DESIGN OF SOLAR COOKER BASED ON CONCENTRATING COLLECTOR USING HEAT TRANSFER FLUID

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Abstract

A solar cooker based on concentrating collector using a heat transfer fluid is designed, built and tested. The solar cooker is intended to be used for indoor cooking. Estimates of the thermal energy demand for cooking is studied and based on this the solar cooker components are designed. The solar cooker uses parabolic trough collector of aperture area 2m^2. The energy obtained from the present parabolic trough solar collector is transported to a separate cooking place using a heat transfer fluid. Heat transfer fluid, soya bean oil, flows in a natural circulation through a copper pipe of 16mm diameter and in to a storage system, where cooking takes place. Two sizes of absorber plates and two arrangement of the solar cooker are investigated. Maximum temperature of 126^{0}C at the absorber plate and oil temperature of 86^{0}C at the cooking pot has been achieved with solar radiation at 800W/m^2. Performance test of the solar cooker is evaluated for Ethiopian environmental conditions.

1. Introduction

Many people in the developing world suffer from access to energy services. Limited access to energy services such as electricity, heating, and cooking fuels paralleled with inefficient use of biomass are some of the many problems. Improving access to modern energy services is essential input to both social and economic development (Modi et al., 2005).

Energy from the sun can be utilized for cooking using different technologies. The principle of solar cooking is that the radiation from the sun is collected and converted in to heat for cooking. Early box type solar cookers suffered from convective heat losses and convenience of cooking. Box type solar cookers proved to be cost effective but failed to meet efficiency and ease of cooking. Later improved designs were the reflector type of solar cookers in which reflector material is added to assist more radiation to be focused on the cooking chamber. Further improved performance of concentration and cooking has been achieved due to the introduction of parabolic dish solar cookers. These cookers used a large parabolic collector area which concentrates solar radiation to a focal point where cooking is performed.

Indirect solar cookers use heat transfer fluid to transport heat from absorber to a cooking system. Such types of cookers are convenient for cooking indoors but they are also more expensive (Klemens et al., 2003). In this research an indirect solar cooker based on parabolic trough concentrator using a heat transfer is designed and built. The cooker is designed to concentrate radiation into a relatively small absorber area to attain high cooking temperature and minimize heat losses. A heat transfer fluid is then used to collect and transport heat energy to the cooking place. The system is designed to work in a thermosyphon principle, where heat transfer fluid is circulated by natural convection.

2. Approach

2.1. Design data and location

Ethiopia, located at the Horn of Africa, lying between 3^0 – 15^0 latitude and 33^0 – 48^0 longitude, enjoys sunshine throughout the year. Many places in the country have short rainy season and mostly dry weather with a clear sky radiation (NMSA, 2001). This makes it an ideal place for concentrating solar collectors which basically utilize beam radiation. Solar radiation data are available from National Metrology Agency of

Ethiopian and NASA. Performance mesurement is taken during test at the solar center of Department of Mechanical Engineering Mekelle, Ethiopia.

2.2. Solar energy demand for cooking, cooker size and testing

The principle of cooking is that the temperature is raised to a cooking temperature and then maintained at cooking temperature to facilitate chemical change associated with the process of cooking (Lof, 1963). Hence thermal load of the solar cooker is determined based on the amount of energy and temperature required for cooking for an average family size.

The area of the collector is determined using the average daily solar radiation for the month with lowest solar radiation and the amount of energy that is required for cooking. The minimum solar radiation occurs at 5.46 kWh/m^2 day in August (RETScreen, 2010). Based on the design calculations the solar cooker model was built at the workshop of the Mechanical Engineering Department in Mekelle University. Locally available materials were used for the prototype development of the cooker. The main design features of the solar cooker are the parabolic trough development, the combination of the absorber tube and absorber plate, the pipe network, the storage system and the tracking mechanism.

3. Design of parabolic trough collector

3.1. Description of the solar cooker

The solar cooker with concentrating collectors is designed to concentrate radiation into a relatively small absorber area to attain high temperature. A storage system in the form of a tank is built to keep the heat transfer fluid oil temporarily and power the cooking plate. The main features of the solar cooker are the absorber plate, the parabolic trough collector, the storage system and the piping network system (Figure 1). Summary of the parameters of the solar cooker is given on Table 2.

For optimum utilization of the solar energy resource, the orientation of the parabolic trough is important parameter in the system design. Since Ethiopia is on the northern hemisphere, the collectors face south for a maximum energy collection. It is logical that the collector be tilted an angle equal to the latitude of the place in which the collector is mounted. Hence the collector is tilted approximately 14^O which is equal to the latitude of Mekelle.

Figure 1: The solar cooker installed at the solar center of the Department of Mechanical Engineering

3.2. Parabolic collector area and geometry

The design of the parabolic collector is based on the amount of radiation to be concentrated on the absorber area so that it meets the thermal energy demand. The main design features are the size of the collector area and the geometry. The solar parabolic trough geometry is designed in such a way that it collects and concentrates the radiation in to the absorber plate.

