International Journal of Heat and Technology
Vol. 42, No. 5, October, 2024, pp. 1671-1677
Journal homepage: http://iieta.org/journals/ijht

Construction of an Indirect Solar Cooker

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https://doi.org/10.18280/ijht.420521

Received: 15 July 2024
Revised: 3 September 2024
Accepted: 18 September 2024
Available online: 31 October 2024

Keywords:
solar cooker, energy storage, phase change material, polypropylene

ABSTRACT

Our work consisted of producing an indirect solar cooker, equipped with a thermal energy storage system for cooking food under shelters. To achieve this objective, we proceeded to the dimensioning of the system by defining the components necessary for its realization. For this purpose, various processes for the development of parts, such as foundry and welding were used. Thus, an indirect solar cooker was designed, integrating a cylindrical-parabolic concentrator focusing the heat which is conveyed to a cooking tank filled with commercial polypropylene, serving as a phase change material (PCM). The system was subsequently tested under different weather conditions in order to evaluate and validate its performance. It emerges from this work that the integration of a PCM in an indirect solar cooker ensures its energy autonomy, that is to say its use in times of no sunshine, considerably improves its efficiency and offers a viable solution for cooking in rural areas without access to electricity. This device helps reduce dependence on fossil fuels and improve food security in sunny regions.

1. INTRODUCTION

Côte d'Ivoire has a significant solar deposit where all solar applications can emerge. One of the most attractive applications is solar cooking. This application is a solution to limit deforestation [1-4] and the abusive use of fossil fuels whose greenhouse gas emissions can jeopardize the future of humanity [5, 6]. Indeed, for citizens who are settled in several isolated regions of our territory, cooking food is very expensive when we exploit conventional energy sources and induces disastrous consequences on the ecosystem by exploiting the wood of the few remaining shrubs in these regions [7-9]. Solar cooking technology, although simple and practical, faces challenges. Indeed, its limited capacity to operate at sunset and in cloudy weather [10], requires the incorporation of an energy storage system, hence the use of phase change materials (PCM). Several authors have worked on the behavior of PCMs in cooking devices. Sharma et al. [11] studied the use of phase change materials for thermal energy storage in solar applications. Their study showed that PCMs can significantly improve the efficiency of solar cooking systems by extending the cooking time after sunset. However, they recommended that the melting temperature of a PCM should be in the range of 105-110℃ for evening cooking. Abhat [12] conducted a detailed study on the thermal properties of phase change materials and their application in solar energy storage, confirming that PCMs can store and release large amounts of latent heat during heating and cooling cycles. Buddhi et al. [13] used acetanilide (melting point 118.9℃) as a PCM in a cooking device. To store solar energy, the cooking unit was exposed to sunlight between 10:00 and 17:00 and was loaded with 0.50 kg of food (0.15 kg of rice and 0.35 kg of water). In the evening at 17:00, the temperatures of the PCM, absorber plate and food were 121.0, 120.0 and 35.2℃. The food was removed at 20:00 and was found to be well cooked. On December 8, 2000, the solar cooker with a single reflector was exposed to sunlight between 10:00 and 17:30 and was loaded with the same amount of food at 17:30 (half an hour later) for evening cooking. Before loading the cooker, the temperatures of the PCM, absorber plate and food at 17:30 were 104.0, 111.3 and 31.9℃. The food was found well cooked at 19:30. A similar experiment was repeated on 9 December 2000. On that day, the solar cooker was loaded at 18:00 and the food was not cooked.

In their operation, cookers capture energy either by direct exposure to the sun or through a parabolic trough concentrator. Thus, there are two types of solar cookers: Direct solar cookers and indirect solar cookers.

The indirect solar cooker using a PCM is the one we chose given the limitations of direct cookers, including the exposure of the housewife to the sun, etc. The indirect solar cooker consists of an external solar collector with an internal cooking unit using a heat transfer fluid [14] to convey the captured heat to the cooking area. The main advantage of this device is the possibility of cooking under cover.

Thus, the object of our work is to produce an indirect solar cooker, equipped with a thermal energy storage system, using 40% glycolated water as a transfer fluid and isotactic polypropylene as a phase change material (PCM).

