Phase change materials for energy storage in solar box cooker: Sustainable innovations in energy technology

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Abstract

The use of solar energy for cooking offers an alternative source of energy to the high cost of petroleum products and the diminishing wood fuel products for cooking and heating applications. Kenya is located on the equator and receives a daily insolation of 4-6kWh/m^2 hence most areas can be considered as having high potential for solar energy utilization. Most of the solar cooker designs do not have thermal storage systems and can only be used for cooking when there is sunshine and cannot be used during cloudy weather or in the evening. The aim of this study was to design and assess the performance of a double reflector solar box cooker with an energy storage unit. The use of phase change materials (PCMs) as a technique of storing energy was used to overcome the time mismatch between solar availability and demand. The PCM used is acetanilide with a melting point ranging from 113°C to 116 °C. The box cooker was designed so that the length to width ratio for the reflector and the glass window was 4:1. This eliminated the azimuth tracking towards the sun. Three sets of experiments were carried out at the School of Engineering and Technology Demonstration Centre, Kenyatta University. The first without loading the cooking pot of the cooker, the second with water as the cooking load and the third with different actual cooking loads. The measured parameters included, the solar radiation, ambient air temperature, temperatures of the different components of the solar cooker, load temperature and wind speed. The data values were read and recorded by use of a data logger at regular intervals of 10 minutes. Data analysis was done using statistical measures. An average stagnation temperature of 85.9 ± 24.0 °C and 82.7 ± 24.3 °C was achieved in the two pots. The average solar radiation was 637.1 ± 212.0 W/m^2. The cooking power tests achieved a coefficient of performance of 0.754. The results showed that the double reflector solar cooker with energy storage can be used to cook meals throughout the day and in the evening. Noon cooking does not affect evening cooking. The adoption of this study will be beneficial to Kenyans as it will increase the acceptability of the solar cookers hence reduce the consumption of wood fuel and petroleum products. This will reduce the rate of depletion of wood resources, and provide a clean environment devoid of hazardous emissions associated with wood and fossil fuel combustion.

Keywords - Clean environment, Energy storage, Phase change material, Solar box cooker.

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1.0 INTRODUCTION

Energy consumption for cooking in developing countries is a major component of the total energy consumption, including commercial and non-commercial energy sources [1]. (Sharma *et al*. 2008). Woodfuel in Kenya is the most important source of energy. More than 70% of Kenya′s energy is directly supplied by fuelwood or charcoal [2]. Wood energy is becoming scarce and more expensive and is of great concern since the depletion of forests leads to serious consequences such as soil erosion, floods and desertification [3]. Hence there is need to use alternative sources of energy and solar energy appears to be the most promising resource, in terms of both immediate availability and existing technology. It is free, safe, and the most environmentally clean of all energy. It has no pollution [1].

Kenya is located along the equator. It lies between latitudes 5^{o}N and 4.5^{o}S and longitudes 34^{o}E and 43^{o}E of the Greenwich meridian [4] . It thus receives solar irradiance of between 4 and 6 kWh/m^2/day. The country's annual average is about 5 kWh/m^2/day, equivalent to 250 million tonnes of oil equivalent (Toe) per day [5]. Direct solar cookers use solar radiation directly in the cooking process, while the indirect solar cookers use solar radiation to heat thermal fluids that transport heat to the place of the cooking process [6]. The simplest type of solar cooker is the box cooker first built by Horace de Saussure in 1767. A basic box cooker consists of an insulated container with a transparent lid. These cookers have been used effectively with partially overcast skies and will typically reach temperatures of 150^{o}C [7].

Solar energy is intermittent by its nature and at night there is no sunshine. Unreliability is the biggest retarding factor for extensive solar energy utilization [1]. The application of solar cookers is restricted if they are not equipped with energy storage system since it is impossible to use solar energy in cloudy conditions, evenings and at night [8]. Energy storage may be in form of sensible heat of a liquid or solid medium, as heat of fusion in chemical systems, as chemical energy of products in a reversible chemical reaction and as latent heat using phase change material (PCMs) [9], [10]. PCMs have a high thermal energy storage capacity. They store large amounts of energy while changing from the solid to liquid phase and release the energy while changing from liquid to solid phase at a particular temperature. Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of the energy systems and plays an important role in conserving energy.[10].