The parabolic curve generated from the width of the aperture area and for a rim angle of 118^0. Choice of rim angle has no significant effect on the efficiency of the solar cooker (Egbo et al., 2008). Therefore, a rim angle of 118^0 is chosen so that the focal point remains within the parabolic trough to avoid the heat losses due to the high wind speed. A smooth curve is then generated by taking a number of points from the parabolic equation. Using these points, a parabolic trough structure is fabricated. Three of the collector steel structure frames are assembled in such a way to form the surface of the parabolic trough collector. On top of the steel structure, an aluminum sheet metal is laminated to generate a smooth profile so that the pieces of mirror are attached on top.

3.3. Absorber area and coating material

The absorber is fabricated from a copper absorber tube of 16mm outside diameter and 1 mm thickness. An aluminum sheet of 1mm thickness is used to support the tube. The plate is also used to capture as much concentrated radiation as possible and acts as a fin, which transfers heat in to the tube in cases of concentration inaccuracy. The system is designed to track the sun every 15 minutes and hence within this time limit the image of the sun remains in the absorber plate. The optimum dimension of the absorber plate is determined from the earth's movement around the sun. Hence, for the purpose of this research an absorber plate width of 180mm and 120mm were tested.

3.4. Reflecting material

Different reflecting materials have been used as reflecting materials ranging from simple aluminum foil to complex coated films. In this research, glass mirrors cut into pieces of dimension 50mm by 200mm are attached into the parabolic trough curve. Silicone sealant, a powerful adhesive is used to attach the mirrors to the collector surface. Mirror is chosen as it is locally available and it has good reflectance of 94 % – 96 %. The disadvantage of using glass mirror is that it cannot fit into the parabolic curve. Hence the image formed by the reflection on the absorber plate is not a line but a two dimensional area.

3.5. Heat transfer fluid

Many heat transfer fluids have been developed for a variety of applications. They range from organic to water based fluids. High temperature fluids operate up to 400 ^{O}C, above 315 ^{O}C options are limited to synthetic fluids. Below that temperature, mineral oil-based fluids are viable (Canter, 2009).

Vegetable oil has been successfully used in solar thermal applications as heat transfer fluids (Kalifa et al., 1986 and Balzar et al., 1996). In this research, soya bean oil with a maximum temperature (flash point temperature) of 280 ^{O}C and kinematic viscosity of 35.4 E-6 m^2/s at 37 ^{O}C is used as a heat transfer fluid. Properties of soya bean oil are given on Table 1. The advantage of using soya bean oil is that it is easily available in local market.

Table 1: Properties of soya bean oil (Source: http://www.chemicalland21.com)

Soya bean oil	
Viscosity	50 E-6 m^2/s @ 25 ^{O}C
Specific gravity	0.925
Heat capacity	1.97 kJ/kg.K
Flash point	280 ^{O}C

3.6. Storage and cooking pot system

Solar energy is stored in the form of sensible heat due to the change in temperature in the soya bean oil. The storage is filled with oil of 18 liters and space is left for the thermal expansion for the oil as it gets heated. A relief valve is also attached at the bottom of the storage to control the pressure developed due to the expansion oil. The storage system is a cylinder made of mild steel of thickness one millimeter insulated using 5cm thickness of fiberglass. Inside diameter of the storage is 35cm and height of 22cm.

3.7. Tracking mechanism

A manual tracking mechanism using a circular wheel is designed to keep the solar collector to follow the sun's position. It is fixed with the focal point of the collector and is held in position by an arm attached to the stand of the collector. Such tracking mechanism results in low concentration ratio and intercept of reflected radiation but they are technologically simple and very cheap.

Table 2: Solar cooker parameters

Item		Value/type	
Collector aperture area		2	m2
	Aperture length	1.67	m
	Aperture width	1.2	m
Absorber plate area		0.2	m2
	Absorber length	1.67	m
	Absorber width	0.12	m
Rim angle		118	degrees
Tracking mechanism			
	Mode of tracking	Manual	
	Tracking frequency	15	Minutes
Storage and cooking pot			
	Volume	18	Liter
	Diameter	0.35	m
Insulation		Fiberglass	
Absorber tube diameter		16	mm
Reflecting material		Glass	
	Length	50	mm
	Width	200	mm
Parabolic curve equation		$Y = 7x^2 -126.5x + 569.5$	
	Focal length	220	mm
	Height	445	mm
	Arc length	1.6	m

4. Results and discussions

4.1. Standard stagnation temperature of absorber plate without coating

Stagnation temperature is the maximum temperature that can be achieved by the cooker under no load condition. This test is first made on the 180mm aluminum absorber without application of coating material. Radiation and temperatures measured on 13 September 2010 are presented on Figure 2. This test is made between 11:10 hrs and 12:30 hrs. During the test a maximum temperature of 105.6 ^{O}C has been achieved at the absorber plate at around 11:50 hrs with a radiation of 964 W/m^2.