To do this, we will carry out an experimental study of the device, by recording the temperature levels of the PCM as a function of time, comparing the efficiency of the indirect solar cooker based on glycolated water with those of systems using other heat transfer fluids and concluding.

2. MATERIALS AND METHODS

2.1 Materials

The components of our final device are summarized in the following Tables 1-5.

Table 1. Technical specifications of the cylindrical-parabolic concentrator

Geometric Characteristics of the Reflector	Value
Length	1.80 m
Diameter or Aperture Width	0.764 m
Height	0.21 m
Opening Angle	125°
Focal Distance	0.19 m
Aperture Area	1.3752 m^2

Table 2. Technical specifications of the absorber tube

Characteristics of the Absorber Tube	Value
Inner Diameter	0.01 m
Outer Diameter	0.012 m
Length	1.80 m
Absorption Surface Area	0.06788 m^2

Table 3. Technical specifications of the glass

Characteristics of the Glass	Value
Inner Diameter	0.02 m
Outer Diameter	0.024 m
Glass Thickness	0.002 m
Envelope Length	1.80 m

Table 4. Technical specifications of the heat exchanger

Characteristics of the Heat Exchanger	Value
Inner Diameter of the Pipe	0.01 m
Outer Diameter of the Pipe	0.012 m
Number of Coils	8

Table 5. Other system parameters

Coefficients	Value
Thermal conductivity of the absorber (K_{ab})	389 W/m.K
Thermal conductivity of the glass envelope (K_v)	0.93W/m.K
Absorption of the absorber tube (α_{ab})	0.96
Absorption of the glass envelope (α_v)	0.05
Transmittivity of the glass envelope (τ_v)	0.92
Transmittance-absorbivity factor (α_0)	0.817
Thermal capacity of the absorber (C_{ab})	380 J/Kg.K
Thermal capacity of the glass envelope (C_v)	840 J/Kg.K
Fluid heat capacity (C_f)	2400 J/Kg.K
Fluid density (ρ_f)	1043 Kg/m^3
Density of PCM	0.90-0.91 g/cm^3
Melting temperature of PCM	160-170℃
Specific heat capacity of PCM	1900 J/kg.K
Thermal conductivity of PCM	0.22 W/m.K
Emissivity of the absorber (ε_{ab})	0.12
Emissivity of the glass envelope (ε_v)	0.85
Reflector reflection (ρ_0)	0.92
Interception factor (γ)	0.823

A transparent cover (glass tube) is used in this type of solar collector due to its transparency to visible solar radiation and to achieve the greenhouse effect. The type of glass used is low in iron oxide.

2.2 Cooker construction method

2.2.1 Design and sizing of the system

Preliminary study: The first step involved designing the indirect solar cooker by defining the thermal capacity requirements and the optimal operating conditions. The amount of energy consumed per month by a household is given by the following equation [15]:

$$q=m_g \cdot Pci,g+m_c \cdot Pci,c$$

where,

m_g=mass of gas in kg;
m_c=mass of coal in kg;
Pci=lower calorific value.

A cylindrical-parabolic concentrator model was chosen to capture the necessary heat [16]. Using a copper pipe, the heat transfer fluid is directed to the MCP storage tank, which is housed inside the cooking pot.

Thermal and mechanical calculations: The calculations were used to size the main components, including the volume of the tank and the wall thickness. The selection of polypropylene as the phase change material (PCM) was based on its thermal capacity and melting temperature following its characterization [17].

2.2.2 Material and component selection

Main materials: The body of the cooker was made of stainless steel due to its corrosion resistance and ability to withstand high temperatures. Commercial polypropylene was used as the PCM for thermal energy storage.

Heat transfer system: A 40% glycol-water mixture was chosen as the heat transfer fluid due to its good thermal conductivity and stability at high temperatures.

2.2.3 Fabrication of components

Casting: The pot housed in the storage tank was manufactured by casting, which allowed for the creation of complex shapes and precise dimensions.

Welding: The various metal parts of the cooker, including the supports, heat transfer fluid pipes, and fastening elements, were assembled by welding. This process ensured good mechanical strength and a perfect seal.

