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Conference paper

An Experimental Study Analysis of The Suitability of Sensible Heat Storage Materials for Solar Cooking Under Algerian Sahara Conditions

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ABSTRACT

Solar power stands as a crucially sustainable energy source, primarily harnessed for heating and generating power. Various energy storage materials exist, enabling the improvement of diverse solar heating systems' performance. In this study, we've experimentally examined the thermal storage capabilities of small masonry brick pieces within a box-type solar cooker. This material was utilized atop the cooking plate in the tested cooker. The authors focused on making box cookers more efficient without breaking the bank, particularly benefiting those in remote areas. They explored using cost-effective heat storage materials, making it accessible even to those with limited education. Cooking trials showed promising results, indicating the practicality of affordable energy storage materials. These findings hint at the possibility of widespread adoption of the tested model. The cooker boasts a thermal efficiency of approximately 36.8%, a cooking power of around 61.10 W, and a thermal storage capacity of roughly 7 hours per day. The estimated cost for the cooker tested comes in at about $75.

1. INTRODUCTION

One of the most abundant and pure resources on Earth that is always free to use is solar energy. With its ability to meet everyday demands for cooking, heating, cooling, power, and other things, its technology is a huge benefit to people all over the world. Since the 1800s, pioneers in this sector have created a wide range of applications with the goal of benefiting humanity, including dryers, stills, cars, freezers,

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air conditioners, spacecraft, photovoltaics, and more. Examples of these applications include solar cookers, air warmers, and water heaters (Cabeza, 2021; Benbaha et al., 2022; Mussard, Gueno, & Nydal, 2013; Nayak et al., 2018; Osei et al., 2021). Nonetheless, amid these diverse uses, solar water heating and cooking systems play crucial roles in providing for the everyday needs of households or entire countries in terms of water heating and cooking. Moreover, nearly all applications of solar energy technology are currently accessible in commercial markets. A notable advantage of this technology is the ease with which consumers can either construct their own solar cooker, still, or air heater or purchase them from the market, albeit at a slightly higher cost. Entrepreneurs within the solar energy market persistently explore and develop new opportunities (Saxena, Agarwal, & Norton, 2021).

Solar cookers serve as valuable tools for preparing food using incoming solar radiation. Beyond cooking, they're also employed for crucial processes like food drying, sterilization, and pasteurization. Classifying solar cookers often proves challenging due to the array of styles found in literature. However, solar cookers are classified into three categories: box, parabolic, and panel cookers (Benbaha et al., 2024). Impressive thermodynamic performance parameters, such as energy and exergy efficiency, cooking power, and cooking duration, are typically delivered by solar box cookers. Their exceptional durability and stability ensure over 20 years of continuous operation at a consistent thermal efficiency (Saxena et al., 2022). However, during the cooking process, variations in solar intensity have a major impact on their performance. Because cooking power is mostly dependent on the temperature of the absorber plate, significant variations in sun intensity have a negative impact on the cooking process. As a result, for consistent and effective cooking, solar box cooker integration with a thermal energy storage medium becomes crucial.

When solar box cookers are equipped with thermal energy storage, their total thermal performance is much improved, allowing for cooking at night or on overcast days while keeping efficiency levels close to constant (Saxena, Goel, & Karakilcik, 2018). Both sensible thermal energy storage applications and latent thermal energy storage technologies are commonly employed in these cookers. Because latent thermal energy storage has a well-established track record of producing consistent, excellent outcomes in total thermal performance and has been well-documented in the literature, it is especially significant in solar box cookers (Saxena, Norton, Goel, & Singh, 2022). Osei et al. (2021) provided a thorough overview of the various functions of various Phase Change Materials in solar cooking, concentrating primarily on the thermal evaluation of 2.5 kg of erythritol used in an electric box cooker powered by the sun. This modified cooker was found to have an efficiency of almost 77% and a total estimated cost of about $100 (Saxena, Srivastava, & Sharma, 2010). Therefore, there is considerable demand for developing a cooking system that enhances efficiency for the targeted communities. In response, a user-friendly solar cooker has been developed, enabling consumers to independently boost its efficiency using the proposed technique at minimal cost.

