5-gallon drum insulated with fiberglass and heated with 100 W PV panel.
Sagade *et al*. (2019) [21]	Experimental study of SBC with hybrid cooking pot	Jharkhand (India) Cooking vessel with glazed lid	Improved thermal performance of cooker with hybrid cooking pot because of reduction in heat loss. Benefits of visualization of solar cooking
Vengadesan and Senthil (2021) [12]	Experimental study of SBC with finned cooking vessel	Chennai (India) Aluminium cooking vessel with varying cylindrical fin lengths of 25, 35, 45 mm and 4 mm diameter.	Thermal efficiency with 45 mm fin increases by 6.37%, 4.72% and 3.54% in comparison to no fin, 25 mm fin, 35 mm fin configuration. The maximum heat transfer coefficient and cooking power is 58.54 W/m^2 °C and 73.69 W for a 45 mm fin length.
Arif *et al*. (2021) [11]	Performance comparison of SBC in tropical climate	Aligarh (India) Effect of lugs height, number of pots and load.	Thermal performance of SBC is improved when the cooking pot is placed directly on the floor of absorber plate in comparison when place on copper rod lugs. Lugs reduces heat transfer rate to pot contents Second figure of merit increases with load and number of vessel.

Fig 1: Photograph of Box- Type solar cooker used in experiments

3. Results and Discussion

The test standards are followed as per test procedure suggested by Mullick *et al*. (1987) [3]. The two identical SBCs are placed in south facing direction. Ambient temperature, cooker plate temperatures, water temperature in cooking vessel with different loads are measured using thermocouple (Ni-Cr, K type) attached to data logger. The pyranometer is used to measure solar insolation. The No load tests were conducted on a clear sunshine day on 16.5.2023. The no load test is performed by measuring absorber plate temperature with time of the day. Temperature variations are noted at 10 minutes time interval for 10 A.M to 1 P.M every day. The first figure of merit is obtained by stagnation temperature of absorber plate without load and it is given by (Mullick *et al*. 1987) [3]

$$F_1 = \frac{\eta_o}{U_L} = \frac{(T_{ps} - T_a)}{H_s} \quad (1)$$

Where T_{ps}, T_a, H_s are Stagnation plate temperature, ambient temperature, and solar insolation respectively. Both the solar cookers were exposed to the sun after 10.00 A.M. without the use of the booster mirror. The absorber plate temperature of cooker started to rise and reaches to stagnation point at 12.10 P.M of clock time. At, this point a quasi-steady stage is reached and stagnation temperature is noted along with corresponding ambient temperature and solar insolation at the level of the glazing of the solar cooker for calculation of first figure of merit. The maximum value of plate temperature and ambient temperatures are noticed as 130 ºC and 34 ºC at 12.10 h respectively. The value of first figure of merit for these solar cookers on given day was found to be 0.116 and 0.115 for two cookers respectively. The result concludes that the given box type solar cooker are identical and exhibit similar thermal behavior.

For evaluating the performance of solar cooker when the vessel filled with water is kept on the lugs and comparison when the vessel filled with water is kept directly on the absorber plate, two identical cookers (Fig. 2 schematic diagram of cooking vessel placed in cooker-I and cooker-II) were used simultaneously. In one cooker-I vessel filled with water is put on the absorber plate directly while in another cooker-II the vessel filled with water was kept inside the cooker on three aluminium lugs.

3.1 Performance Evaluation using the Vessel on lugs

The lugs are placed at 120° spacing; each of the vessels is loaded with a fixed mass of water. The total mass of the water and initial temperature of water in each of the vessels, ambient temperature and solar insolation values are recorded at ten minutes time intervals. Water temperatures in each of the two vessels are measured by a copper constantan thermocouple submerged in water. The water temperatures and solar insolation are noted for fixed time interval (10 minutes) and comparison between water temperatures is studied for a vessel on lugs in a solar cooker and vessel on floor on a solar cooker. The experiments are repeated for different height of lugs ranging from 2 mm and 9 mm. The observations are recorded over number of days for different height of lugs. The tests are done without the use of booster mirror and the vessel inside the cookers remains covered by lids during the course of the test. The final water temperatures are recorded after fixed time interval of 120 minutes. The observations are recorded over number of days for the month of May 2023 for the different height of lugs. Typical temperature with time history of the water in the cooking vessels on date 18.5.23 is shown in Fig. 3 (a) and 3 (b) for 2 mm and 9 mm lugs.