2.2.4 Final device (assembly)

Component assembly: The cylindrical parabolic concentrator was mounted on a manually adjustable structure with a pivot joint, allowing it to follow the sun's trajectory. The tank containing the PCM was placed inside the cooking unit and connected to the concentrator via pipes through which the heat transfer fluid circulates.

PCM integration: The polypropylene housed in the tank is heated by the glycol-water mixture circulating through a coiled heat exchanger. This tank acts as a thermal buffer, storing the energy captured during the day for use in the evening. The absorber tube must absorb as much concentrated solar flux as possible and convert it into heat. This heat is transferred to the heat transfer fluid (the 40% glycol-water mixture). It is crucial that the receiver be metallic (a copper tube painted black) because only metals have good thermal conductivity coefficients (in our case, copper: 389W/m·K).

The absorber tube surface must have the following characteristics:

- Good thermal conductivity and diffusion;
- An absorption factor as close to 1 as possible;
- Good chemical resistance to the thermal fluid used.

After assembly, we proceeded with temperature measurements under open weather conditions. The temperature readings were taken over sixteen (16) consecutive days, from August 3 to August 18, 2023, from 6:00AM to 5:00PM. Among all the measurement days, we selected the following curves: a fully sunny day (5575Wh/m²/day), a moderately sunny day (3021Wh/m²/day), and a cloudy day (2649Wh/m²/day). The temperatures measured were ambient temperature (Tab), absorber inlet temperature (TEab), absorber outlet temperature (TSab), cooking pot inlet temperature (TEc), cooking pot outlet temperature (TSc), PCM temperature (Tm), and solar irradiance at the time of measurement.

Temperatures were measured using digital display probes, and solar irradiance was measured using a pyranometer. Temperature readings were taken every ten minutes. The absorber tube (copper) is at ambient temperature when the experiment begins. The Figures 1 to 6 illustrate the temperature evolution of the different components of the system (absorber tube, cooking pot, PCM) and the solar irradiance for the selected days. All this information was automatically recorded on an integrator.

Figures 7, 8 and 9 represent respectively the exploded diagram of the pot, the different components of the device and the final device.

Once the cooking pot was made and for the purpose of taking measurements, we connected it to the concentrator to obtain the following final device.