For a brief, box solar cooker has been designed to function using inexpensive SHS materials for cooking trial, evaluating their impact on the cooking performance compared to a conventional design cooker, particularly during periods without direct sunlight. This material consists of small black bricks. Importantly, this performance-enhancing element is easily accessible to consumers. They can readily obtain them from local markets and employ them without hassle whenever needed, as recommended in this study. The innovation lies in the ease with which consumers can independently implement cost-effective modifications to enhance the cooking device's thermal performance. Implementing these suggested techniques poses no challenge, making it accessible even to individuals with limited education. This straightforward process not only saves time and money but also reduces reliance on fossil fuels. It serves as a crucial resource for nomads in the Algerian desert, offering a vital energy source where none is otherwise available due to their nomadic lifestyle.

2. THEORY AND ANALYSIS

2.1 Mathematical model

Energy balance at absorber plate:

$$(mc_p)\frac{dT_p}{dt} = \alpha_p\tau_g \quad IS\big(A_p - nA_v\big) - h_{r,p-g_2}(A_p - nA_{vb})(T_p - T_{g_2}) - h_{c,p-i}(A_p - nA_{vb})(T_p - T_i) - U_{sw}A_{sw}(T_p - T_a) - \left(\frac{k_v}{X_v}\right)nA_{vb}(T_p - T_v) \tag{1}$$

Energy balance of the outer glass cover:

$$(mc_p)_{g_1}\frac{dT_{g_1}}{dt} = \tau_g\alpha_g A_g IS - h_{r,g_1-s}A_{g_1}(T_{g_1} - T_s) + hr_{g_2-g_1}S_g(T_{g_2} - T_{g_1}) - h_{c,g_1\to a}A_g(T_{g_1} - T_a) + hc_{g_2-g_1}S_g(T_{g_2} - T_{g_1}) \tag{2}$$

Energy balance of the inner glass cover:

$$(mc_p)_{g_2}\frac{dT_{g_2}}{dt} = \tau_g\alpha_g A_g IS + hc_{i-g_2}A_g(T_i - T_{g_2}) + h_{r,v-g_2}nA_{vb}(T_v - T_{g_2}) + h_{r,p-g_2}(A_p - nA_{vb})(T_p - T_{g_2}) - hr_{g_2-g_1}S_g(T_{g_2} - T_{g_1}) - hc_{g_2-g_1}S_g(T_{g_2} - T_{g_1}) \tag{3}$$

Energy balance of air inside the cooker:

$$(mc_p)_i\frac{dT_i}{dt} = h_{c,p-i}(A_p - nA_{vb})(T_p - T_i) + h_{c,v-i}nA_v(T_v - T_i) - hc_{i-g_2}A_g(T_i - T_{g_2}) \tag{4}$$

Energy balance at vessel :

$$(mc_p)_v\frac{dT_v}{dt} = \tau_{g_2}\alpha_v nA_{vb}IS + U_{vb}nA_{vb}(T_p - T_v) - h_{c,v\to f}nA_{vf}(T_v - T_f) - h_{r,v-g_2}nA_{vb}(T_v - T_{g_2}) - h_{c,v-i}nA_v(T_v - T_i) \tag{5}$$

Energy balance inside vessel fluid:

$$(mc_p)_f\frac{dT_f}{dt} = h_{c,v\to f}nA_{vf}(T_v - T_f) - h_{c,f-l}nA_l\big(T_f - T_l\big) \tag{6}$$

2.2 Thermal efficiency

The thermal efficiency (η_{therm}) serves as a primary performance metric for assessing the overall effectiveness of any thermal system. In the context of Box Solar Cooker, it can be calculated by considering of two key parameters: energy input and energy output (Osei et al. 2021).

$$\eta_{therm} = \frac{m.c.\Delta T}{t.I.(A_{abs} - A_{cons})} \tag{7}$$

3. EXPERIMENTAL SETUP

The SHS material examined was sourced from areas allocated for construction waste disposal. Initially, red bricks discarded by construction workers were gathered. Subsequently, these bricks were fragmented into small pieces, ranging from 1.5 to 3.5 cm, and assembled for soaking in black ink to enhance solar energy absorption. Following this treatment, the samples were air-dried in an open environment. Table 1 displays the thermo-physical characteristics of the solid-state sensible heat storage material, which encompasses the tested SHS material.