In this paper a solar box cooker with two reflectors and latent heat storage unit was investigated.

2.0 DESRIPTION OF THE SOLAR COOKER

In this study a solar box cooker with two reflectors and an energy storage unit using phase change materials, was designed, constructed and tested. The whole system consists of a rectangular double walled box, a storage unit, cooking unit, reflectors and a double glass cover. Figure1 show the experimental set up of the solar box cooker with reflectors and pots in place.

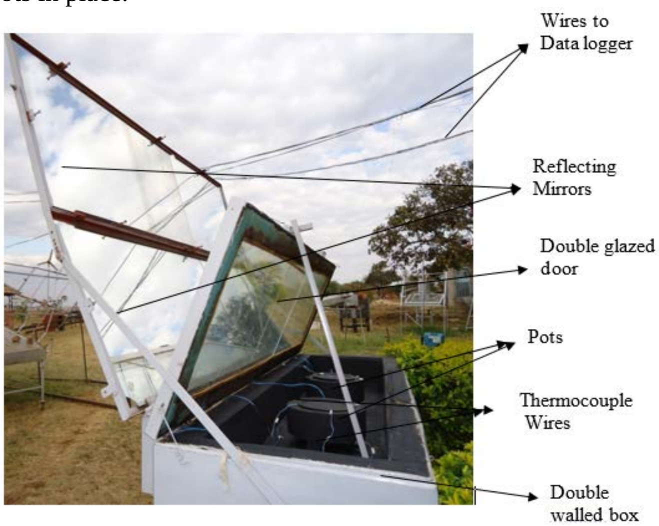

Figure 1: Photograph of experimental set up

In order to attain cooking temperature at the solidifying point of the PCM at 6.00pm the energy released by the PCM and the food should be equal to the energy loss from the cooker as given in the following equation,

$$M_f C_w (T_f - T_m) + M_{PCM} (T_{PCM} - T_m) + M_{PCM} L = U_L A (T_f - T_A) \Delta t$$

[11] **(**1)

The storage unit has two concentric black sheet metal cylinders of diameters 30cm and 20cm with a depth of 10cm and 2mm thickness. The space between cylinders was filled with the PCM. The cylinders were painted black on the inner and outer sides. (See Fig 2)

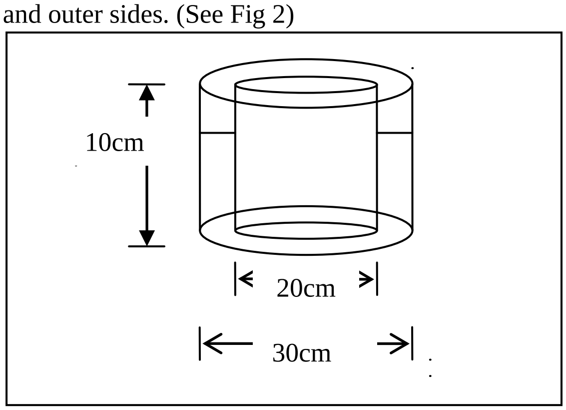

Figure 2: Phase change material storage unit

Generally, phase change materials have a positive volumetric expansion on melting therefore, the storage unit catered for an extra volume [12]. Two storage units were loaded onto the box cooker one with PCM and one without. The storage unit was placed on lugs to lift it above the floor of the box cooker. This provides more surface area and, hence, makes the heat transfer more effective [13],[14]. Two small holes about 2 mm diameter were drilled on the top side of the PCM storage unit through which the thermocouple wires were passed through to take the temperature of the PCM. Another hole 1.5cm diameter was drilled on the top side of the PCM storage unit through which the PCM was put and later was fitted with an overflow pipe in case of PCM overflow. The cooking pot was designed to fit into cylindrical space. Figure 3 shows the photograph of PCM storage unit.