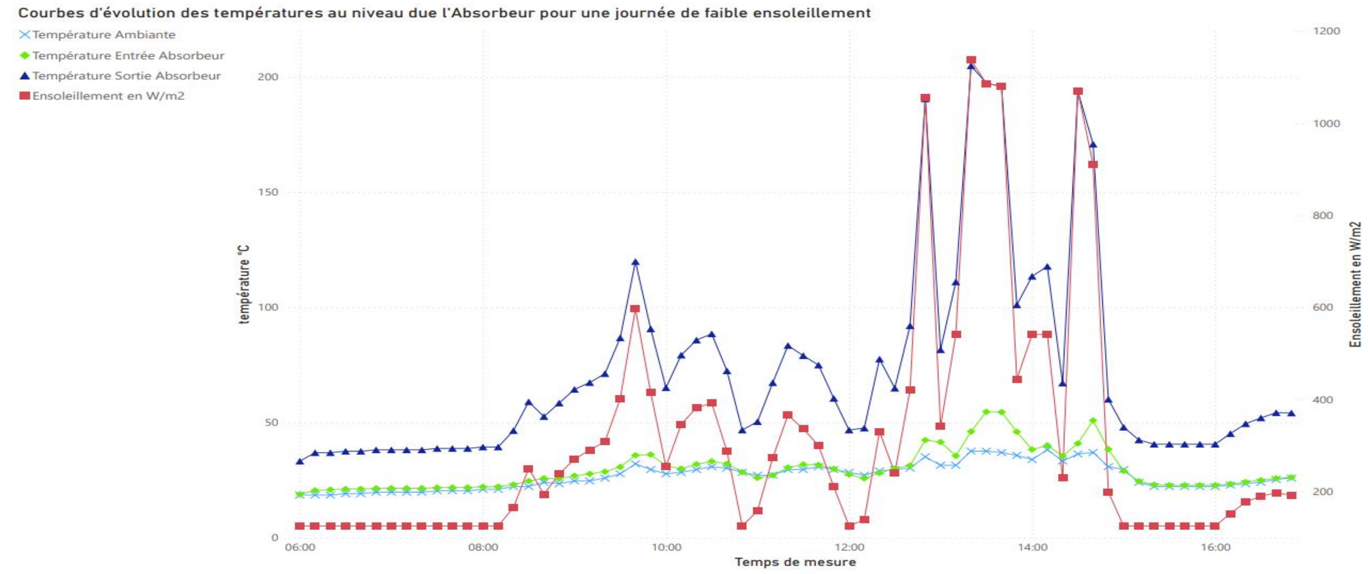

Figure 1. Temperature evolution curves for the absorber during a day of low sunlight with MCP

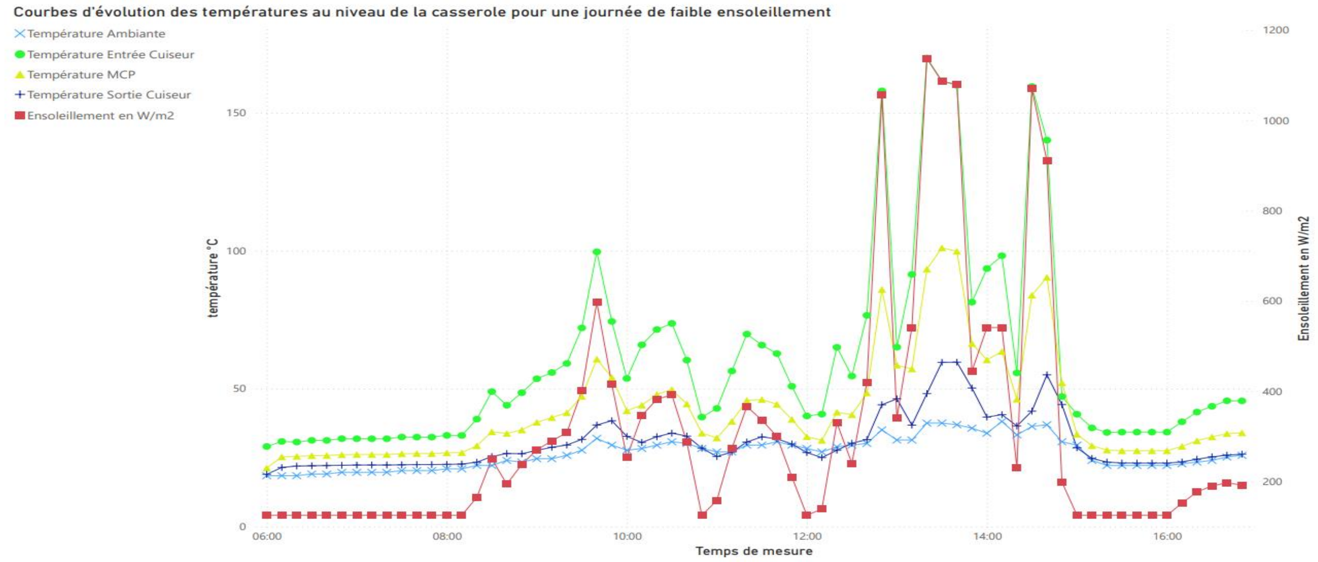

Figure 2. Temperature evolution curves for the casserole during a day of low sunlight with MCP