The standard stagnation temperature (*SST)* gives the temperature to which the absorber will rise under a horizontal insolation of 850 W/m^2 and is given by:

$$SST = \left(\frac{T_s - T_a}{(I_{measured})}\right)(850 W/m^2)$$

$$SST = (\frac{105.6 - 28.4}{964 W/m^2})(850 W/m^2)$$

$$SST = 68^{O}C \qquad \text{(Eq.1)}$$

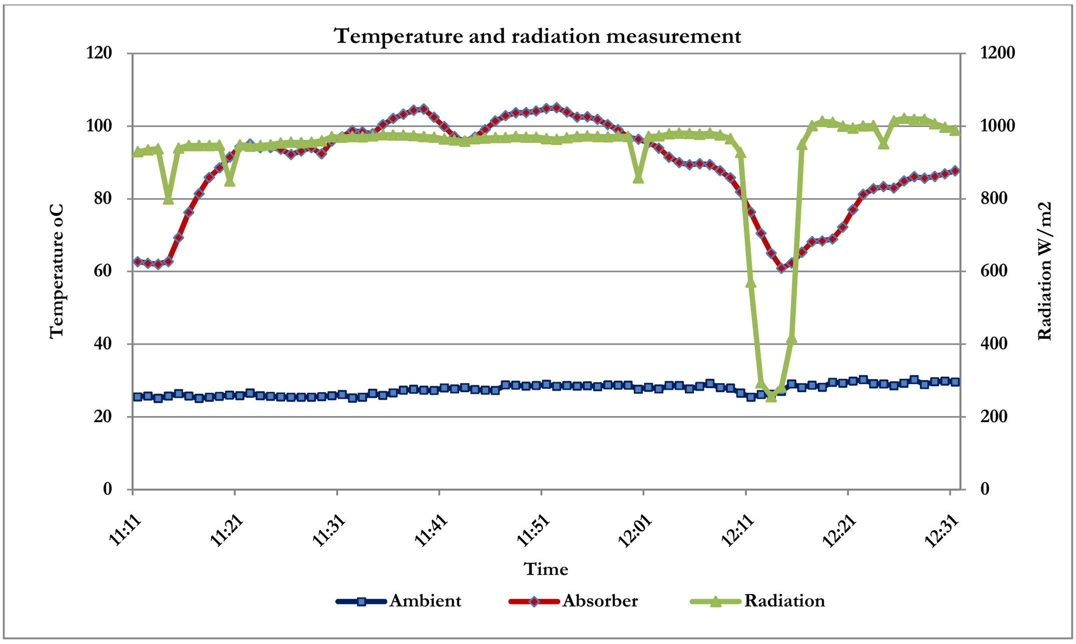

Figure 2: Radiation and temperature measured on 13 September 2010

4.2. Standard stagnation temperature of absorber plate with black coating

The stagnation temperature of the absorber plate is then measured by coating the absorber plate with a black spray paint to enhance the absorption of solar radiation. Radiation and temperature measurements taken on 20 September 2010 are shown in Figure 3. This test is made between 8:36 hrs and 15:36 hrs for seven hours. It is observed that a maximum temperature of 124 ^{O}C is achieved at around 10:50 hrs with a radiation of 954 W/m^2. The standard stagnation temperature given by (eq 6.1) is 87 ^{O}C. This increase is attributed due to the black paint coating material put on the absorber plate.