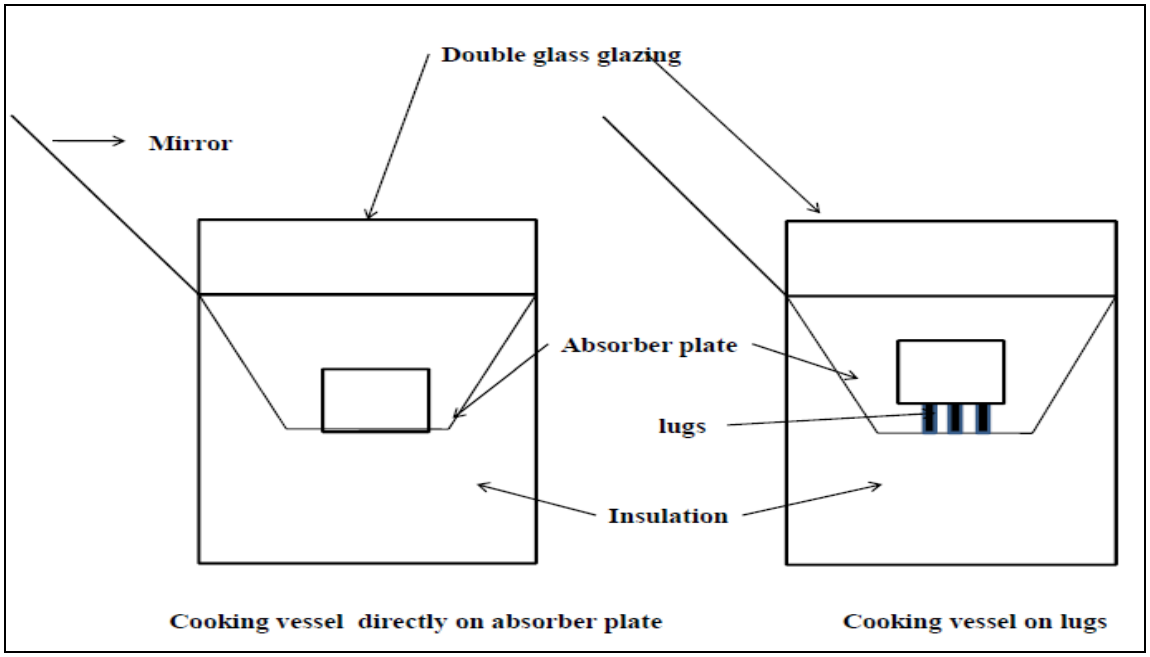

Fig 2: Arrangement of cooking vessel inside solar box cooker directly on absorber plate and lugs