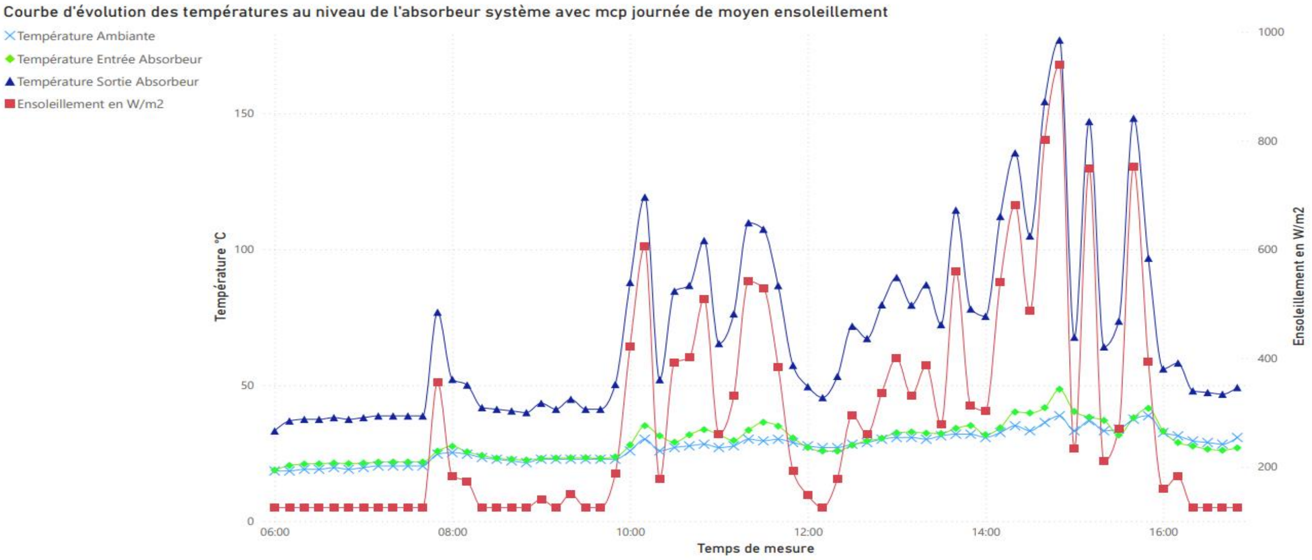

Figure 3. Temperature evolution curves for the absorber during a day of moderate sunlight with MCP

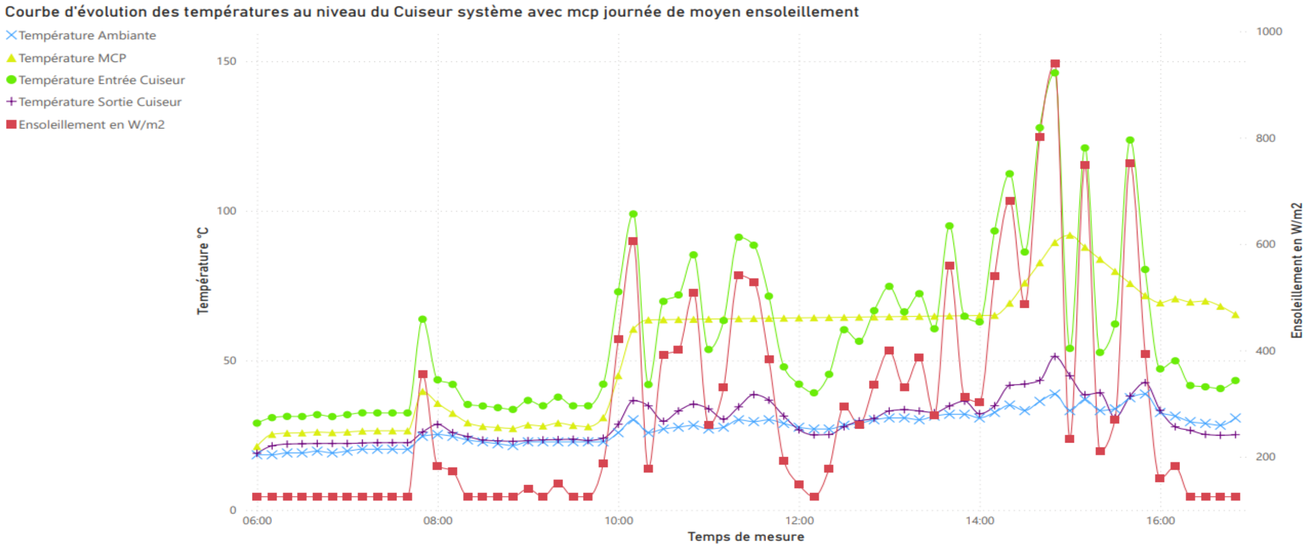

Figure 4. Temperature evolution curves for the casserole during a day of moderate sunlight with MCP