The box cooker specifications include a double wall with 4 cm thick glass wool insulation. A 1 mm thick aluminum cooking plate maximizes solar radiant heat absorption, leveraging extra reflected solar radiation from an attached mirror booster. The box cooker utilizes double-glazed, featuring glazing dimensions of around 570 × 370 mm², and an absorber area measuring about 460 × 370 mm². Its aperture area is approximately 0.21 m², as shown in Fig. 1. Fig. 2 shows the synoptic diagram of the installation. The equipment utilized to measure the necessary performance characteristics at a given time interval are displayed in Table 2.

Fig 1. Experimental setup

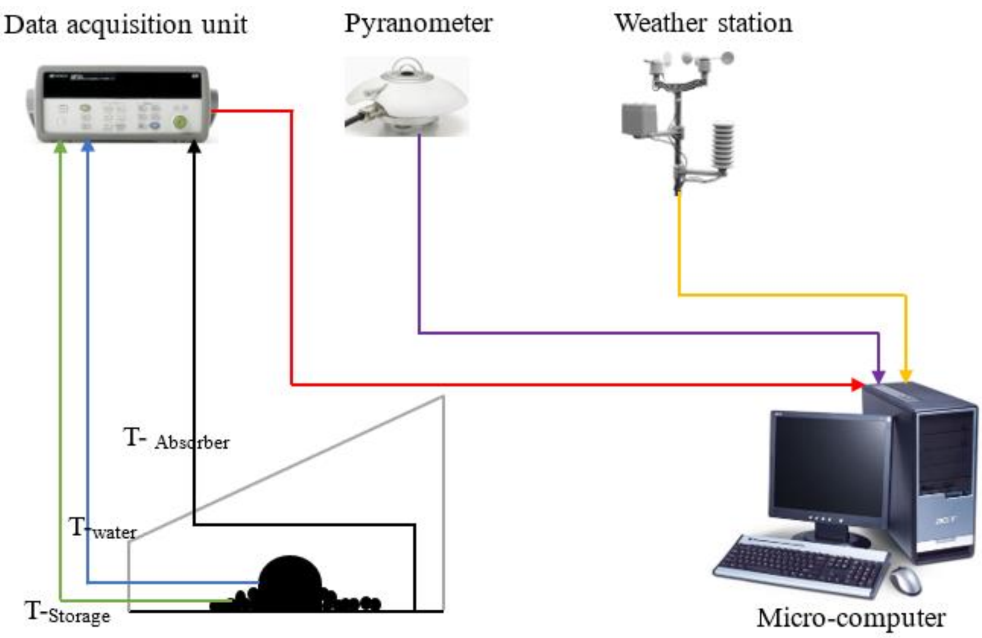

Fig 2. Synoptic diagram of the installation.

Table 1. Characteristics of the SHS material in its solid state.

Storage materials	Heat capacity (J/m^3 K)	Density (kg/m3)	Specific heat capacity (J/kg K)
Bricks	14.263	1600	840

Table 2. Characteristics of the measuring tools used during the experiment

Instruments	Independent variables	Model	Measurement range	Accuracy
Thermocouple	Temperature	K-Type	-50-1300°C	±2.2°C
Pyranometer	Solar radiation	CMP6	0-1500W/m²	±2W/m²
Anemometer	wind speed	Testo 440	0-40m/s	
Multimeter	-	UNI-T UT71C	-40- 400°C	±1°C
Data acquisition unit	-	Agilent 34972A	-	-

4 RESULT AND DISCUSSION

4.1. Test without water

Stagnation tests were performed on the unloaded cooker on November 20, 23 to evaluate the effectiveness of the modified cooker and the performance of our solar cooking system. The modified unit was placed in a sunny setting at 09:00 h to reach a stable state. This experiment aimed to measure the temperature profiles of the absorbent plate. By conducting this experiment, we could gather valuable data regarding the thermal behaviour and heat transfer capabilities of the system, providing insights into its overall effectiveness.