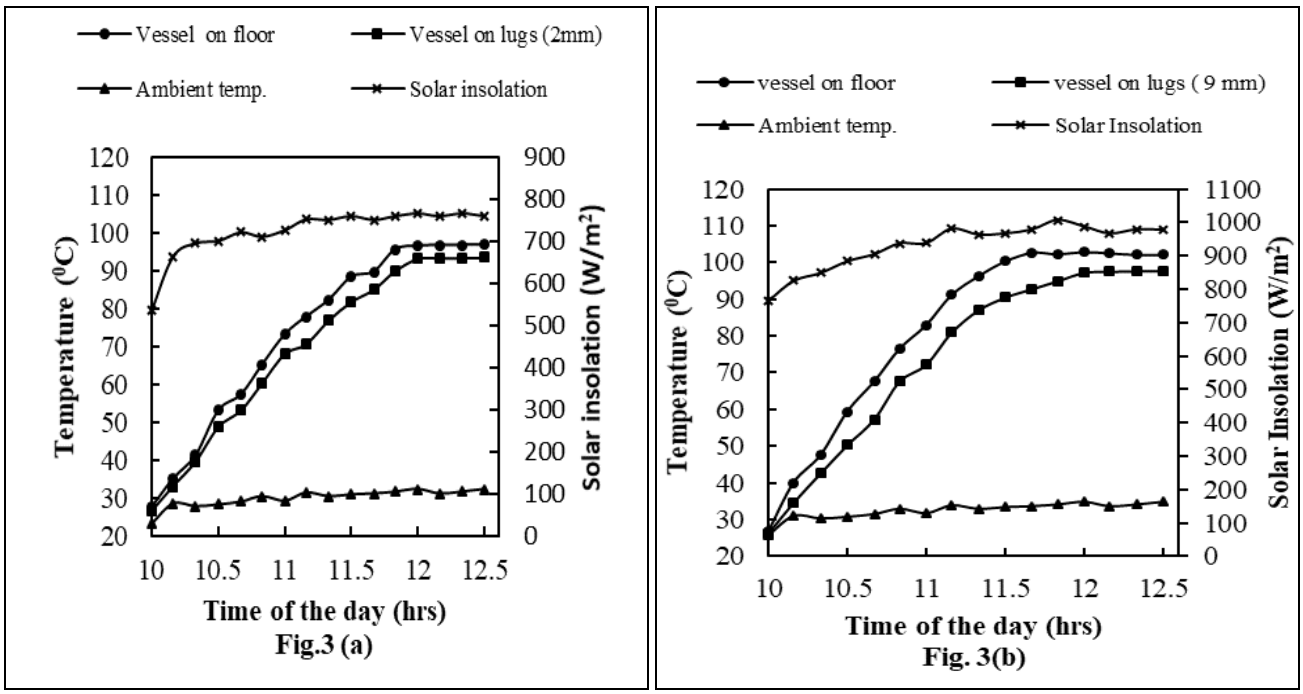

Fig 3 (a), 3 (b): Comparison between temperature of water in the vessel kept directly on the absorber plate and that raised above the absorber plate with height of 2 mm and 9 mm aluminium lugs.

It is visible from graph that the temperature of the water kept in the vessel supported on lugs achieves less temperature rise as compared to the vessel kept on the base. It is a clear indication that lugs doesn't help in improving the performance of the solar cooker. Raising the vessel on lugs in one solar cooker as compared to conventional method with vessel on the base of the solar cooker results in decrease in temperature rise of water for the same time duration. This is because that for a vessel placed directly on the absorber plate (base) of the cooker, the heat transfer to bottom of the vessel is by conduction (thermal conductivity of absorber plate 235 W/mK) and from the base of the vessel to the water in the vessel is by convection heat transfer. The heat transfer to the vessel on the lugs placed inside the solar cooker occurs through convection of air (thermal conductivity 0.024 W/mK) from absorber plate to bottom of the vessel and then again heat energy is transferred to water by convection between bottom of the vessel and water inside the vessel. For a vessel on lugs, the heat transfer occurs by convection of air which is lesser as compared to the heat transfer by conduction from absorber plate to base of the vessel when the vessel is placed directly on the absorber plate. The rise in temperature of water for different heights of aluminium lugs (1mm-9mm) for time duration of 2.00 hrs is studied by number of experiments on various days. The rise in temperature for different heights of lugs for the same time duration (2.00 hrs) on different days of experiment and observation for this effect is shown in Fig. 4. The rise in temperature of water for the same time duration is more for a vessel without lugs as compared to

vessel with lugs. However, the rise in temperature of water for same time duration doesn't show any particular trend for different height of lugs, as the rise in temperature of water depends on solar radiation, ambient temperature and wind speed. However, the rise in temperature of water for the vessels on the base is always more than the rise in temperature of water when the vessel is on the lugs. The use of lugs adversely affects the heat transfer to the vessel placed inside the solar cooker and it doesn't improve the cooker performance. Reduction in cooking time is not possible by raising the vessel on lugs and hence cooking vessel are advised to directly place on absorber plate for all universal adoption.