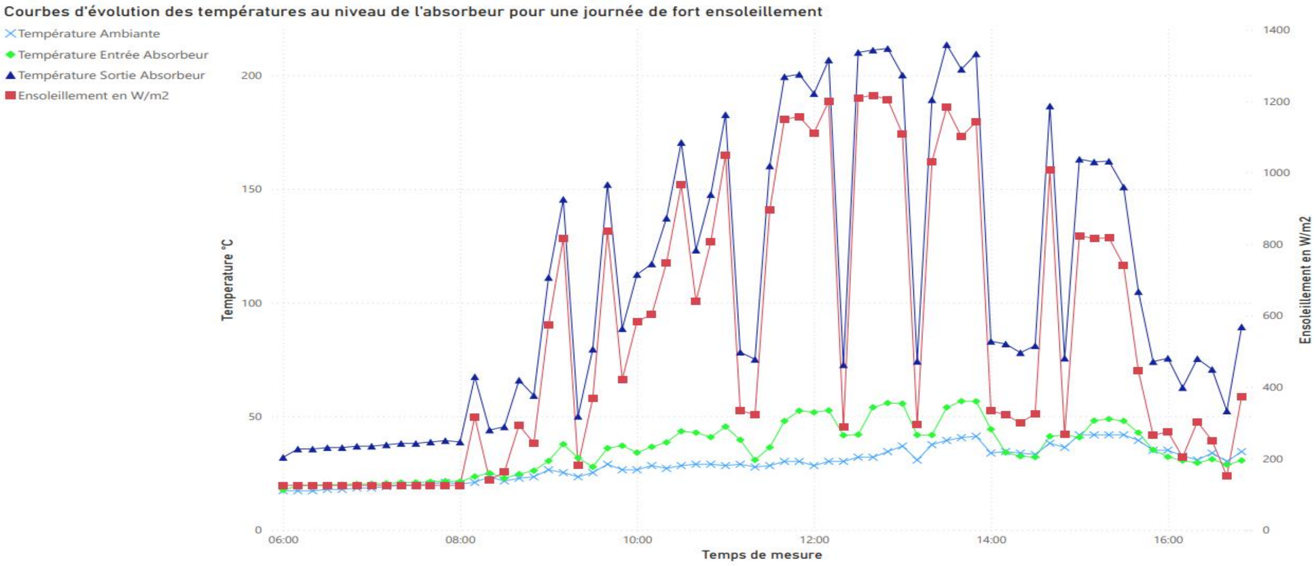

Figure 5. Temperature evolution curves for the absorber during a day of high sunlight with MCP

