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Experimental Investigation on Vapor Condensation and Removal in a Box Solar Cooker Using a Pressure Cooker Integrated with a Flexible Pipe

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Abstract

Solar cookers represent an environmentally friendly and sustainable technology for cooking applications, as they rely on solar energy, a clean, renewable, and widely available resource. This study investigates the effect of vapor condensation on the glass cover of a solar box cooker and its impact on thermal efficiency. Experimental investigations were conducted through controlled stagnation and sensible heat tests under two operating configurations: a conventional simple cooking pot and a pressure cooker equipped with a flexible pipe to vent steam outside the cooker enclosure. Experimental results showed that, when using the simple pot, vapor condensed on the inner surface of the glass cover, leading to reduced solar transmittance, increased thermal losses, and a gradual decrease in absorber plate temperature. In contrast, the pressure cooker configuration successfully discharged steam through the flexible pipe, preventing condensation on the glass surface and maintaining stable absorber temperatures during operation. The thermal performance of the cooker was evaluated using standard figures of merit, which were determined to be 0.11 m²°C/W and 0.427. These findings confirm that mitigating vapor condensation improves thermal performance and demonstrate that integrating a pressure cooker with an external steam-release system enhances solar box cooker efficiency and reliability.

Keywords: Solar box cooker; Pressure cooker; Flexible pipe; Thermal performance.

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1. Introduction

Cooking serves as a significant and routine component of household life. The reliance on fossil sources such as LPG, Coal, and gas for cooking has major environmental, health, and socioeconomic impacts. While these fuels are convenient and energy-dense, they contribute to air pollution, climate change, and public health issues, particularly in low- and middle-income nations where access to clean energy is limited. By harnessing solar energy, solar cookers heat and cook meals without the need for electricity or gas. This sustainable technique reduces fuel costs, minimizes pollution, and is ideal for sunny regions. Solar cookers come in different designs, such as parabolic cookers, where by harnessing sunlight to convert it into heat at a point to cook food (Mekonnen et al, Maurice Ky et al) [1,2], and indirect cooking using a fluid to transfer the heat through it into the cooking chamber (Hosseinzadeh et al) [3]. A hybrid solar cooker incorporates base solar energy with another energy source, for instance, electricity, biomass, and LPG (Saxena and Agarwal; Recioui et al) [4, 5]. Each is suited for various cooking needs (Yettou et al) [6]. Solar cooking requires abundant insolation and clear weather to succeed in the cooking operation. Nevertheless, these dependencies can limit its reliability in regions with frequent cloud cover or seasonal variability. Solar box cookers are insulated enclosures with transparent covers that admit sunlight. Under optimal conditions, solar box cookers achieve steady-state temperatures ranging from 120°C up to 150°C, a thermal regime particularly suited for slow-cooking methods, including boiling, steaming, and stewing. Tawfik et al [7] constructed an inclined box cooker that was incorporated with a parabolic