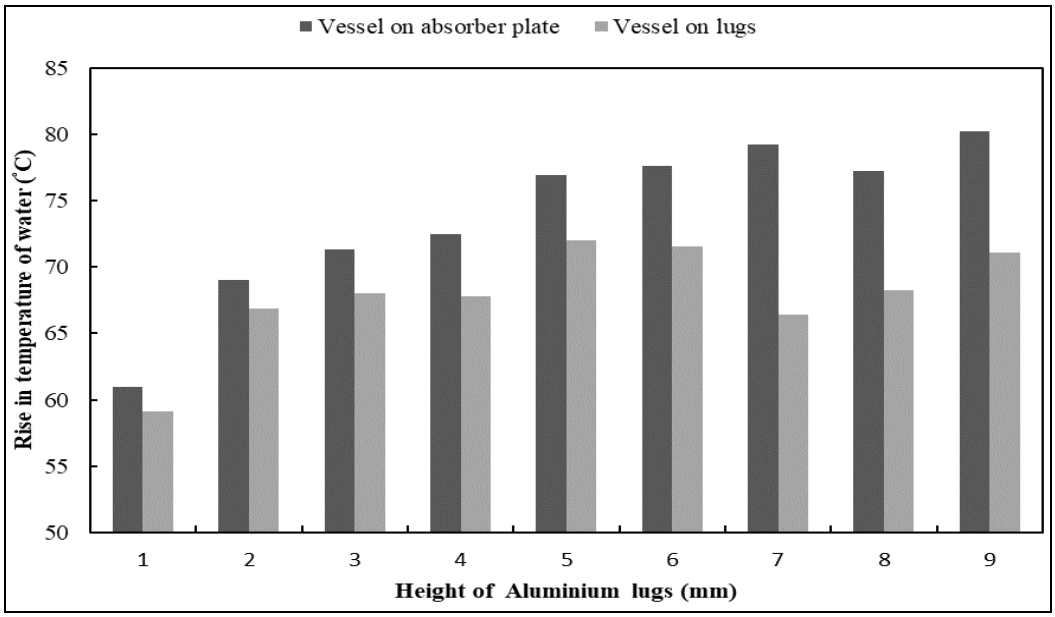

Fig 4: Bar graph for rise in temperature of water (0.5 kg) for 120 minutes time duration when cooking vessel is placed directly on absorber plate and raising the vessel on lugs of different height 1-9 mm.

3.2 Performance evaluation using Phase change materials (PCM) embedded on cylindrical vessel

The effect of phase change materials is investigated to improve the heating efficiency and increasing heat transfer effect to interior of vessel during off sunshine hours. The experiment was conducted with PCM Paraffin wax filled between outer and inner concentric finned vessel in one vessel (cooker-I) while another vessel (cooker-II) is tested without PCM. The experiment was conducted with a full load 0.5 kg of water in both the vessel. The mass of PCM taken is 0.6 kg. The experiment started at 10.30 h and after water attains maximum temperature (90 ºC) both the solar cookers are closed and brought in shadow. The discharging of PCM takes place after 2 P.M and readings are measured till 8 P.M. The observation data for variation in water temperature with Paraffin wax and without Paraffin wax in finned cooking vessel on date 1.5.23 is shown graphically in Figure 5. The PCM kept the water temperature higher during discharging phase as compared to water temperature without PCM.