Fig. 3 presents the typical results obtained on a sunny day, displaying the radiation intensity, ambient temperature, and various temperatures recorded within the cooker. Tp was measured at approximately 28.93 ◦C, slightly higher than Tamb (around 17.74 ◦C) as depicted in Fig (3), with an observed irradiance level of about 710.74 W/m² on the horizontal surface. Readings were taken from 09:10 hour to 14:30 hour, revealing a subsequent rise in Tp compared to ambient conditions. At 14:30h, the maximum Tp and Tamb values were recorded at approximately 143.11°C and 24.08°C, respectively. Throughout the experiments, the computed value of F_1 remained within a satisfactory range of 0.11 to 0.13.

4.2 Test with water

To ensure that heat is transferred from the absorbent plate to the contents of the container—in this case, 1.5 kg of water—an efficient loading test is carried out. This test ensures that the system effectively delivers and maintains the desired temperature within the cooking vessel or container, enabling optimal heating and cooking performance. At the initial moment, Tp and Tamb were measured at 26.03°C and 15.99°C, respectively, as illustrated in Fig. 4, with an observed irradiance level of about 682.56W/m² on the ground surface. Readings were taken at 10-minute intervals between 09:10 h and 13:00 h. The absorbent plate temperature reached 112.46 °C, also, ambient temperature also reached 21.8 °C., occurring during the peak sunny hours at 11:50 h. The water remains at a temperature above 37.24°C for a duration of 540 minutes, as shown in Fig. 5.

Achieving thermal efficiency (η_{therm}) between 36.2% and 41.94%, with an average of 39.07%, and obtaining F2 between 0.54 and 0.57 are other crucial criteria. The range of values for the heat transfer coefficient (h) was 56.5 W/m°C to 105.33 W/m°C. Approximately 61.10 W was the maximum value of the computed cooking power (Psbc), and 5.08 W/m°C was the total heat loss coefficient.

The cost of the modified solar cooker totals approximately $75. All of the designs (Saxena, Verma, Srivastava, & Kishore, 2020; Yadav, Kumar, Agrawal, & Yadav, 2017) demonstrate merit and underscore the importance of the techniques employed in enhancing the thermal performance of various cookers worldwide. Nonetheless, some of these designs require further optimization in terms of both design and cost to achieve global acceptance. It is evident that complex or expensive designs are beyond the means of impoverished individuals or small households (Saxena, Goel, & Karakilcik, 2018). In contrast to previous efforts, the present device not only boasts affordability but also delivers satisfactory thermal performance.

These results demonstrate the exceptional efficacy of our system in prolonged heat retention, offering a dependable solution for preserving food temperature during a late dinner.

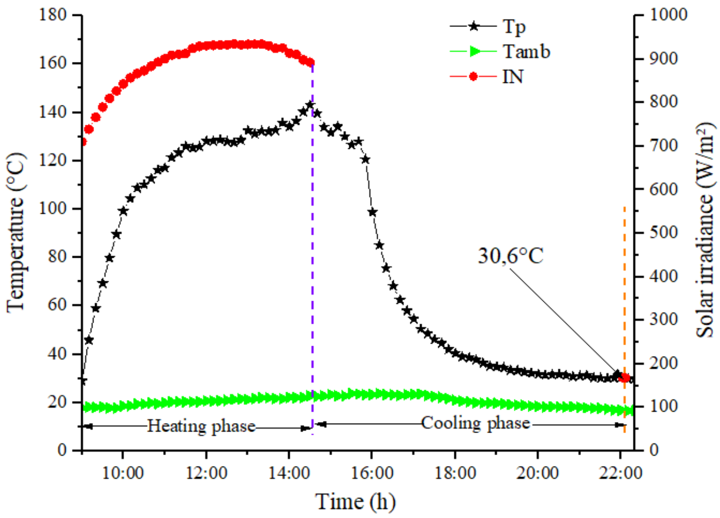

Fig 3. Temperature variations of absorber plate.