reflector. Furthermore, an evaluation was performed to examine the thermal efficiency in both scenarios: with a parabolic reflector and without one, and the authors revealed that the cooker recorded an intermediate temperature of about 140–150 °C and overall efficiency with and without a parabolic reflector to be 10.7% and 12.5%, and additionally, lessen cooking time by 36 min. Goyal and Eswaramoorthy [8] analyzed and tested a solar box oven. Where use an optimized cooking container incorporated with a triangular fin affixed to its exterior surface, aimed at augmenting the process of heat transfer through convection. The results of the simulation indicated that heat losses were in the top, bottom, and side 4.26, 0.77, & 0.64 W/m^2, and at experiments the box oven achieved in the test load (1.5 Kg) a cooking power was 77.06 W, and efficiency augmented from 36.16 % up to 40.55 % and reduce cooking time from 95 min to 85 min hence the augmentation of the surface area of a cooking vessel through the implementation of a triangular fin configuration significantly enhances the convective heat transfer. Verma et al [9] constructed and developed a solar box oven comprising two identical parts and conducted a comparative study by utilizing black matt paint and five material mixed paints such as CuO, TiO2 (titanium oxide), activated carbon (copper oxide), Tungsten, and mica mixing with black paint on the absorber tray in order ameliorate the thermal performance of the cooker. Furthermore, experimental tests were performed with a water load and without it by using different coating materials. Titanium oxide TiO_2 and Mica blended with paint were proven effective in enhancement by ameliorating 5-7 °C, and during tests without load gave the absorber plate difference of about 1-14°C, and water load difference of about 1-7 °C for two box ovens. Ademe and Hameer [10] performed and assessed a box cooker with a glazing wiper mechanism. Furthermore, the cooker was tested with and without the wiper mechanism. The results indicated that the figures of merit, standard cooking power, and the boiling duration of 1.43 kg of water fresh in mode without vapor mechanism were 0.123 Km^2/W, 0.540, 36 W, and 88.84 minutes, as well as in mode with vapor mechanism were 0.123 Km^2/W, 0.827,51 W, and 53.54 minutes respectively. Goyal and Eswaramoorthy [11] analyzed and tested a box cooker that used the waste marble pieces as integrated sensible thermal storage to enhance the potential of evening cooking. The researchers proposed which uses sensible heat storage (marble) with an aluminum sheet cover, matte black coated, and without. The aluminum was used under glass to reduce top heat losses. The experimental findings, a power and efficiency without sheet cover and with were 56.62 W, 48.21 W, 25.79 %, and 31.19 %, respectively, as well as the sheet cover can lessen top heat losses and marble as a heat storage capable in evening cooking. Based on most literature reviews of the relevant, which particularly utilized methods and techniques to optimize the performance of a cooker, the enhancements, also modifications, involved particularly the cooking pot, coating, reflectors, and wiper mechanism to reduce vapor on the glass. In this research work, a thorough experimental investigation was carried out on a box cooker, with emphasis on the integration of a flexible pipe system designed to minimize or prevent vapor condensation on the indoor surface of the glass cover, thereby improving the overall thermal efficiency and visibility during operation.

