

*Research article***Design and experimental investigation of solar cooker with thermal energy storage****Muluken Biadgelegn Wollele^{1,2,*} and Abdulkadir Aman Hassen¹**

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Abstract: Solar cookers can be of great use in saving fuel and enabling in eco-friendly cooking of food. Solar energy is available during daytime only and also intermittent. So, thermal energy storage is very important for indoor solar cooking requirements and will ensure continuity utilization. The overall system is designed theoretically to cook 1 kg of rice in 45 minutes requiring the power of 421 W which is obtained from the stored energy from the sun. As it is shown in the experimental result, due to so many losses, the energy transfer to the water reduced to some extent and its temperature reaches 355 K. Even if it has low energy, it is possible to reduce energy of TES to the surrounding by placing it in the insulated tank during discharging. However, there is a variation between experiment and analytic calculation because the model did not account the basic losses and variation of solar radiation. The discharging of TES is started after it is lifted from solar collector but immediately it is placed on the insulated tank and loaded by the pot with water. Thus, the maximum temperature of water reached after 40 minutes is 355 K.

Keywords: solar collector; solar cooker; thermal energy storage (TES)

1. Introduction

The world has major industrial development and population growths have caused a major increase in energy demand. Energy is very important in the generation of wealth and the main factor in economic development [1]. The main energy demand of population was mainly covered by the

source of fossil fuels. Other factors such as global warming and environmental problems have pushed the scientific research and technological development to find new energy solutions based on the use and diversification of energy resources efficiently. From the new resources, renewable energy is considered as the engine of development of new generation on the horizon for the coming decades [2].

Cooking is one of the most important and necessary household work in every society of the world. In most of rural areas of the developing countries; cooking is usually done in open fires fueled by fire-wood. In the cities, stoves are more common and fueled by wood, charcoal, kerosene and sometimes flue gas. In many regions of the developing world including East Africa, oil fuels are expensive, and wood-based fuels are becoming increasingly scarce.

Moreover, combustion of fuel and wood release carbon dioxide (CO₂), other greenhouse gases and pollutants that have contributed to environmental problems such as global warming, air and water pollution and other damage to earth eco-system.

Renewable energy technologies produce marketable energy by converting natural phenomena into useful forms of energy. Therefore, the sun is one of renewable energy and source of life on the earth, but at the same time, it is a “free” source of energy forms any systems using this resource to power a process [3]. Therefore, solar energy is the major part of renewable energy which is radiant light and heat from the sun harnessed using a range of technologies such as solar heating, solar photovoltaic, solar thermal electricity, solar architecture and artificial photosynthesis [4].

Solar energy is one of the best ways of reducing the use of non-renewable resources [5]. Solar thermal energy is a solar energy source widely used worldwide [6]. The solar energy is converted to thermal energy by solar collectors.

A solar cooker is a device which uses direct sun rays (which are the heat from the sun) to heat and cook. The solar cooking which saves a significant amount of conventional fuels is the simplest, safest, clean, environment-friendly, and most convenient way to cook food without consuming fuels or heating up the kitchen [7,8].

However, solar energy is available during only daytime and intermittent. This is main limitation of solar energy for solar energy applications. Thus, food is required all over the day. Therefore, solar energy storage is used to alleviate the mismatch between solar heat energy supply and energy demand for cooking. Thus, this paper conducts the design and experimental investigation of solar cooker with heat storage.

1.1. Solar cooker with thermal energy storage

It is usual that solar radiation is an inherently time-dependent energy resource, storage of energy is essential to meet energy needs at morning and evening or during daytime periods of cloud cover. Generally, the choice of storage media depends on the end use of the energy and the process employed to meet the cooking. The capacity of the storage device for a given solar process depends on the time of the solar availability, the nature of the load, the cost of auxiliary energy, and the price of the process components [9].

Schwarzer K, et al. [10] conducted a performance analysis of flat plate type solar cooker with vegetable oil as the TES material. They designed flat plate collector, the heated TES naturally conducted upwards. After several experiments, it is found that oil is a good material as the heat storage material.

Mussard M. [11] carried out a low cost small-scale solar concentric collector coupled with a thermal energy storage unit for higher temperature cooking. The system is built without pump (self-circulation) and uses thermal oil. He compared different types of heat storage materials and concluded that latent heat-based system is relevant. He also concluded that the heat storage mainly based on thermal oil is more efficient than on aluminum crossed by thermal oil channels.