Figure 3: Photograph of Phase change material energy storage unit

In this study commercial grade acetanilide was used. Its melting temperature is 118^{0}C and is available in the market. 3kg of PCM was put in the storage unit. The energy stored by the PCM is given by;

$$Q_{stored} = M_{PCM} (C_{PCM} (T_M - T_a) + L + C_{PCM} (T_{PCM\,max} - T_m \quad (2)$$

3.0 EXPERIMENTAL PROCEDURE

Tests were conducted under various weather conditions from September 2010 to January 2011. The measured parameters included temperature, solar irradiance and the wind speed. The cooking power tests were done according to ASAE, [15] and [16] Standards. All the measured parameters were recorded at intervals of ten minutes using FLUKE 2286 series data logger. At the end of the day the data was retrieved from the data logger and entered into an Excel spreadsheet.

3.1 The Stagnation Temperature

The stagnation temperature gives an understandable figure for the maximum possible temperature achievable by the cooker under a specified set of conditions. This was conducted using dry empty cooking pots. The temperature of the absorber plate (ABST), the pot container temperatures (PT_1) and (PT_2), and the food temperature (FTP_1) and (FTP_2) (the pots were empty) were recorded at intervals of 10 minutes using the thermocouples

3.2 The Cooking Power

The effective cooking power was used as the primary figure of merit to represent thermal performance for the box cooker. The test was conducted according to the American Society of Agricultural Engineers ([15] and The International Standard Procedure for Testing Solar Cookers and Reporting Performance [16]. All tests were performed under clear sky conditions and measurements were recorded at intervals of 10 minutes. The tests were conducted between 10:00 and 14:00 solar time as recommended [16].
Each of the two pots contained 1 ± 0.001 kilogram of water. Thermocouple junctions were immersed in the water pots and secured 10mm above the pot bottom at the centre [15] and [16]. The water temperature (°C), ambient temperature (°C) and insolation were measured and recorded every 10 minutes.

3.3 Evening Cooking Test

During the evening cooking, the solar cooker was exposed to solar radiation from 10.00am to 16.00pm. At 16.00pm the temperatures of the pots were recorded. The pots were then loaded each with food 0.5 kg rice + 1.0 kg of water at 16.00 pm. The food temperature was sensed with thermocouples. Thermocouple junctions were immersed in the food in the pots and secured 10mm above the pot bottom at the center [15] and [16]. Solar radiation and ambient temperatures were also recorded during the experiment on different days from 10.00 am to 20.00pm at intervals of 10 minutes

4.0 RESULTS AND DISCUSSION

4.1 Stagnation Temperature

The stagnation air temperature inside the cooking pots was recorded for cooker with PCM and compared with the one without the PCM. Figure 4 illustrates the variation of the stagnation temperatures with time without the cooking load. . The solar radiation reaches a maximum of 800 W/m^2 around 13.00 solar time. The temperature rise was slightly faster in the cooker without the PCM compared to the one with the PCM up to around 14.00 solar time after which it drops faster than the one with the PCM. This is due to the fact that the PCM takes in some energy in form of sensible heat to raise its temperature. When it reaches its melting point this energy is stored as latent heat as it melts. The temperature of the pot without the PCM heats up faster and reaches a maximum of 122°C because it doesn't have a load to heat. This can be attributed to the fact that the energy stored in the PCM does not reduce when the solar radiation decreases but is decreases slowly as it is released when the PCM solidifies. This figure of merit is useful for determining alternative materials for construction of the cooker and also dictates the type of cooking that can occur (flying, baking or boiling).

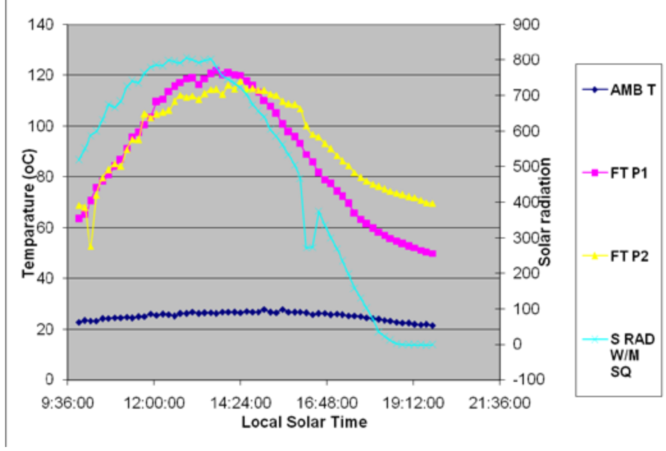

Figure 4: Variation of stagnation temperatures in pots P1 and P2 with local solar time and solar radiation