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2. Materials and Methods

2.1 Description of System

The experiment was conducted using a Box solar cooker, which was evaluated both with a cooking container & without it. The cooking vessels utilized in the experiment included a simple cooking pot and a pressure cooker. Figure 1 demonstrates a trial procedure of the solar cooker, which incorporates a flexible pipe connected to the vent pipe of the pressure cooker, facilitating the release of vapor through it. The readings have been recorded by the measuring instruments and are stated in Table 1.

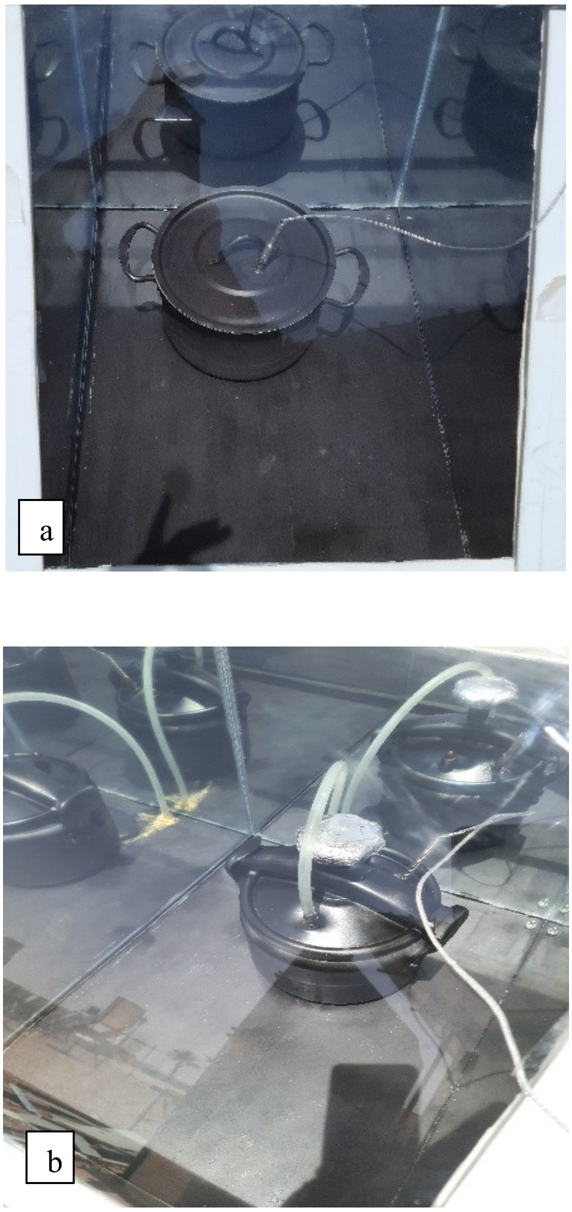

Figure 1. Experimental procedure on a box cooker: (a) a simple cooking pot ;(b) a pressure cooker with a flexible pipe.

Table 1. Specifications of measuring gadgets

Characteristic	Type	Range	Accuracy

Solar Irradiation	Pyranometer CMP6	0 – 1500 W/m^2	±2%
Wind Velocity	Anemometer	0 – 40 m/s	±0.5
Temperature measurement	The Campbell CS215	-40 up to 70	±0.4°C
	Thermocouple type K	-50 – 1250 °C	±2.2°C
Data Acquisition	AGILENT 34972A	-	-

3. Performance Measures

3.1 The figures of Merit

The two parameters assess the performance of the cooker, where F_1 (m^2 °C/W) represents the optical efficiency to the heat loss. In addition, F_2 is identified under complete load conditions and can be articulated both through the expression provided as follows [12]:

$$F_1 = \frac{\eta_0}{U_L} = \frac{T_{p_s} - T_{a_s}}{I_s} \tag{1}$$

$$F_2 = \frac{Mc_p.F_1}{t.A}.\ln\left[\frac{\left(1-\left(\frac{1}{F_1}\right).\left(\frac{T_{w_i}-\overline{T_a}}{\overline{I_s}}\right)\right)}{\left(1-\left(\frac{1}{F_1}\right).\left(\frac{T_{w_f}-\overline{T_a}}{\overline{I_s}}\right)\right)}\right] \tag{2}$$

Where Tp_s, as (°C), are the temperatures of the absorber and ambient, and I_s is the solar irradiation (W/m^2). Furthermore, T_{wi}, Tw_f are the temperatures of water (initial, final), t is the time required (min), and A is the aperture area (m²).

4. Results and Discussion

The experiment of the first configuration and the sensible testing concerning the simple cooking pot and the pressure cooker were performed in May 2025.

4.1 First configuration (Stagnation test)

As seen in Figure 2, the stagnation test was performed (no load condition). The graph illustrates solar irradiation and ambient, trapped air temperature, as well as their impact on the stagnation temperature recorded on the absorber of the cooker. The highest temperature recorded for the absorber was 130.4 °C, achieved after a duration of 2 hours and 20 minutes, specifically at 12:20. The associated insolation value at that time was 932 W/m^2. F_1 estimated 0.11 m^2 °C/W by using Equation 1, where the ambient, absorber temperature, and solar irradiation at stagnation were 129 °C, 27°C, and 918.5 W/m^2.

The initial figure of merit ranges from 0.10 to 0.14 [12]. A higher F_1 value signifies better optical efficiency as well as a reduced heat loss. The solar cooker we have developed exhibits a satisfactory value of the parameter F_1 (0.11 m²°C/W) due to the good interception of solar rays, a consequence of the inclined receiving surface design realized. The significant temperature of 80 °C, which is appropriate for cooking an item, was achieved merely 1 hour after the commencement of the trial. This impressive efficiency can be ascribed to the characteristics of every element within the constructed box cooker.