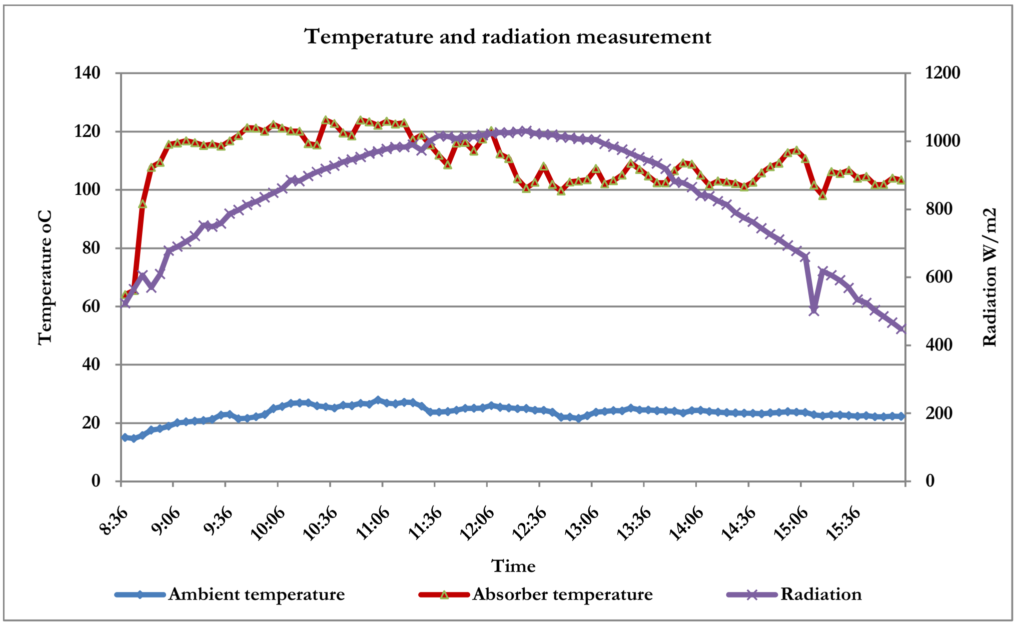

Figure 3: Radiation and temperature measured on 20 September 2010

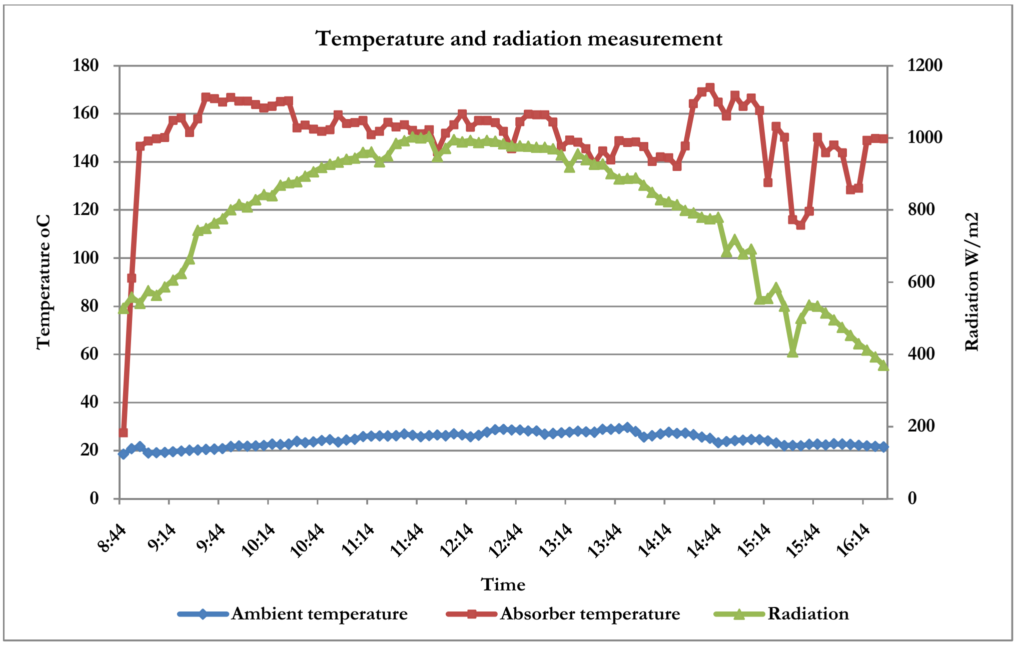

Figure 4: Radiation and temperature measured on 18 October 2010

Further improvement in stagnation temperature has been achieved by decreasing the absorber width to 120mm. Radiation and temperature measurements taken on 18 October 2010 are shown Figure 4. This test is made between 8:44 hrs and 16:14 hrs for eight hours and thirty minutes. Maximum radiation is measured at noon between 11:44 hrs and 12:14 hrs but maximum temperature at the absorber plate are observed early in the morning and in the afternoon. This is because many of the radiation coming from sides of the parabolic trough collector have been observed to miss the absorber plate.

Standard stagnation temperature at this point is calculated by taking the maximum temperature of 171^{O}C observed at 14:34 hrs. Therefore, the stagnation temperature given by (eq. 6.1) is 159 ^{O}C.

4.3. Performance evaluation of the solar cooker when using heat transfer fluid

The solar cooker is loaded with a heat transfer fluid and the thermal performance is presented and discussed by taking two different arrangements of the storage. First arrangement is when the storage is placed closer to the collector and second arrangement when the storage is placed fifty centimeters away from the collector

The performance of solar collectors is made by the energy balance. It is important to analyze the quantity of energy received to the energy distribution in the system. Hence, important parameters in determining the thermal performance such as radiation, collector and storage temperature distribution, wind and ambient temperature measurements are taken along some points in the cooker.

4.3.1. Test arrangement 1 Storage distance 100m and absorber plate width 180mm

In this arrangement, the experimental test is made by placing the storage as much closer as the geometrical limitation allows. The distance between the collector outlet and the storage inlet is ten centimeters. The first test shown in Figure 6.4 is made by using the 180mm absorber plate.