4.2 Cooking Power

The effective cooking power was used as the primary figure of merit to represent thermal performance for the box cooker. The test was conducted according to the American Society of Agricultural Engineers [15] and The International Standard Procedure for Testing Solar Cookers and Reporting Performance [16] All tests were performed under clear sky conditions and measurements were recorded at intervals of 10 minutes. The tests were conducted between 10:00 and 14:00 solar time as recommended [16]. This is because the solar zenith angle is constant at midday and the difference between insolation measured in the plane of the cooker aperture and the plane perpendicular to direct beam radiation is minimum. Each of the two pots contained 1 ± 0.001 kilogram of water Thermocouple junctions were immersed in the water pots and secured 10mm above the pot bottom at the centre according to [15] and [16]. Standards. The water temperature (°C), ambient temperature (°C) and insolation were measured and recorded every 10 minutes. At the end of the day the data was retrieved from the data logger and entered into an Excel spreadsheet.
The average water temperature (°C) average ambient temperature (°C) and average insolation were measured and recorded every 10 minutes. The Cooking Power P was given by equation 3.3 as follows:

$$pi = \frac{(T2 - T1)MCv}{600}$$ [15] and [16].

(3)

Where; Pi = cooking power (W)
T_1 =Initial water temperature (°C)
T_2 = Final water temperature (°C)
M =Mass of water (kg)
C_v =Specific heat capacity of water (4186 Jkg^{-1}K^{-1})

The sensible heat gain in a cooking pot is the best measure of the cookers ability to effectively cook food. The cooking power $P_{i,}$ is standardized to a figure of 700W/m^2 through equation 3.4 as follows:

$$P_S = P_i(700/I) \quad (4)$$

Where; P_s = Standardized cooking power (W)
P_i = Interval cooking power (W)

I = Interval average solar insolation (W/m^2)

The temperature difference T_d is given by equation 3.5 as follows:

$$T_d = T_w - T_a \quad (5)$$

Where;

T_d = Temperature difference (°C)
T_w = Water temperature (°C)
T_a = Ambient temperature (°C) [15] and [16].

According to [16], the heat loss increases with the difference in temperature between the solar cooker interior and the cooker's surroundings. The standardized cooking power (W) was plotted against the temperature difference (°C) for each time interval and a linear regression on all data points obtained. The regression line was used to determine the relationship between the cooking power and temperature difference according to the equation:

$$P_s = a + bT_d \quad \text{[15] and [16].} \quad (6)$$

Where:
Ps = standardized cooking power (W)
a = Y intercept (W)
b = slope (W/°C)
T_d = Temperature difference (°C)

Regression analysis was used to obtain the values of *a* and *b*. t-statistics was used to obtain the coefficient of determination (R^2) [15] and [16]. This is the proportion of variation in cooking that can be attributed to the relationship found by the regression. The value for standardized cooking power (W) was computed for a temperature difference of 50 °C. According to [15] and [16] this single measure of performance provides insight as to the cookers ability to cook food and is used by consumers as a tool for comparison and cooker selection. Data values for the standardized cooking power are presented in Table 1.

Table 1: Comparison of the pot's performance on different days. (Pot P_1 without PCM and Pot P_2 with PCM

Solar cooker Pot	Date	Cooking power Regression equation		Adjusted cooking power (W) at 50°C ΔT	R^2	Average ambient temperature (°C)	Average Solar radiation (W/m2)
Pot P_1	28-09-10	51.03	-0.533	25	0.621	24.9 ± 1.4	650.1 ± 91.6
Pot P_1	19-10-10	59.48	-0.665	27	0.741	24.0 ± 1.0	739.3 ± 94.1
Pot P_1	18-12-10	55.09	-0.557	26	0.555	24.7 ± 1.4	695.7 ± 91.6
Pot P_1	26-01-11	46.17	-0.543	25	0.551	25.8 ± 2.0	756.0 ± 101.5
Pot P_2	28-09-10	46.65	-0.484	23	0.437	24.9 ± 1.4	650.1 ± 91.6
Pot P_2	19-10-10	63.53	-0.666	30	0.659	24.0 ±1.0	739.3 ± 94.1
Pot P_2	18-12-10	52.69	-0.495	27	0.378	24.7 ± 1.4	695.7 ± 91.6
Pot P_2	26-01-11	52.59	-0.531	25	0.516	25.8 ± 2.0	756.0 ± 101.5