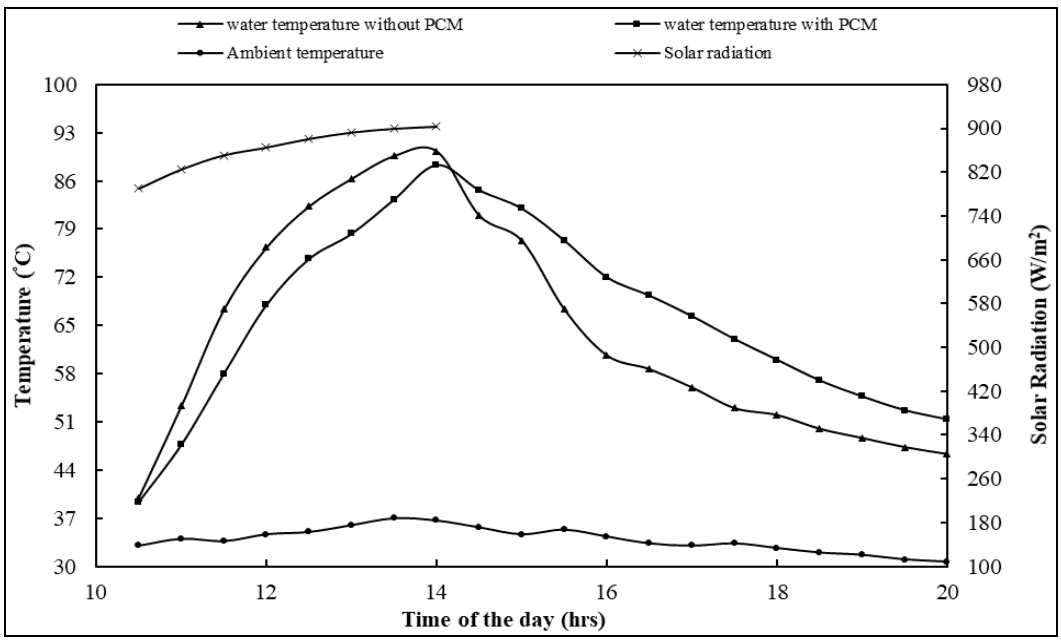

Fig 5: Comparison of PCM vessel and without PCM vessel (0.5 kg load, paraffin wax)

3.3 Heat transfer Mechanism

Based on our experimental observations the following mechanisms of heat transfer to contents of the vessel are established. Fig. 6 shows the heat transfer mechanism of SBC. The interior of the cooker and vessel are painted black and it absorbs the solar insolation (electromagnetic radiation) and gets heated. The reradiated heat in the infrared region is prevented from escaping from the cooker by glass covers, which are opaque to infrared regime of the incident radiation. The outside of the vessel gets heated due to infrared radiation and it heats the air present inside the solar cooker. The water inside the vessel has three boundaries: The top, side, and bottom. The heat flows from the bottom of the vessel to water layer firstly by conduction between the absorber plate and bottom of vessel ($Q_{cond\,abs-b}$) and then, secondly by convection between bottom of vessel and water layer ($Q_{convb-w}$) above it. The heat transfer from the side of the vessel occurs by convection between the hot air inside the cooker and boundaries of the sides of the vessel ($Q_{conva-vs}$). The convective heat from the vessel flow to PCM ($Q_{convvs-pcm}$). The PCM then transfer heat to inner vessel and and finally heat energy transferred to water contents by convection between inner sides of the vessel and water ($Q_{convvs-w}$). The upper lid however doesn't effectively transfer heat to water as there is air gap between water and upper lid but it will generate a current of hot air inside the cooker. The heat carried by this air circulation reaches water via the sides of the vessel. Thus the heat energy is transferred to contents of the vessel through conduction, convection and radiation between bottom, side and top of the vessel and the hot air circulation inside the SBC.