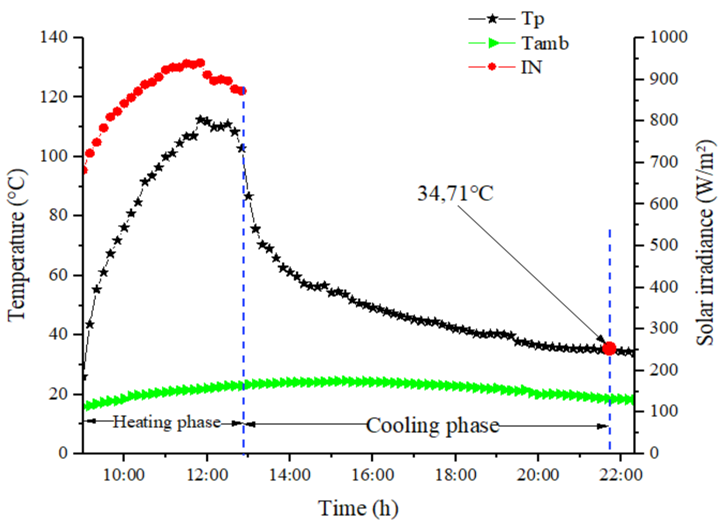

Fig 4. Absorber plate temperature during sensible test

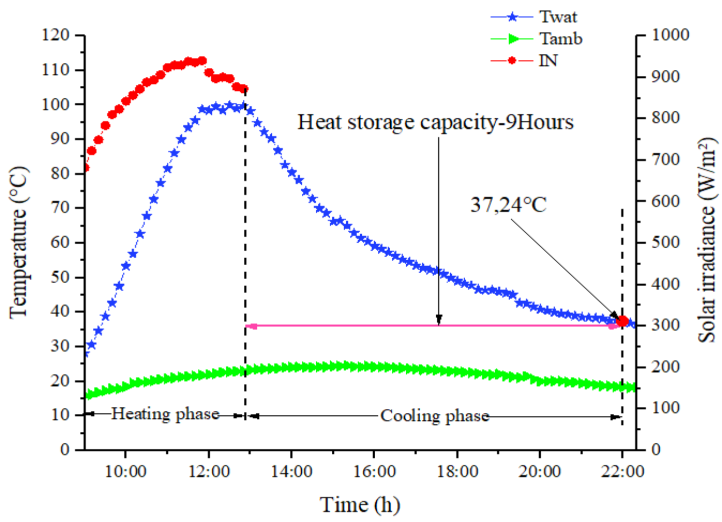

Fig 5. Water temperature during sensible test.

5. CONCLUSION

In conclusion, this study delved into the feasibility of heat storage within a solar cooker and its real-world usability. Rigorous experimentation and analysis revealed the cooker's impressive ability to retain high temperatures over prolonged periods. This discovery bears considerable promise, particularly for cooking enthusiasts and those in regions with scarce conventional energy sources, notably the nomadic communities in the Algerian desert. Upon the successful completion of experiments, the following concluding remarks have been drawn:

- The integration of small masonry brick pieces for thermal heat storage proves to be advantageous for box cookers.
- The enhanced thermal efficiency of the modified cooker shows a 41.94% improvement.
- The cooking power of the modified cooker has seen an improvement of approximately 61.10 watts.
- The cooker offers continuous cooking capabilities for extended durations.

The system showcased exceptional performance by maintaining water temperature above 37°C for a remarkable duration of 9 Hours.