Senthil R. et al. [12] proposed that the sensible heat transfer materials were found effective in the storage of heat as well as aiding conduction heat transfer during the cooking process. The near spherical-shaped solid materials can provide better conduction heat transfer. They compared stone pebbles and sun flower oil for heat storage. It is concluded that stone pebbles have high efficiency due to its higher specific heat, whereas sunflower oil in better performance because of its high density and high specific heat capacity compared to other oils.

Sharma SD. et al. [13] had investigated a solar cooker based on an evacuated tube solar collector coupled with phase change material (PCM) commercial grade erythritol. They conducted boiling tests after charging the PCM till temperatures of 130 °C. However, the authors concluded that the ratio of the storage energy to the solar intensity was low and the system was considered expensive for the low-income peoples.

Schwarzer K. et al. [10] conducted several types of a solar cooker, with and without heat storage. The system uses thermal oil as HTF and heat storage device without circulating pump in copper pipes. The pipes are extended till a wall to allow for indoor cooking. The thermal efficiency was investigated experimentally using a water boiling test and was found to be about 40%.

Saxena A. et al. [14] studied several types of PCMs to check their suitability as heat storage for cooking purposes using a box type solar cooker. Authors investigated solar cooker with and without thermal storage. The Performances of the two solar cookers were carried out using stagnation temperature tests and water boiling tests during cooking. And it is concluded that, solar cooker with TES showed good performance.

Mussard M. et al. [15] carried out a comparative investigation on direct cooking with the SK14 solar concentrator and an indirect cooker with a parabolic trough solar concentrator system with naturally circulating TES (oil) from the absorber to Solar Salt TES. The thermal efficiency comparison was conducted with a water boiling test and a meat frying test.

Furthermore, different authors have studied different solar cookers with different thermal energy storage. Now this paper conducted compound parabolic solar collector for cooking purpose with oil and rock as heat storage. Thus, cooking is indoor cooking and the main difference of this cooking from the above literature is that an absorber with thermal energy storages is placed on the focal point of the two dishes until an absorber store enough thermal energy for cooking. Then after an absorber is removed from the solar collector and placed within insulating material inside the kitchen for cooking. Therefore, this is used to remove the extra materials need like a pump, motor and circulating insulated pipe which reduces the cost of the overall system and losses of heat energy in the pipe and pump.

2. Materials and methods

2.1. Sizing and thermal analysis of parabolic solar concentrator

Solar cooker has compound parabolic dish concentrator and thermal energy storage (oil and

rock) on absorber to increase the duration of effective temperature period and store thermal energy for night cooking without any tracking mechanism.

The mode of cooking is indoor cooking; as shown in Figure 1, an absorber with thermal energy storages is placed on the focal point of the two dishes until an absorber store enough thermal energy (from 9: 00 am to 3: 00 pm) for cooking. Then after an absorber is lifted from the solar collector and placed within insulating material inside the kitchen for cooking.

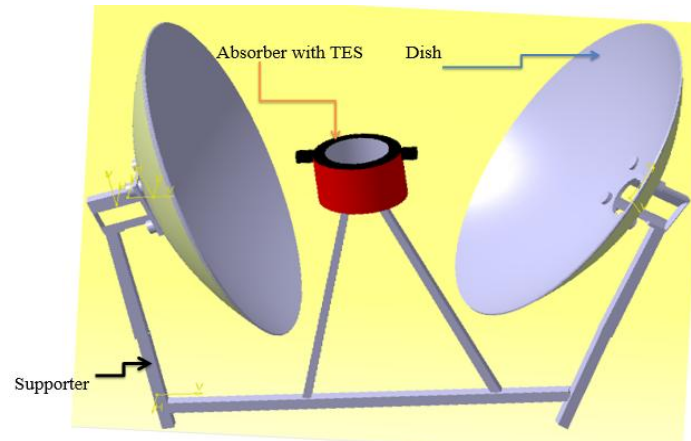


Figure 1. 3D drawing of overall system.