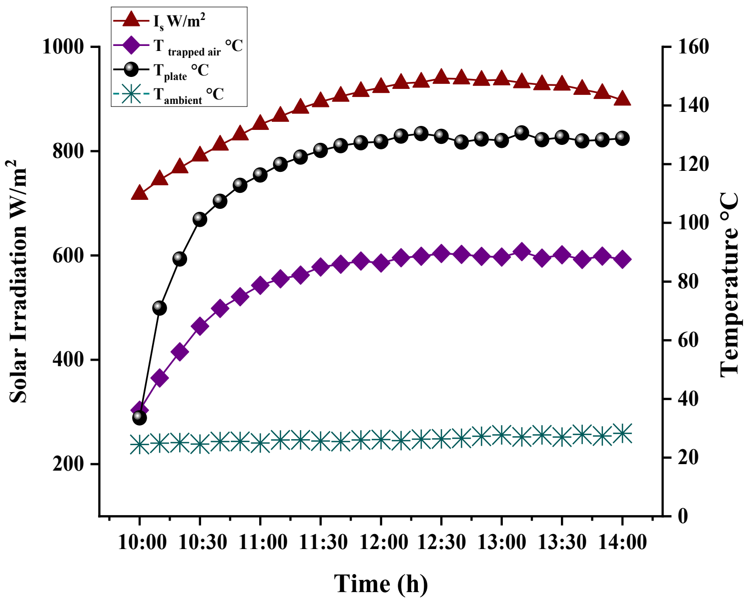

Figure 2. Stagnation testing of the box cooker configuration 1.

4.2 Second configuration (Sensible heat test)

The sensible testing was implemented under the full load conditions, where 1 kg of water is considered the cooking medium.

As depicted in Figure 3, the profile temperature of the absorber, water, ambient, and trapped air temperature in the case used a simple vessel. The maximum absorber temperature reached was 113.3 °C, while T_w, T_a, Ttrapped air, and I_s have been found to be 96 °C, 30 °C, 84.6 °C, and 938.3 W/m^2 (around 12:40 hrs).

During the experimental evaluation, significant vapor condensation was observed across the entire inner surface of the solar cooker's glass cover, as illustrated in Figure 4. This condensation phenomenon adversely affected the thermal performance by progressively reducing the absorber plate temperature from an initial peak of 113.3 °C to a lower value of 103.8 °C. Subsequently, a second figure of merit, denoted as F_2, was computed using the established formula (2) and found to be 0.427, where the aperture area is 0.24 m². This value indicates an improved thermal performance and confirms that the cooker meets the minimum performance standards outlined in the Bureau of Indian Standards (BIS) criteria based on the figures of merit. Furthermore, the duration required to reach a water boiling (98.3 °C) was recorded at approximately 180 minutes, corresponding to around 13:00 hrs, under a solar irradiance level of 936.6 W/m².

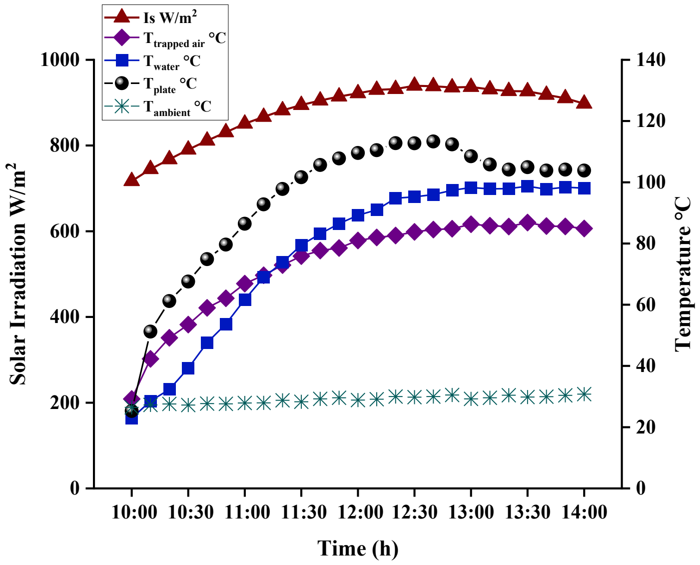

Figure 3. Sensible testing of the box cooker with a simple cooking pot.