NOMENCLATURE

IN	Normal direct illumination (W/m²)
IS	Cooker' available solar flux (W/m²)
h_r, h_c	Radiation and convective heat transfer coefficient (W/m². K)
mc_p	Heat capacity (J/K)
$\alpha_g, \alpha_p, \alpha_v, \alpha_{lf}, \alpha_{pot}$	Absorptivity (–)
τ_g, β_B	Transmissivity and reflectivity (–)
ε, F_{Bg}	Factors (–)
Ws	Wind speed (m/s)

REFERENCES

Benbaha, A., Yettou, F., Azoui, B., & Gama, A. (2022). Comparative Study of Simple and Double-Glazingn Box Solar Cookers by Performances Identification. In 2022 2nd International Conference on Advanced Electrical Engineering (ICAEE) (pp. 1-6). IEEE. https://doi.org/10.1109/ICAEE53772.2022.9962133

Benbaha, A., Yettou, F., Azoui, B., Gama, A., Rathore, N., & Panwar, N. L. (2024). Novel mixed solar cooker: Experimental, energy, exergy, and economic analysis. Heat Transfer, 53(4), 2095-2127. https://doi.org/10.1002/htj.23023

Cabeza, L. F. (2021). Advances in thermal energy storage systems: Methods and applications. In Advances in thermal energy storage systems (pp. 37-54). Woodhead publishing. https://doi.org/10.1016/B978-0-12-819885-8.00002-4

Mussard, M., Gueno, A., & Nydal, O. J. (2013). Experimental study of solar cooking using heat storage in comparison with direct heating. Solar Energy, 98, 375-383. https://doi.org/10.1016/j.solener.2013.09.015

Nayak, J., Sahoo, S. S., Swain, R. K., Mishra, A., & Thomas, S. (2018). Thermal performance analysis of a box-type solar cooker with finned pot: an experimental approach. In Advances in Smart Grid and Renewable Energy: Proceedings of ETAEERE-2016 (pp. 575-582). Springer Singapore. https://doi.org/10.1007/978-981-10-4286-7_57

Osei, M., Staveland, O., McGowan, S., Unger, J. B., Christler, N. R., Weeman, M., ... & Schwartz, P. (2021). Phase change thermal storage: Cooking with more power and versatility. Solar Energy, 220, 1065-1073. https://doi.org/10.1016/j.solener.2021.03.040

Saxena, A., Agarwal, N., & Norton, B. (2021). Design and performance characteristics of an innovative heat sink structure with phase change material for cooling of photovoltaic system. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-25. https://doi.org/10.1080/15567036.2021.1968545

Saxena, A., Cuce, E., Kabeel, A. E., Abdelgaied, M., & Goel, V. (2022). A thermodynamic review on solar stills. Solar Energy, 237, 377-413. https://doi.org/10.1016/j.solener.2022.04.001

Saxena, A., Goel, V., & Karakilcik, M. (2018). Solar food processing and cooking methodologies. Applications of Solar Energy, 251-294. https://doi.org/10.1007/978-981-10-7206-2_13

Saxena, A., Norton, B., Goel, V., & Singh, D. B. (2022). Solar cooking innovations, their appropriateness, and viability. Environmental Science and Pollution Research, 29(39), 58537-58560. https://doi.org/10.1007/s11356-022-21670-4

Saxena, A., Srivastava, G., & Sharma, N. K. (2010). Performance study of a modified cooking vessel for solar box-type cooker. TERI Information Digest on Energy and Environment, 9(3).

Saxena, A., Verma, P., Srivastava, G., & Kishore, N. (2020). Design and thermal performance evaluation of an air heater with low-cost thermal energy storage. Applied Thermal Engineering, 167, 114768. https://doi.org/10.1016/j.applthermaleng.2019.114768

Yadav, V., Kumar, Y., Agrawal, H., & Yadav, A. (2017). Thermal performance evaluation of solar cooker with latent and sensible heat storage unit for evening cooking. Australian Journal of Mechanical Engineering, 15(2), 93-102. https://doi.org/10.1080/14484846.2015.1093260