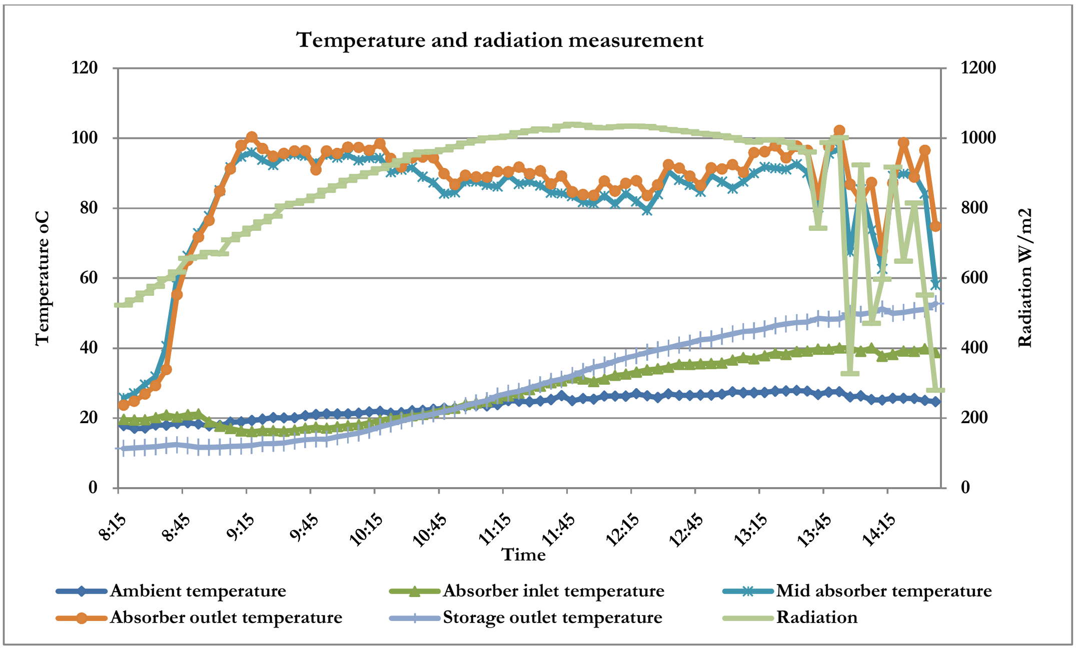

Figure 5: Radiation and temperature measured on 24 September 2010

Measurement of radiation and temperature started early in the morning at 8:15hrs. Then after 15 minutes, the collector is positioned to track the sun. It can be shown on Figure 5 that the time response of the absorber (time taken to reach 63% of the maximum temperature) after a step change in radiation is on average 30 minutes. The temperature increases sharply to a maximum of 100^{O}C. As one expects, the temperature values increase with the increase in radiation during the day. However, due to the geometry of the absorber plate some part of the radiation that was designed to fall on the absorber plate were seen to miss the absorber. This is because the projection of the absorber when viewed from above and side is different. Hence, the temperature reaches its pick early in the morning and remains constant during the day until in the afternoon when it again starts to increase (Figure 7).