Figure 4. A photo illustrates vapor condensation on the glass cover of a box cooker.

As illustrated in Figure 5, the temperature variation was analyzed for the configuration in which a pressure cooker was used in conjunction with a flexible pipe to redirect steam. The highest temperature achieved by the absorber reached 112.5 °C, while the corresponding water temperature (T_w) and the trapped air temperature ($T_{trapped\ air}$) were measured as 95.2 °C and 73 °C, respectively, around 13:10 hours, under a solar irradiation of 930.367 W/m². Notably, the duration needed for the water temperature to attain 95.25 °C was approximately 160 minutes, corresponding to around 12:40 hours under a surrounding temperature of 30.01 °C. A key observation in this experiment was the successful elimination of steam condensation on the internal surface of the glass, which contributed to maintaining the absorber's thermal performance without any noticeable temperature decline, thus enhancing the overall efficiency of the cooking process.

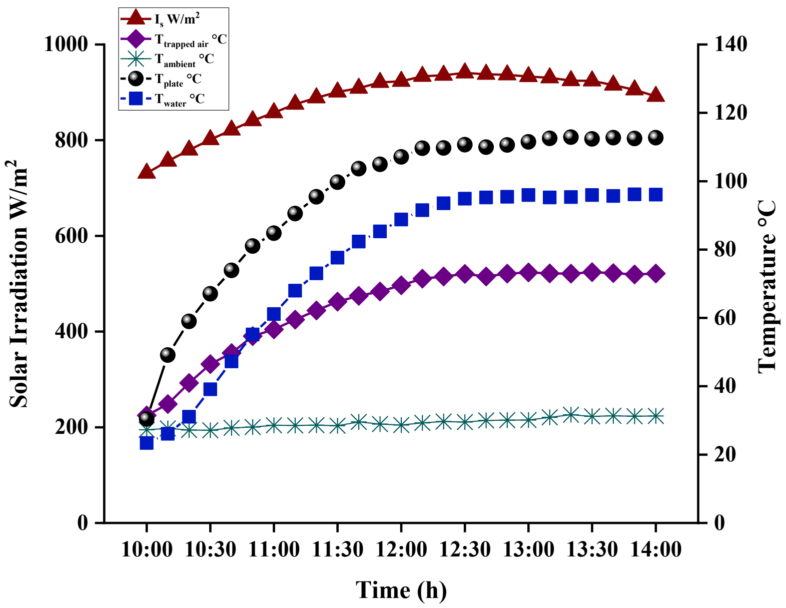

Figure 5. Sensible testing of the pressure cooker with a flexible pipe of the box cooker.

5. Conclusion

According to the findings of an experimental investigation implemented on a solar box cooker, the system underwent evaluation under two different configurations to assess its thermal performance. In the first configuration, the cooker was tested using a conventional simple pot, while in the second configuration, a pressure cooker was employed, equipped with a flexible pipe designed to direct and release hot vapor outside the cooking chamber. This design aimed to mitigate the effects of steam condensation on the inner surface of the glass cover. In the simple pot configuration, the peak temperature recorded by the absorber reached 130.4 °C, as well as the figures of merit were identified to be 0.11 m² °C/W & 0.427. Notably, the occurrence of vapor condensation on the glass significantly impacted the performance by reducing the efficiency of heat transfer to the absorber, which in turn influenced both the effectiveness of cooking and the thermal storage capacity. However, the integration of the pressure cooker with a flexible pipe successfully prevented condensation, maintained higher absorber temperatures, and demonstrated a promising enhancement in the overall efficiency of a box cooker, rendering it a viable solution for enhanced solar cooking applications.

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