Performance Test of Parabolic Trough Solar Cooker for Indoor Cooking

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ABSTRACT

Fuel-wood scarcity is a growing problem that has so far been poorly addressed. Solar cooking is one possible solution but its acceptance has been limited partially due to low performance and convenience of use of most of the solar cookers that currently are available. The objective of this research is to test the performance of a solar cooker based on concentrating collector and increase its temperature and performance. Parabolic trough cooker (PTC) was constructed in a way allowing cooking to be done indoors, which the cooking sections were placed indoor whiles the collector parts out-door with soya bean oil conveying the energy from the absorber to the cooking stove. Ray tracing and standard stagnation tests show a 30 mm diameter copper pipe is the optimum size for the absorber. Maximum temperatures of 191^0C at the mid absorber pipe and 119^0C at the cooking stove were obtained. The efficiency of the system was found to be 6%.

Keywords: Solar cooking, Concentrator, Stagnation test, Ray tracing.

1. INTRODUCTION

The increasing cost and scarcity of oil, gas, and severe environmental damages have focused attention on the need for a switching to renewable energy sources. Solar energy will play an essential role in this effort, particularly for domestic and commercial space heating (and cooling), cooking and water heating. In developing countries, especially in rural areas, 2.5 billion people rely on biomass, such as fuel wood, charcoal, agricultural waste and animal dung, to meet their energy needs for cooking. In many countries, these resources account for over 90% of household energy consumption (IEA, 2006). Had the animal wastes alone been used to fertilize the soil, 14 million additional tons of grain could have been grown and harvested-more than twice the level of all grain contributed to global food aid (Miller and Tangely, 1991).

In the absence of new sustainable, cleaner, more efficient use of energy for cooking the number of people relying on biomass will increase to over 2.6 billion by 2015 and to 2.7 billion by 2030 because of population growth. That is, one-third of the world's population will still be relying on these fuels (IEA, 2006). With this many people cooking with wood daily the sustained impact on the surrounding forest is obviously enormous.

Solar cookers are heat exchangers designed to use solar energy in the process of cooking. In supplying the needed energy, solar cookers can fully or partially replace the use of firewood for cooking in many developing countries. Optimists have estimated that 36% of the developing world's use of fuel-wood could be replaced by solar stoves (Lampinen, 1994). Even partial reliance on the sun instead of complete dependence on the forest for cooking needs would save huge amount of fuel-wood (Ethiopia Project, 1997) but aside from the cost, convenience of use and certain social conditions, current solar cookers, if they are to gain wide-scale acceptance, must meet secured performance requirements.

The available solar cookers are broadly categorized under two groups as solar cookers with and without storage (Pohekar et al., 2005). Solar cookers without storage are classified into direct and indirect depending upon the heat transfer mechanism to the cooking pot (Muthusivagami et al., 2009). Box type cookers and concentrating type cookers are included in direct category.

In indirect type solar cookers, the pot is physically displaced from the collector and a heat-transferring medium is required to convey the heat to the cooking pot. Solar cookers with flat plate collector, evacuated tube collector and concentrating type collector are commercially available cookers under this category (Muthusivagami et al., 2009).

This paper deals with improving and testing performance of a concentrating cooker for indoor cooking with soya bean oil conveying the heat from the collector to the cooking section. Two experimental setups have been tested where in the first setup 16 mm diameter copper pipe impinged in a corrugated aluminum plate was used as an absorber pipe. In the final setup the corrugated aluminum plate was removed and the experiments were conducted with bare 16 mm copper pipe and 22 mm galvanized steel pipe respectively. Modifications were also made for the storage tank and cooking pot. Comparison of parameters of these two setups is shown in table 1.

2. DESCRIPTION OF THE PARABOLIC SOLAR COOKER (PSC)

In this research a solar cooker with concentrating collectors is designed to concentrate radiation into a relatively small absorber area to attain high temperature. A heat transferring fluid is then used to collect and transport heat energy to the cooking place. The system is designed to work in a thermosyphon principle that is, heat transferring fluid is circulated by natural convection. Low temperature fluid by virtue of its high density moves down and high temperature fluid moves upward.

Table 1. Comparison of results for the initial and final setups.