This research is conducted to demand the heat energy of cooker to cook 1 kg of rice at a time. In cooking process, the optimum ratio of rice to water by volume is 1 to 2 [16,17]. Therefore, the volume of water (V_{w1}) required for cooking and the volume of rice (V_{r1}) is given by:

$$V_{w1} = 2 V_{r1}; V_{r1} = \frac{m_{r1}}{\rho_{r1}}$$

The overall volume of food (V_{f1}) to be cooked is:

$$V_{f1} = V_{r1} + V_{w1} \quad (1)$$

Again the total mass of food to be cooked (m_{f1}) is: $m_{f1} = m_{r1} + m_{w1}$; where m_{r1} = mass of rice to be cooked and m_{w1} = mass of water required for cooking. After the rice is cooked, the volume of rice V_{f2} (including water) expands from 3.2 to 3.5 times the volume of uncooked rice [18,19]. An average factor of 3.35 is taken for this study. Therefore, $V_{f2} = 3.35 V_{r1}$. It is expected that the amount of water lost is proportional to the amount of water required. Thus, the amount of water lost during cooking is assumed 10%. Therefore, the mass of water, m_{r2} = remaining in the cooked food is:

$$m_{w2} = 0.9 m_{w1} \text{ and mass of water lost; } m_{r2} = m_{w1} - m_{w2}$$

Therefore, the internal volume of the cooking pot = the volume of the food after cooking. For optimum design the internal diameter of pot and internal height of pot is equal.

$$\frac{\pi D_{in,pot}^2}{4} \times H_{i,pot} = V_{f2} \quad (2)$$

Then, the effective surface area of an absorber is:

$$A_{\text{abs}} = \frac{\pi D_{o,\text{abs}}^2}{4} + \pi D_{o,\text{abs}} H_{o,\text{abs}} \quad (3)$$

The useful energy (Q_u) for cooking in one cycle is obtained as:

$$Q_u = Q_{u1} + Q_{u2} \quad (4)$$

Where Q_{u1} : is sensible heat energy required to raise the temperature food to 93 °C and Q_{u2} is the latent heat energy required to convert 0.2458 kg of water at 93 °C to steam.

$$Q_{u1} = (m_{w1} C_{pw} + m_{r1} C_{pr}) (T_{f1} - T_{fo})$$

Where, the specific heat capacity of water and rice is 4186 J/(kg K) and 1552.816 J/(kg K) respectively. The temperature of food raises from (T_{fo}) = 22 °C to T_{f1} = 93 °C, the boiling point of water at Addis Ababa is 93 °C.

$Q_{u2} = m_{w1} \times L_w$; Where, L_w = is the latent heat of vaporization of water. The thermal efficiency is the ratio of the useful energy delivered, to the energy incident at the concentrator aperture. It is given as:

$$\eta_{\text{th}} = \frac{\dot{Q}_u}{A_{\text{ap}} I_b} ; (I_b \text{ is from Addis Ababa, Ethiopia solar radiation})$$

The incident solar radiation consists of the beam and diffuse radiation. However, the majority of solar concentrating collectors can use only beam radiation. The thermal efficiency range of most solar concentrators is 40–60% [20]. Thus, for this study, the average thermal efficiency of 50% is used by considering the optical performance and manufacturing accuracy of the solar collector.

Therefore, the area of an aperture can be calculated as:

$$A_{\text{ap}} = \frac{\dot{Q}_u}{\eta_{\text{th}} I_b} \quad (5)$$

The "concentration ratio" is used to describe the amount of light energy concentration achieved by a given collector [21]. The concentration ratio C is the ratio of the effective area of the concentrator aperture to the area of the receiver and is given as:

$$C = \frac{A_{\text{ap}}}{A_{\text{abs}}} \quad (6)$$

The focal length of the dish is given as:

$$f = \frac{D_{\text{ap}}^2}{16 h} \quad (\text{h: depth of the dish})$$

Basic dimensions of the cooker and design parameters are presented in Table 1 below.

Table 1. Basic dimensions of solar collector.