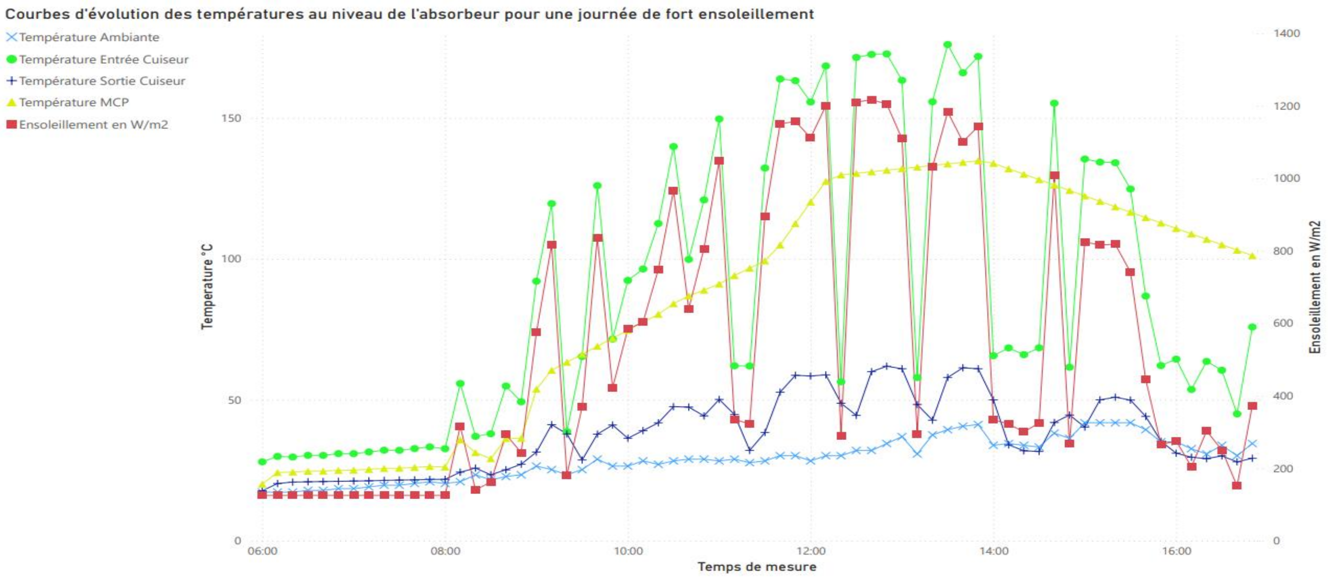

Figure 6. Temperature evolution curves for the casserole during a day of high sunlight with MCP

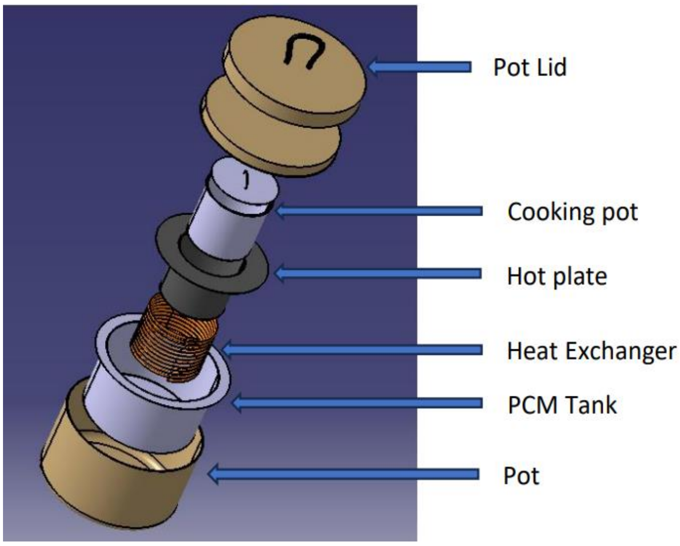

Figure 7. Exploded diagram of the cooking pot [18]

Figure 8. Different components of the final device: 1. Cylindrical-parabolic concentrator, 2. Cooking pot, 3. Heat exchanger, 4. Fiberglass, 5. PCM (phase change material)

Figure 9. Final device

3. RESULTS AND DISCUSSION

3.1 Results

After sixteen (16) days of data collection, three representative days were selected for plotting the curves based on solar irradiation levels. These days are as follows:

- Aug. 3, 2023: Moderate sunlight (3021Wh/m²/day);
- Aug. 4, 2023: Low sunlight (2649Wh/m²/day, with fog);
- Aug. 6, 2023: High sunlight (5575Wh/m²/day).

The parameters measured for each of these days include ambient temperature (Ta), absorber inlet temperature (TEab), absorber outlet temperature (TSab), cooking pot inlet temperature (TEc), cooking pot outlet temperature (TSc), PCM temperature (Tm), and solar irradiance. We will analyze the overall temperature trends for each of these days.

Low sunlight: The curves show a slower temperature rise with lower peaks, reflecting the reduced amount of solar energy captured and stored by the system.

Moderate sunlight: A faster temperature rise and higher peaks compared to the low sunlight day indicate improved performance of the cooker.

High sunlight: Temperatures reach high peaks quickly, demonstrating the system's maximum efficiency under optimal sunlight conditions.

3.2 Discussions

3.2.1 Comparative analysis of the curves

Absorber vs. cooking pot: The comparison of temperatures between the absorber tube and the cooking pot highlights the efficiency of heat transfer in the system. The temperature difference between these two components is a key indicator. A significant gap could indicate thermal losses or inefficient heat transfer. In our study, the outlet temperature of the absorber reached a maximum of 213.52°C at 1:50PM with solar irradiance of 1143Wh/m², demonstrating effective heat transfer to the cooking pot.