Parameter	***Initial setup***	***Final setup***
Absorber pipe type and diameter	Copper pipe of 16 mm	- Copper pipe of 16 mm - Galvanized steel pipe of 22 mm - Copper pipe of 16 mm fixed in folded aluminum plate
Corrugated aluminum plate width	120 mm	-
Volume of storage tank	18 liters	17.5 liters
Height of cooking pot	50 mm	30 mm
Copper fins at bottom of cooking pot	Exist	Removed
Heat transferring medium	Soya bean oil	Soya bean oil
Coating material	ABRO black	ABRO black
SST	87 ^{0}C	- 144^{0}C with 16 mm copper pipe as an absorber pipe - 143^{0}C with 22 mm galvanized steel pipe as an absorber pipe - 142^{0}C with 16 mm copper pipe fixed in folded aluminum plate
Maximum temperature reached at mid absorber pipe	126^{0}C	- 191^{0}C with 16 mm copper pipe as an absorber pipe - 178^{0}C with 22 mm galvanized steel pipe as an absorber pipe - 175^{0}C with 16 mm copper pipe fixed in folded aluminum plate as an absorber pipe
Maximum temperature reached at cooking pot after filling the soya bean oil	86 ^{0}C	- 126^{0}C with 16 mm copper pipe as an absorber pipe - 103^{0}C with 22 mm galvanized steel pipe as an absorber pipe

A storage system in the form of a tank is built to keep the heat transferring fluid temporarily and power the cooking plate. The cooking unit is placed 50 cm far from the collector assuming a wall can be constructed in between the collector and cooking unit thus making it possible to cook inside a house or shading. This distance can be extended to some more distance upon demand with proper insulation of the connecting pipes and hence minimize the shading effects of the wall. Thus there is no danger of burning due to concentrated radiation, the cooker is user friendly and suits conventional cooking arrangement.

2.1. Initial Setup

Figure 1 shows the three dimensional drawing of the parabolic solar cooker. The main features of the solar cooker are the absorber plate, the parabolic trough collector, the storage system and the pipe networking system.

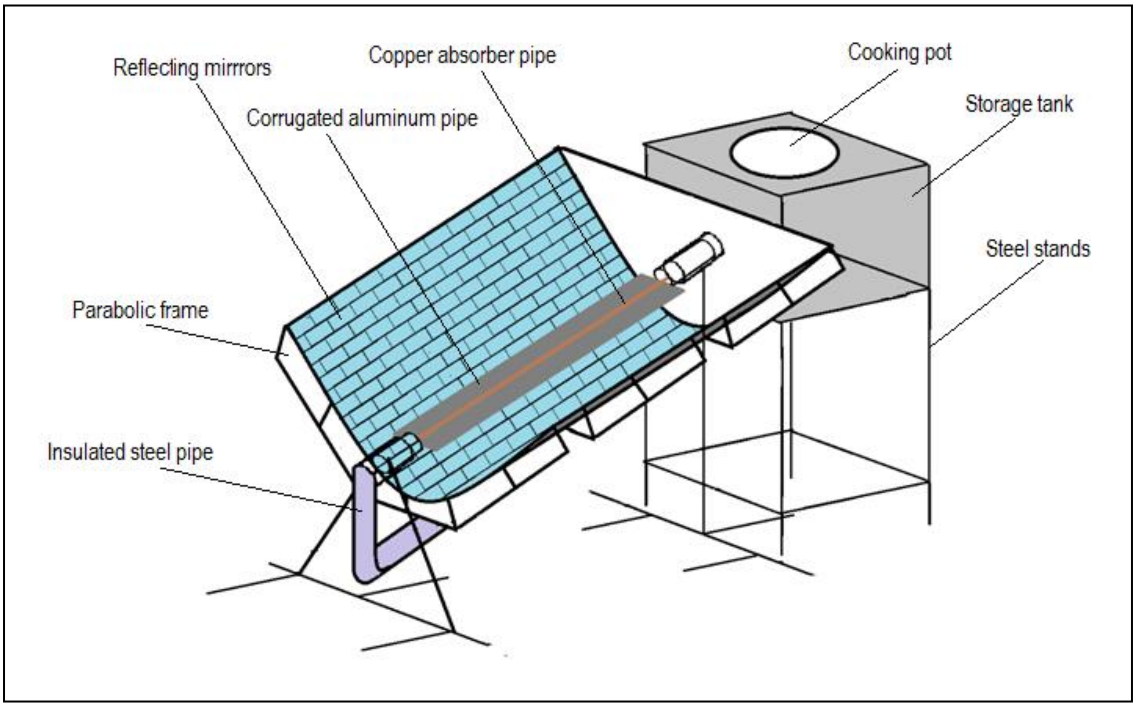

Figure 1. Sketch assembly of the solar cooker.