Parameters	Quantity	Parameters	Quantity
Diameter of pot (D_{pot})	0.1747 m	Diameter of aperture (D_{ap})	1.25 m
Diameter of the absorber (D_{abs})	0.3427 m	Area of aperture (A_{ap})	1.2 m ²
Volume of oil	1.529 liter	Focal length (f)	0.65 m
Mass of rock	0.747 kg		

The solar cooker has two equal parabolic solar collectors and the solar radiations received at the aperture area of parabolic dish reflector are calculated by the formula:

$$I_{ap} = 2 A_{ap} I_b \quad (7)$$

The radiations after falling on the solar dish are reflected at the receiver plate of the dish. Highly reflective Aluminium sheets with a reflectivity of 80% are used. The solar radiation reflected by the dish is given as:

$$I_{RD} = I_{ap} \rho_{ap} \quad (8)$$

An absorber is made up of Aluminium material absorptivity of 85%. Radiation absorbed by the absorber is:

$$Q_{absorbed} = I_{abs} \alpha_{abs} \quad (9)$$

Again, not all energy absorbed at the absorber surface is converted into useful energy. Therefore, temperature gradients between absorber and ambient arise and become a driving force for heat losses; the absorber becomes hotter than the surrounding. As a result, heat losses may occur in different modes (mainly convection and radiation). Since solar absorber is exposed in the moving air so it has convection and radiation heat losses. The ability of the absorber to minimize heat losses is connected to the thermal efficiency of the absorber. The thermal efficiency of the absorber is given by the following expression:

$$\eta_{absorber} = \frac{Q_u}{Q_{absorbed}} \quad (10)$$

From the energy balance equation formulated for the absorber;

$$Q_{absorbed} = Q_u + Q_{loss} \quad (11)$$

The major Heat losses found in the system are the convection and radiation heat losses. The convective heat loss depends upon the coefficient of convection of air. The coefficient of convection

is dependent on the velocity of air. Hence, the heat loss by the convection is higher than radiation heat loss. The heat loss (convection and radiation) from an absorber to the environment is determined as:

$$Q_{loss} = Q_{conv,loss} + Q_{rad,loss} = Q_{absorbed} - Q_u$$

This indicates that only 28.2% of energy is lost to the surrounding by convection and radiation mode of heat transfer from the absorber. The absorbed heat energy on the solar absorber is also given as;

$$Q = m_{abs} c_{p,abs}(T_{av} - T_{amb}) \quad (12)$$

Where T_{av} and T_{amb} are the average temperature of the absorber and ambient temperature respectively and an absorber is made up of Aluminium with density = 2700 kg/m³, specific heat capacity = 0.88 kJ/(kg K) and thermal conductivity 204 W/m °C, Assume that the properties of aluminum do not vary with the variation of the temperature of an absorber.

$$m_{abs} = \rho_{Al} \times V_{abs}$$

For theoretical design the solar absorber is placed on the focus of the two collectors and the system is exposed to solar radiations from 9: 00 am to 3: 00 pm. After 3: 00 pm an absorber is lifted from the parabolic solar collector and placed in the insulator box and loaded for evening cooking. Therefore, the average temperature of the absorber surface is calculated as;

$$T_s = \left(\frac{Q_{abs}}{m_{abs} c_{p,abs}} \right) + T_{amb} \quad (13)$$

Table 2. Analytically calculated parameters.

Parameters	Quantity
Power needed to cook	421 W
Solar radiation received by aperture area (I_a)	862.08 W
Solar radiation reflected by the dish (I_{RD})	689.664 W
Radiation absorbed by the absorber (Q_{abs})	586.21 W
Average minimum beam solar radiation (I_b)	359.2W/m ²
Absorber efficiency (η_{abs})	0.51
Heat loss from absorber (Q_{loss})	165.21 W

This is a surface temperature of an absorber which reaches in 6 hours. However, from this energy 28.2% is lost to the surrounding as the absorber is exposed to air resulting in an absorber efficiency of 51% as presented in Table 2. Therefore, the remaining temperature to be stored on the thermal energy storage and needed for evening cooking is;

$$T = T_s - T_{loss} = 617.1 \text{ K and hence, } T_{left} = 617.1 \text{ K} = 344.1 \text{ }^\circ\text{C}$$

2.2. Heat transfer analysis between an absorber and thermal energy storages

The mode of heat transfers from the outer surface of an absorber to the thermal energy storage and to the cooking pot is conduction heat transfer.