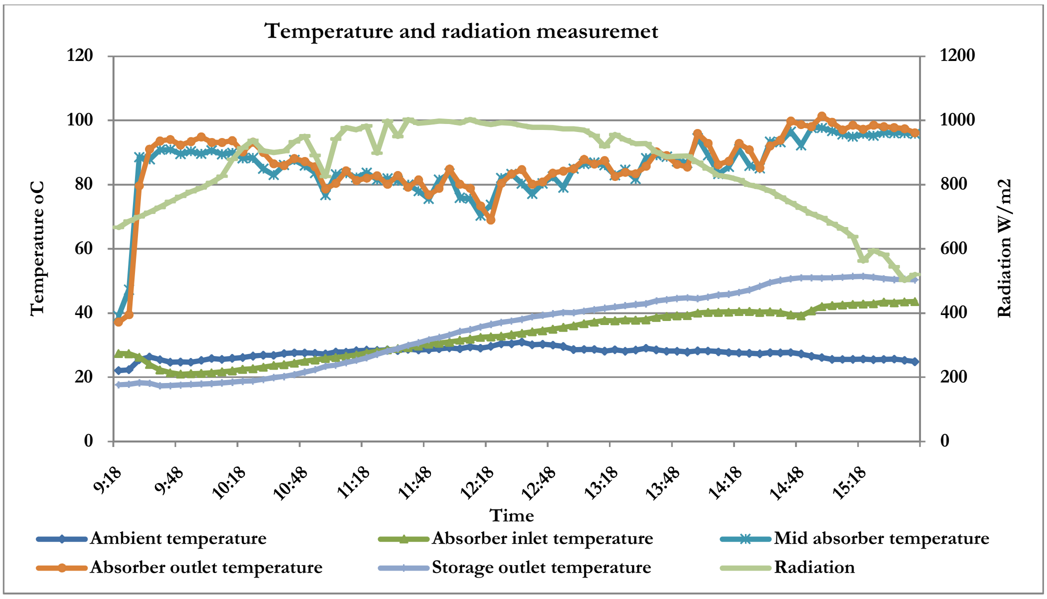

Figure 6: Radiation and temperature measured on 13 October 2010

4.3.2. Test arrangement 2: Storage distance 500m and absorber width 120mm

In the second arrangement, experiments are made by extending the storage 0.5m from the previous setup. Additional thermocouple is added at the inlet to the storage to observe how the temperature changes from the absorber outlet to the storage inlet. Figures 7 and 8 are experimental results taken on 19 and 21 October 2010 respectively. The temperature at the absorber plate increases rapidly when the collector is tracked to face the sun. Consequently, the temperature at the absorber outlet and inlet to the storage increases rapidly as well showing the start of natural circulation of the system. In ten minutes, the absorber temperature increases sharply then slowly increases to its maximum. In Figures 7 and 8 maximum temperatures of 126^{O}C and 121^{O}C have been recorded at the outlet of the absorber plate.

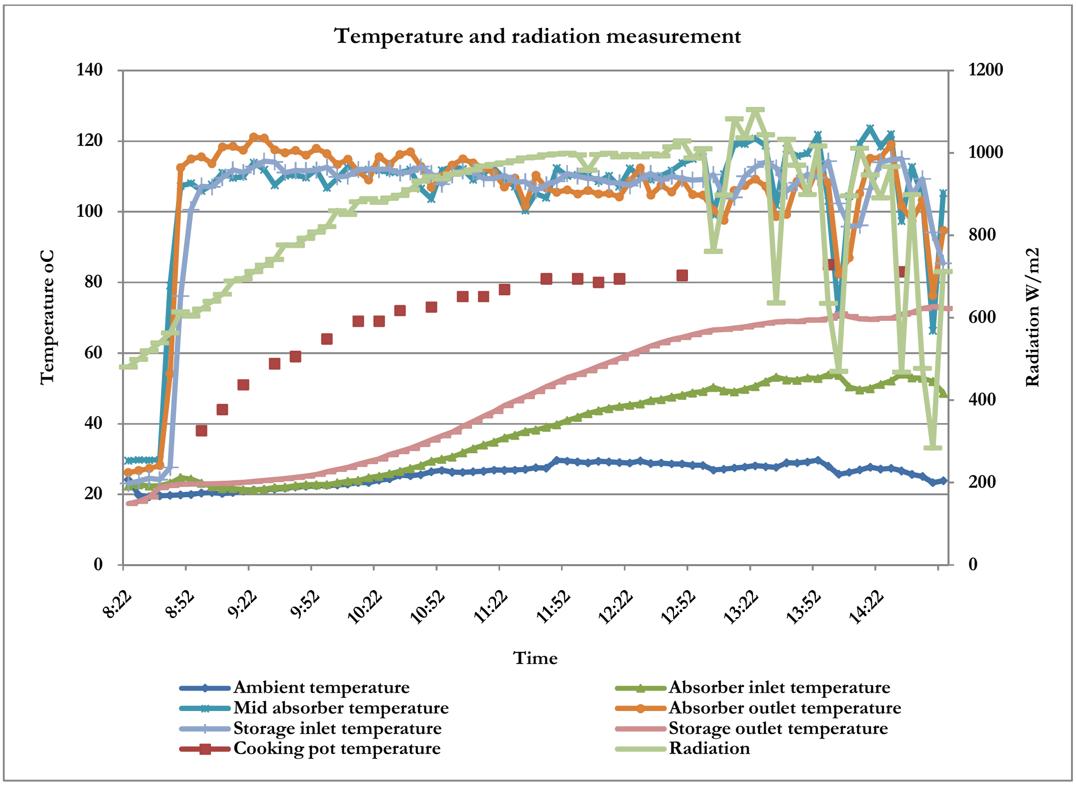

Figure 7: Radiation and temperature measured on 19 October 2010

Temperature measurements on the cooking pot are taken using a surface temperature K-type thermocouple. Maximum temperature of 86^{O}C is achieved at the cooking pot in the afternoon around 14 hrs (shown in Figure 7).

As shown in Figures 7 and 8 the temperature profiles have the same trend; the time response is very fast that is, the temperature increases sharply to its maximum within a short time. Then it remains steady for much of the testing time until in the afternoon around 13:00 hrs where it starts to rise again to its maximum temperature.