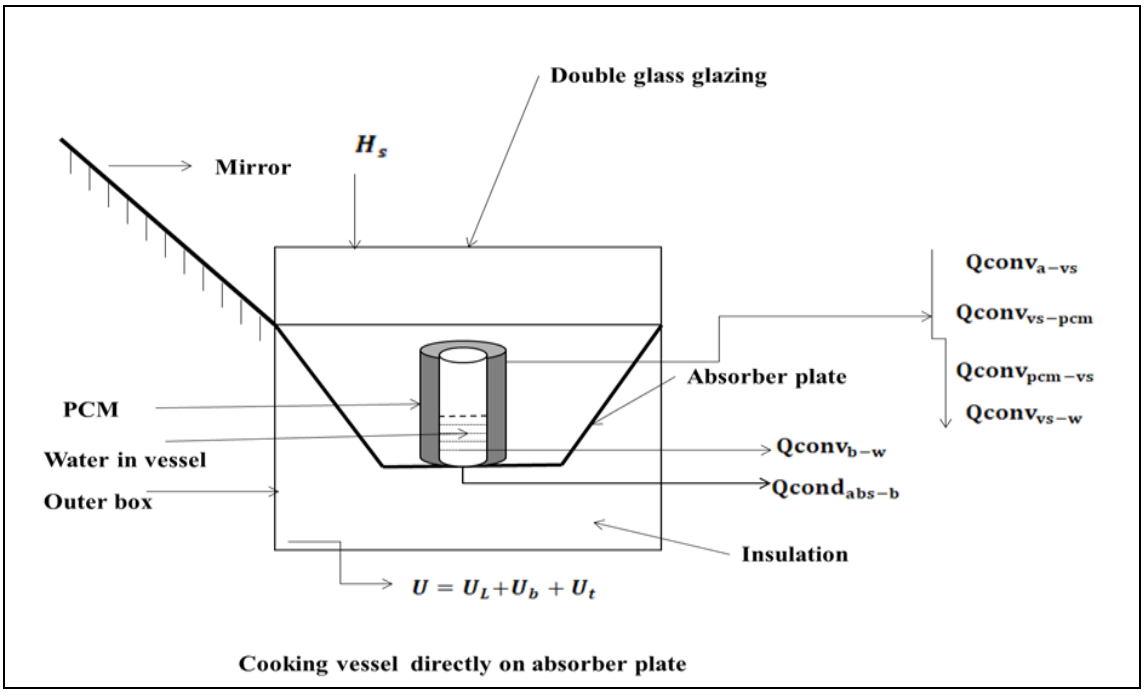

Fig 6: Heat transfer Mechanism in Solar box cooker

4. Effect of reflector

The effect of reflector on the water temperature of a vessel placed in the cooker is studied by taking two vessels filled with 0.5 kg of water with each vessel placed inside the two identical cookers. Experiments were conducted on two different days by interchanging the use of reflector on the cooker. The reflector is used for reflecting the solar radiation on the glazings. The reflector is adjusted hour by hour for tracking the sun on the solar cookers. The experimental observation shows that the use of reflector enhances the temperature of water in the vessel placed inside the solar cooker by 22 °C to 26 °C.

5. Conclusions

The uses of lugs adversely affect the thermal performance of the solar cooker. The rise in temperature of water for the same time duration is more for a vessel without lugs (placed directly on the absorber plate) as compared to a vessel placed on lugs. Hence it can be conclude from the experimental observations that no reduction in cooking time is possible with the use of lugs as raising the vessel on lugs creates a air (conductivity 0.024 W/mk) gap between bottom of the vessel and the absorber plate. However, the use of reflector (booster mirror) enhances the temperature of water in the vessel placed inside the solar cooker by 22 °C to 26 °C. The cooking vessel is recommended to be placed directly on absorber plate for increase in thermal efficiency of SBCs and future universal adoption.

Nomenclature

T_{ps}	Absorber plate temperature [°C]
T_a	Ambient Temperature [°C]
η_o	Optical efficiency (%)
U_L	Heat loss factor [W/m^{2}K] Top, bottom and side loss
F_1	First figure of merit
H_s	Solar Insolation (W/m^2)
SBCs	Solar box cookers
PCMs	Phase change materials

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