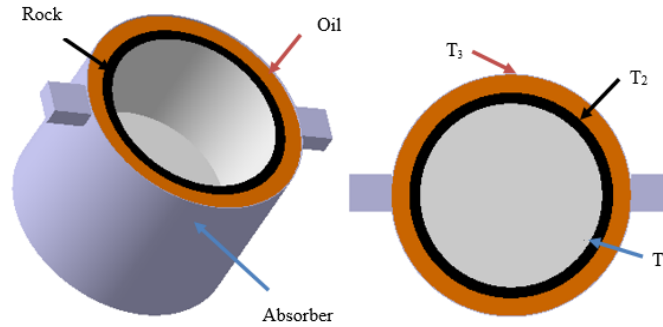
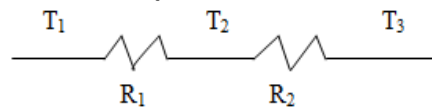


Figure 2. 3D drawing of absorber with TES.

Thermal resistance circuit of the absorber presented in Figure 2 is;



$$R_T = R_1 + R_2 = \frac{\ln (r_3/r_2)}{2 \pi L_{oil} K_{oil}} + \frac{\ln (r_2/r_1)}{2 \pi L_{rock} K_{rock}}$$

Basic Assumptions;

- The flow heat transfer is two dimensional
- Thermal properties of rock and Aluminium did not vary with temperature

Based on the above resistance diagram, the calculated temperatures are presented in Table 3.

Table 3. Analytically calculated temperatures in the absorber.

Parameters	Quantity
Temperature on the absorber surface (T ₃)	617.37 K
Temperature between Oil and Rock (T ₂)	374.57 K
Temperature between the Rock and pot (T ₁)	366 K

The maximum theoretical energy stored in the oil during charging can be expressed as;

$$Q_{\text{TES stored}} = m_{\text{TES}} C_{p,\text{aver}} \Delta T = \rho_{\text{ave}} V C_{p,\text{ave}} (T_{\text{aver}} - T_a) \quad (14)$$

Therefore, 4965.33 KJ of the total energy is stored in TES for six hours.

2.3. Construction of parabolic solar collector and solar cooker with TES

Aluminum with 0.5 mm thickness was selected over steel for the dish construction, due to its lightness, lower cost, energy effectiveness and it has high quality and good specular reflectance with its reflectivity of 85%. In this test, the two dishes are constructed with the diameter of 1 m with a 12 cm depth.

Absorber is also constructed from carbon steel because of its ease of fabrication (welding) and energy effectiveness (thermal conductivity) in use of the material. For this experimental test, 1.5 mm thickness carbon steel is used for an absorber, oil storage and rock storage.

2.3.1. Experimental setup of solar collector and solar cooker with TES

The absorber used for testing and the setup of the overall system used during the experimental work are presented in Figure 3 and 4.

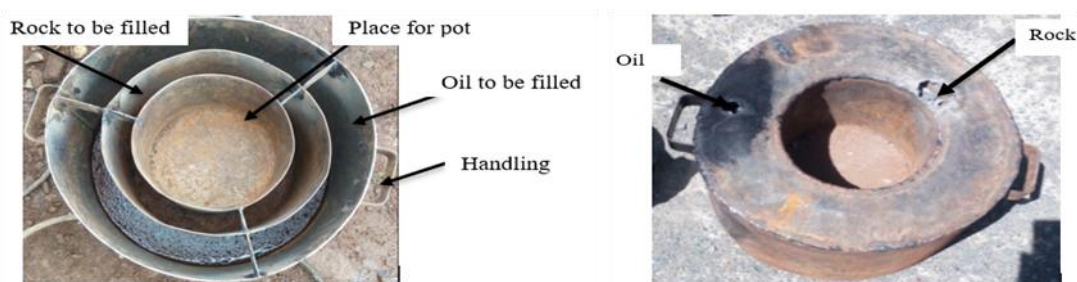


Figure 3. Solar absorber (photograph).



Figure 4. Experimental setup (Photograph). a. Over all system; b. manual tracking of parabolic solar collector.

The test is carried out in Addis Ababa. Thus, the experimental test is involved on September

month in 5 consecutive days and recorded with 30 minutes gap from 9: 00 am to 5: 30 pm. Hence, only average charging temperature of five day of absorber surface, oil and rock is recorded as presented in Figure 5 and reported.

The solar cooker is made up of two hollow concentric cylindrical and a pot is placed at their center. Used engine oil and rock is used as thermal storage and filled hollow space of outer and inner wall of solar cooker, respectively. Therefore, solar cooker is exposed to solar radiation for 8: 30 hours (for test) to charge the thermal energy. At 5: 30 pm the solar cooker is lifted and placed in hollow space cylinder which is insulated by ash and loaded by pot to cook food for evening.