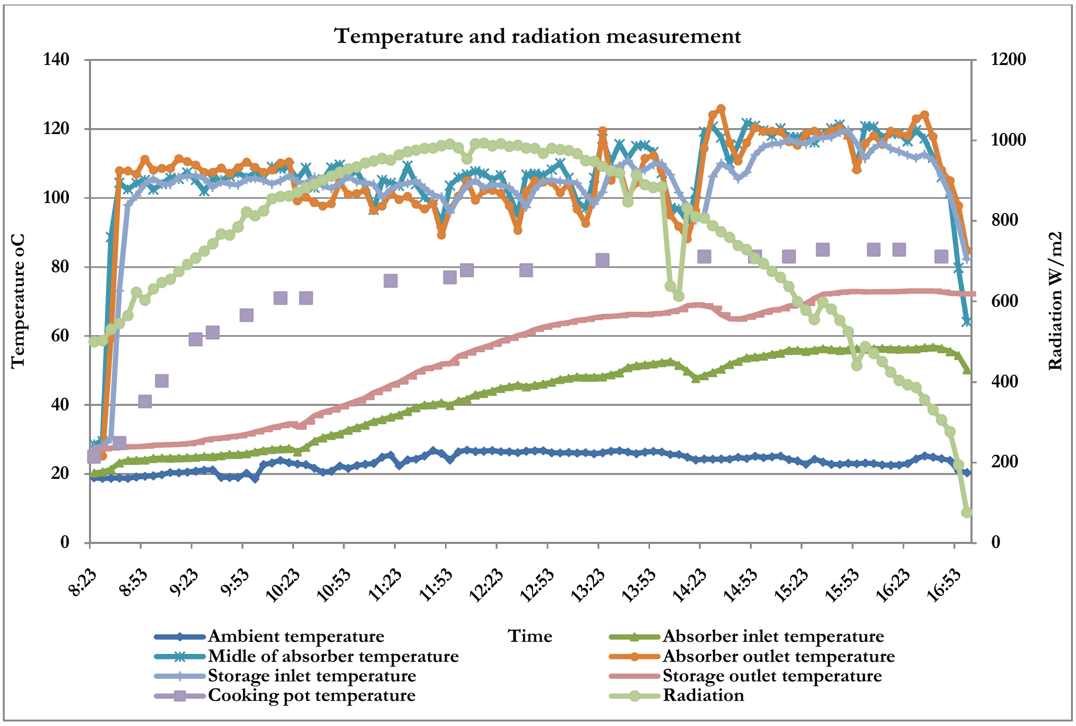

Figure 8: Radiation and temperature measured on 21 October 2010

4.4. Thermal performance

4.4.1. Cooking power

Cooking power for the two arrangements are tested using oil and the change in oil temperature for each ten-minute interval is multiplied by the mass and specific heat capacity of the oil contained in the cooking pot. Two liters of oil have been used for testing the cooking power of the solar cooker. This product shall be divided by the 600 seconds contained in a ten-minute interval. The cooking power is calculated as follows,

$$P = \frac{T_2 - T_1}{600} mc_p \qquad \text{(Eq.2)}$$

According to the world Health Organization fact sheet N^{o}125 (WHO, 2010) it is recommended that food should be cooked thoroughly so that at least the center of the food reaches 70^{O}C. The cooking power and maximum temperature in the first arrangement have been 181W and 60^{O}C respectively. Hence, the temperature obtained in this test is lower than the minimum temperature required for cooking.

Results from the second arrangement showed that maximum cooking temperature of 86^{O}C and cooking power of 327.5W. In this arrangement, the temperature is higher than the lowest temperature required for cooking most kind of food.

4.4.2. Thermal efficiency of the cooking unit

One of the important parameters in the performance of solar cookers is the thermal efficiency. The cooking energy available as sensible heat in the storage and the average incident solar energy falling on the collector can determine the thermal efficiency of the cooking unit. The average efficiency is given by:

$$\eta = \frac{Q_U}{IA_C} = \frac{m_{Oil} C_{Oil} \Delta T}{IA_C} \qquad \text{(Eq.3)}$$

The calculated results of thermal efficiency showed 2.6% and 2.8% for the first and second arrangements respectively. The result predicted the overall performance of the solar cooker as system. This result is similar compared to the efficiency of 3.36% achieved by parabolic dish heat exchanger working in a natural circulation system (Murty et al., 2007). The thermal performance is very low which can be explained by high thermal losses at the absorber plate, cooking pot and very low heat removal efficiency due to very slow flow rate of heat transfer fluid in natural circulation.

4.4.3. Heat loss mechanisms

The main sources where heat loss is expected are the absorber plate, the storage and the pipe system. At higher temperature heat loss are dominated by convection and radiation. Convective heat loss is directly proportional to the object average temperature, ambient temperature, wind speed and object area. Radiation loss is highly dependent on the object's temperature.