Table 1 shows the regression equation coefficients and the standardized cooking power for the two pots P1 and P2 on different days. The Y-intercepts represent the initial cooking power which depends on the average solar radiation, cooker design as well as the wind speed. The slope of the cooking power regression line correlates to the heat loss coefficient. The slope and the intercept values are independent of each other [16]. The slopes of the cooking power regression line are almost the same on the same day because the two pots are subjected to the same factors as shown in figure 5. The regression line coefficients and standardized cooking power at 50°C for each cooker and date are presented in Table 1. Pots P1 without the PCM recorded higher coefficients of determination R2 than pots P2 with the PCM. This can be attributed to the fact that the pots with the PCM require more heat to heat the PCM to raise its temperature to its melting point as well as the water. The data in table 1 was recorded within a period of about 2 hours which can only give 12 observations. This explains the reason why coefficient of determination is lower than the recommended value of 0.75 and above according to the (ASAE) standards. The number of observations should be 30 and above. This is done by combining observations from at least three days [15] and [16].

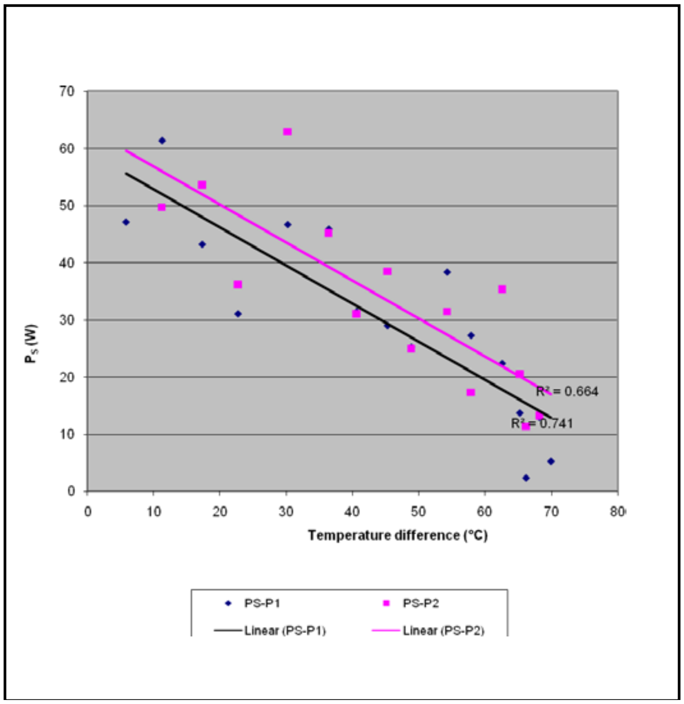

Figure 5: Comparison of cooking power curves for different pots (P1 & P2) on the same day

The combined standardized cooking power Ps (W) was plotted against the temperature difference T_d (°C) for a typical clear day is shown in Figure 6. The initial cooking power is indicated as the Y-intercept with a value of 60.85W. The regression line equation is:

$$Y = -0.700x + 60.85$$

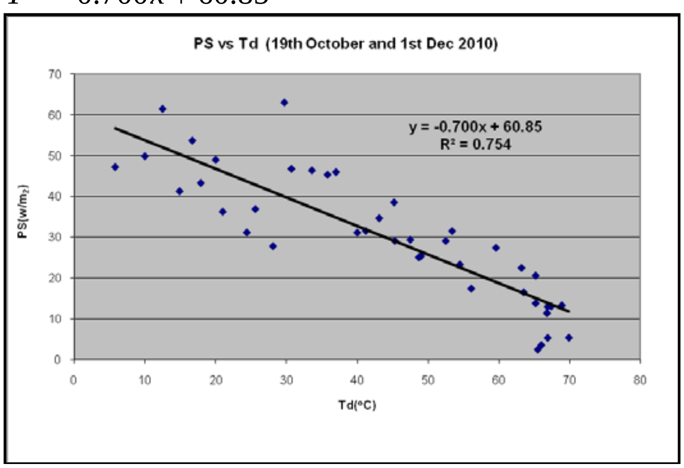

Figure 16: Variation of combined standardized cooking power with temperature difference