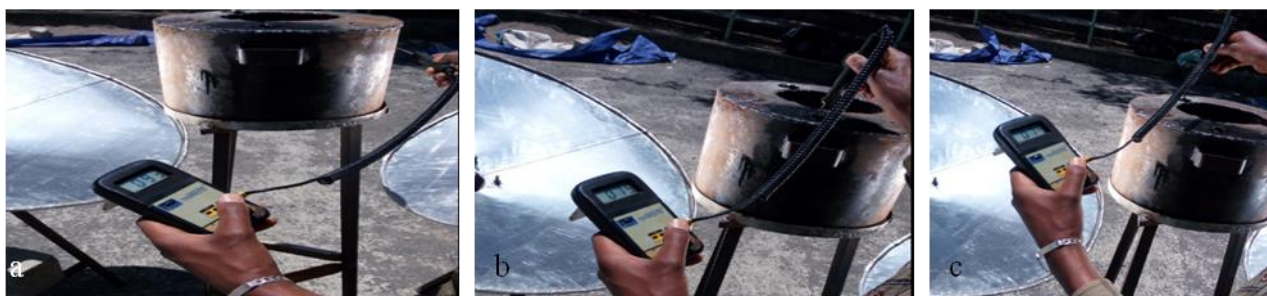


Figure 5. Temperature measurements (photograph). a. Measuring temperature of absorber surface; b. measuring temperature of used engine oil; c. measuring the temperature of the rock.

The solar dish includes concentrator, absorber with thermal storage for placing cooker and frame as shown in Figure 1 & 5. At the focal length of both parabolic dish collector, an absorber with TES is constructed upon which cooker is to be placed. The tracking of parabolic dish collector is done manually and for that tracking, screw is provided at the bottom of the parabolic dish. The parabolic dish collector is adjusted in such a way that the shadow of the tracking screw does not affect. Tracking screw is provided at the bottom of the parabolic dish so that the dish can be tracked with the movement of the sun with 30 minutes.

The temperatures of sensible heat storage materials; absorber surface and cooking medium are measured with a thermocouple which is connected with a digital temperature indicator that shows the temperature in degree Celsius. The charging temperature of absorber surface, used engine oil and rock is recorded as shown in Figure 5. Thus, the temperature is measured within 30 minutes gap.

3. Results

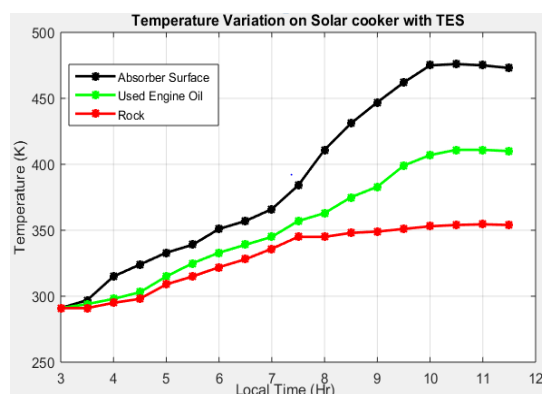
This experiment is performed to investigate thermal performance of solar cooker with rock and used engine oil in inner and outer space respectively. The reason why oil is used on the outer space is that it is used as heat transfer fluid and also used as an insulator during the discharging period (due to its low thermal conductivity).

Table 4. Daily solar radiation and ambient temperature of Addis Ababa in September.

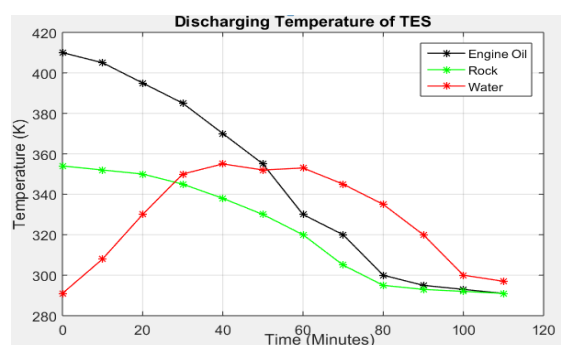
Days	Daily solar radiations (W/m ²)	Ambient temperatures (K)
Day 1	546	290
Day 2	543	291
Day 3	545	292
Day 4	544	290
Day 5	545	291

3.1. Charging temperature of TES

The charging temperature of absorber and thermal storage presented in Figure 6 are started after it is placed on the focal point of the solar collector.