The main heat loss mechanisms are determined as follows (Lienhard IV and Leinhard V, 2006);

Convective heat loss $H_{conv} = hA_b(T_b - T_a)$ (Eq.4)

Where h is the convection heat loss coefficient given by:

$$h = 5.7 + 3.8V \quad \text{(Eq.5)}$$

Where V is wind speed, m/s

Radiation heat loss $H_r = \in \sigma T^4$ (Eq.6)

Conduction heat loss

$$H_{cond} = \frac{k(T_b - T_a)}{\Delta x}$$

$$H_{cond} = \frac{2\pi kL}{\ln(r_2 / r_1)}(T_b - T_a) \quad \text{(Eq.7)}$$

Considerable amount of heat loss are expected from the absorber plate and the top of the cooking pot since they are exposed to the environment. The side and bottom of the storage and the pipe system are well insulated that negligible amount of heat loss is expected. The summarized heat losses are presented in Table 3 and Table 4. The results are obtained from the various measured average temperature of absorber plate, storage and cooking pot and the different pipe network systems. The radiation and temperature measurements taken on 21 October 2010 are used to calculate the heat losses associated with the solar cooker.

The convective heat loss coefficient at a wind speed of 3.1m/s is found to be 17.48 W/m^2.K. The total heat loss from the solar cooker is 663W. More than 76% (511W) heat loss is observed from the absorber plate.

Table 3: Convective and radiative heat losses in the solar cooker

Heat losses					
Absorber	**Dimension**	**Units**	**Cooking pot**	**Dimension**	**Units**
Area	0.200	m^2	Area	0.088	m^2
Length	1.67	m	Radius	0.125	m
Width	0.12	m	Height	0.05	m
Average temperature	105	^{o}C	Average temperature	70	^{o}C
Ambient temperature	23.5	^{o}C	Ambient temperature	23.5	^{o}C
Wind speed	3.1	m/s	Wind speed	3.1	m/s
Convective heat transfer coefficient	17.48	W/m^2.K	Convective heat transfer coefficient	17.48	W/m^2.K
Convective heat loss	**286**	**W**	**Convective heat loss**	**72**	**W**
Average temperature in K	378	K	Average temperature in K	378	K
Emissivity	0.97		Emissivity	0.26	
Boltzmann's constant	5.67E-08	W/m^2.K^4	Boltzmann's constant	5.67E-08	W/m^2.K^4

Radiative heat loss	**225**	**W**	**Radiative heat loss**	**27**	**W**
Total absorber heat loss	**511**	**W**	**Total cooking pot heat loss**	**99**	**W**
Total absorber and cooking pot heat loss	**610W**				

Table 4: Conductive heat losses in the solar cooker

Heat losses					
Storage	**Dimension**	**Units**			
Surface area	0.338	m^2			
Radius	0.175	m			
Height	0.22	m			
Average temperature	95	^{o}C			
Ambient temperature	23.5	^{o}C			
Wind speed	3.1	m/s			
Insulation					
Radius + thickness	0.225	m			
Thermal conductivity	0.038	W/m^2.^{o}C			
Thickness	0.05	m			
Conductive heat loss	**17**	**W**			
Pipe network	**Dimension**	**Units**	**Pipe network**	**Dimension**	**Units**
Internal diameter	2.20E-02	m	Internal diameter	2.20E-02	m
External diameter	8.60E-02	m	External diameter	8.60E-02	m
Thermal conductivity	0.038	W/m^2.^{o}C	Thermal conductivity	0.038	W/m^2.^{o}C
Average temperature	61	^{o}C	Average temperature	105	^{o}C
Ambient temperature	23.5	^{o}C	Ambient temperature	23.5	^{o}C
Pipe length	3.6	m	Pipe length	0.8	m
Conductive heat loss	**24**	**W**	**Conductive heat loss**	**12**	**W**
Total conductive heat loss	**53**	**W**			
Total conductive, convective and radiative heat losses of the collector system is 663 W					

5. Conclusion and recommendation

The solar cooker based on parabolic trough concentrator has been designed, build and tested using locally available materials and technology. Since the cooking area is separate from the collector area, the solar cooker is more user-friendly. It means that cooking can be made in a shaded area to prevent direct solar radiation on the person working on the cooker.

The results presented show that the temperature sharply increases early in the morning and a constant temperature is maintained throughout the day. Maximum temperature of 126 ^{O}C at the absorber outlet and 86 ^{O}C at the cooking pot have been achieved. The very short response time enables the cooking pot to be ready for cooking early in the morning. Results from the second arrangement showed that maximum cooking temperature of 86 ^{o}C and cooking power of 327.5 W. This is lower than the expected 1kW output from the solar collector. In this arrangement, the temperature is higher than the lowest temperature required for cooking most kind of food. Heat retention in the solar cooker storage can further keep food hot after sunset.

Since hot oil remains at the top of the storage due to its density, the storage can simultaneously heat the cooking pot and store energy by heating the oil. The energy obtained from the present parabolic trough solar collector can be transported to a cooking place using a heat transfer fluid. This is associated with small temperature drop along the added pipe and a decrease in the flow rate of the heat transfer fluid.

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