The slope of the cooking power regression line correlates to the heat loss coefficient independent of the solar intercept area (sum of the reflector and aperture areas projected onto the plane perpendicular to direct beam radiation. The linear regression coefficient of determination R^2 =0.754. The recommended regression should be higher than 0.75 [15] and [16]. The experimental value satisfies the standard. The cooking power at a temperature difference of 50°C was 26W. This single measure of performance is a useful tool for comparison of different designs of solar cookers. Therefore, the standard cooking power figure of merit gives the insight as to the cooker's ability to cook food and allows for comparison with device tested under the same conditions

4.3 Evening Cooking

During the evening cooking the solar cooker was exposed to solar radiation from 10;00am to 16.00pm At 16.00pm the temperature of the pots were 117.6°C for the pot in the PCM cooking unit and 103.6°C for the pot in the cooking unit without the PCM. The pots were then loaded with food 0.5-kilogram rice and I kilogram water. Figure 20 shows the temperature profile of the food in the two pots. The initial temperature of the contents was 24°C. The temperature of the food in the pot in the PCM unit rose to a maximum of 91°C while in the unit without the PCM; the maximum food temperature was 53.8°C. At 18.00pm the food in the PCM cooker was well cooked while that of the cooker without PCM was not cooked. The energy stored in the PCM as it melted was released during the cooking process. According to [6] the lowest temperature for cooking most kinds of food is about 75°C.

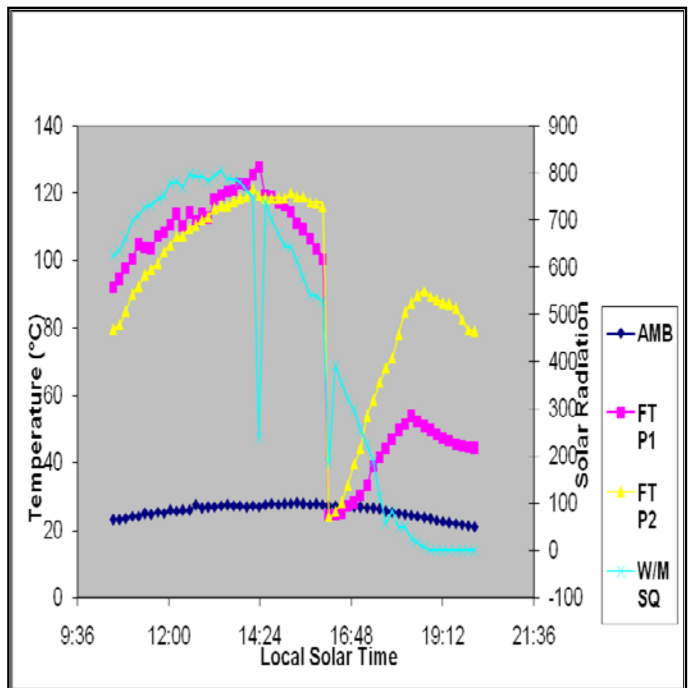

Figure 20: Variation of Food temperatures (FT P1 & FT P2) with Local Solar Time and solar radiation

5.0 Conclusion

The stagnation temperature and the cooking power are measures of performance and useful tool for comparison of different designs of solar cookers. The standard cooking power figure of merit gives the insight as to the cooker's ability to cook food and allows for comparison with devices tested under the same conditions. From the experimental study the following conclusions have been drawn;

Noon cooking does not affect the evening cooking, therefore, two bunches of cooking can be done. One during the day and the other one in the evening

-A solar box cooker with phase change materials can be adopted for cooking in the cloudy weather and in the evening. From the result obtained in this study the adoption of the Solar cooker with storage unit will help in conservation of conventional fuels such as firewood, charcoal, LPG, kerosene, and electricity. The use of the solar cooker would reduce the release of CO_2 in the environment.

-Further work need to be carried on the PCMs to come up with the suitable ones for use in solar cookers. The cost of the PCM is quite high. This makes the application of PCM in solar cookers out of reach to ordinary people. More research needs to be carried out to come up with latent heat storage materials at affordable prices.

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