**Figure 6.** Temperature variation on the solar cooker with TES.

3.2. Discharging temperature of TES

**Figure 7.** Discharging temperature of TES.

The discharging of TES as presented in Figure 7 is started after solar cooker is lifted from the focal point of the compound parabolic solar collector. Hence, it is placed on the insulated tank (insulated

with ash) and loaded by the pot with water.

4. Discussions

In this section the discussion will be mainly focused on the experimental investigation of charging and discharging temperature of thermal energy storage (used engine oil and rock).

4.1. Charging temperatures

The charging temperature of an absorber surface increases nearly linearly with time from 3: 00 to 7: 00 local time and reaches to 366 K. Moreover, it increases rapidly from 7: 00 to 10: 00 local time and reaches 476 K that is why the sun is on the head and solar radiation on Addis Ababa is high at this time compared with other hours. Hence, the day is going to evening and the sun is going to set, therefore, the temperature of an absorber surface is reducing slowly from 10: 00 to 11: 30 local time and reaches to 473 K at 11: 30 local time, in which discharging is started. However, this all heat energy cannot be transfer from absorber surface to oil; this is due to the convection loss, radiation loss and conduction losses. The temperature on the used engine oil increases linearly till 7: 00 local time like absorber surface and reaches 345 K. After 7: 00 local time the temperature increases gradually until 10: 00 local time and reaches 411 K as shown in Figure 6. Thus, the oil stores all this heat energy and it acts as heat transfer medium which transfers this heat energy to rock. Hence, this all heat energy cannot transfer to rock; this is due to low thermal conductivity of oil and losses like radiation and conduction. The temperature of the oil is nearly constant and reducing in a small number from 10: 00 to 11: 30 local time and reaches to 410 K. Therefore, the reason why engine oil is used is that it cannot lose the temperature easily with a short time and it is available freely. Moreover, the thermal conductivity and storage capacity is low compared to thermia oil B. Even though, the TES can store energy which is nearly enough to boil the water. Therefore, it can be concluded that the system can be more effective if Thermia oil B used for a practical test like theoretical study. Engine oil is used as a heat storage medium and insulating material (due to its low thermal conductivity). The temperature of rock increases linearly from 3: 00 to 7: 30 local time and reaches 345 K but it increases slowly for the last hours and reaches 354.5 K at 11: 00 local time. After 10: 30 local time, an absorber is lifted and placed in the insulated tank and loaded by the pot with water.

4.2. Discharging temperatures

The temperature of TES is reducing gradually by discharging (loosing) its heat energy to pot and surrounding. Thus, the temperature of the water is increasing radically till 40 minutes from its ambient condition and it reaches 355 K as shown in Figure 7. Since an absorber is not effectively covered by insulation; this leads to further loss of temperature from TES. However, water itself is used as TES, this why the temperature of the water is nearly constant from 40 minute to 60 minutes and it gradually decreases after 60 minutes.

5. Conclusions

The main limitation of solar energy is its availability only in day time. Therefore, this paper had been investigated by adding the used engine oil and rock as thermal energy storage on the absorber for evening cooking, in which sun light did not exist. That is why this study conducted with TES due to its important characteristics; the length of time during which energy can be kept stored with acceptable losses. In this study, the overall system is designed and the experimental tests are carried out.

In the experimental result, due to many losses which are raised in the above, the energy reached to the cooker (pot) is lower and its surface temperature on average is 380 K. Even if it has low energy, it is possible to reduce the loss of energy of TES to the surrounding by placing inside the insulated tank.

The discharging of TES is started after it is lifted from the focal points of compound parabolic solar collectors. The maximum temperature of water is 355 K and reached after 40 minutes, which is the nearly boiling point. The reason why this study was used water for practical test is that, it is possible to cook the rice immediately after the water is boiled.

However, if the experiment is done in a hot area and in sunny season, the cooker is expected to be more effective than what is done in this paper. Therefore, it is recommended to do this test in the hottest area of Ethiopia like: Samara, Dire Dawa, Gambella, etc. with effective insulation of an absorber to enhance effectiveness of cooker.

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Conflict of interest

The authors declare no conflicts of interest in this paper.

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