PCM (phase change material): The PCM temperature is crucial for understanding how the system stores and releases heat. During the tests, the PCM temperature stabilized around its melting point [16], indicating that the material efficiently stored the captured heat during the day. This storage allows the system to maintain sufficient cooking temperature even when sunlight decreases later in the day. For example, the PCM temperature reached 134.81°C on August 6.

3.2.2 Curve shape analysis

Gaussian shape: The temperature curves of the absorber and the PCM display a typical Gaussian shape, with a performance peak around midday. This shape indicates the system's optimal operation in response to the natural variation of sunlight. The energy stored during the day is then gradually released in the evening, as shown by the PCM temperature curve.

Plateaus: The plateaus observed in some curves (PCM curve) suggest that the system has reached a temporary thermal equilibrium, where the heat generated equals, the heat dissipated. This reflects the system's stability, particularly during periods of strong sunlight.

3.2.3 Implications for cooker efficiency

Performance under different sunlight conditions: The results show that under strong sunlight, the cooker reaches adequate temperatures for cooking various foods, such as rice, potatoes, and lentils, with cooking chamber temperatures ranging from 68°C to 110°C. However, under low sunlight, the temperatures reached are lower, which may not be sufficient for certain types of cooking, highlighting the importance of the PCM to extend cooking times into the evening.

Comparison with literature: Our results are comparable to those obtained by other researchers who also observed high performance under similar conditions [19, 20]. For example, Kumaresan et al. [19] achieved a good maximum temperature in their indirect solar cooker through an experimental investigation of the discharge phase of a dual-stage mode indirect solar cooker. The storage tank contained a heat transfer fluid (Therminol 55 oil) and 126PCM balls (D-Mannitol). It was powered by a parabolic trough collector, and they achieved a maximum temperature of 152°C inside the cooking pot after 15 minutes of operation.

We can also cite the work of Haraksingh et al. [20], who achieved a maximum temperature of 130°C and 144°C under load conditions for two pots in their cooking unit. It should be noted that the thermal fluid used was coconut oil. These comparisons strengthen the validity of our approach and show that the integration of PCM in the solar cooker offers competitive performance.

Limitations and weather conditions: The day of August 19, marked by heavy fog, demonstrated the system's limitations under low sunlight conditions. Although the thermosiphon system operated correctly, the temperatures remained low, underscoring the need for improvements for unfavorable weather conditions.

4. CONCLUSION

This work successfully designed and developed an indirect solar cooker incorporating a phase change material (PCM), polypropylene, and 40% glycol-water as the heat transfer fluid. The experimental results were satisfactory, with maximum measured temperatures of 213.52°C at the absorber and 134.81°C for the PCM. These temperatures enable cooking of various foods both during the day and in the evening, with the PCM temperature maintained at 101.16°C by the end of the day.

The main conclusions of this study are as follows:

- The indirect solar cooker was successfully designed and constructed.
- Measurement tests were conducted, and the temperatures obtained were compared to those reported in previous studies, confirming the system's efficiency.
- Thermal parameter evolution curves were plotted, allowing for a detailed analysis of the cooker's performance.

The comparative analysis of the curves highlights the importance of sunlight intensity on the solar cooker's performance. Higher sunlight allows the system to capture and store more thermal energy, making the PCM more effective in maintaining an adequate cooking temperature. However, in regions where sunlight is often low, the efficiency of the cooker may be compromised.

To improve the solar cooker's performance under low sunlight conditions, several avenues can be considered:

- Improving the thermal storage system by optimizing the cooker design or using PCMs with thermal properties better suited to varying sunlight conditions.
- Adding additional heat capture devices through the

integration of extra solar concentrators or hybrid systems to compensate for periods of low sunlight.
- Further research could explore the use of different heat transfer fluids or new materials to enhance the overall performance of the solar cooker.

ACKNOWLEDGMENT

We would like to thank the Energy Engineering Laboratory of INP-HB, the colleagues who assisted in writing this document, as well as the organizers of the ECRES conference. They have been the gateway through which the scientific community records a new article.

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