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 collector faces south for a maximum total energy collection. Another important angle for the collector is the tilt angle. It is logical that the collector be tilted an angle equal to the latitude of the place in which the collector is mounted (Chetan Singh, 2009). Hence the collector is tilted approximately 14^0 which is equal to the latitude of Mekelle.

In this initial set up 16 mm diameter copper pipe fixed in a corrugated and an ABRO black coated aluminum plate, as shown in figure 2, was used as the absorber pipe. The corrugated plate has a width of 120 mm aiming to capture as much reflected rays as possible.

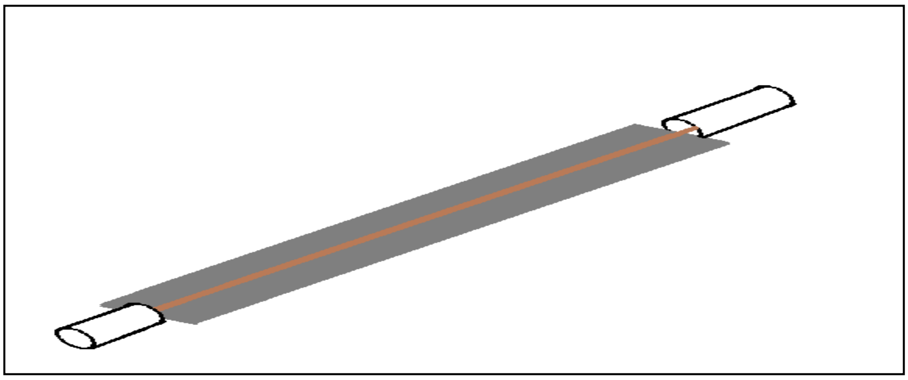

Figure 2. Copper tube in a corrugated aluminum sheet.

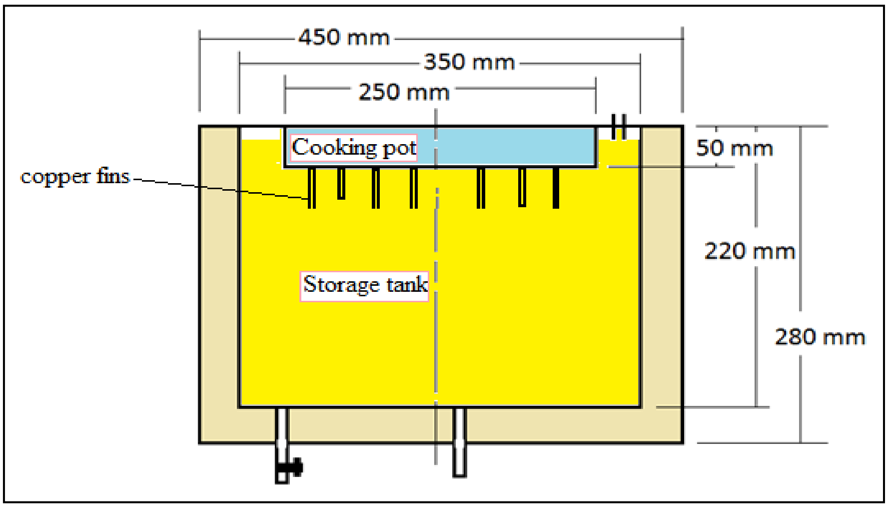

Figure 3. The storage and cooking pot.

The storage system, integrated with the cooking pot, was made of mild steel. For minimum heat loss it has to be insulated using 5 cm thickness of fiber glass. This system was filled with 18 liters of the heat transferring medium, soya bean oil, which would store enough energy for cooking for five headed family. The advantage of using soya bean oil is that it is widely available in local market, has good flash point temperature and kinematic viscosity (Petros, 2011). Transfer of heat is facilitated by connecting small copper tubes at the bottom of the cooking plate, figure 3.

2.2. Final Setup

First the design of parabolic trough was revised and analyzed. Having this, critical components of the collector and cooker were measured and results compared with the theoretically calculated values. Parts that showed significance deviation had been redesigned and manufactured again.

2.2.1. Determination of the Absorber Pipe Diameter

When a perfectly manufactured reflective paraboloid of focal length *f*, rim angle Φ_{rim} and an acceptance angle is aligned to the sun, reflection of the rays at the focal plane forms a circular image centered at the focal point. It has the diameter *d* given by (Aldos and Robert, 2001):

$$d = \frac{f x \theta}{\cos\Phi_{rim}(1 + \cos\Phi_{rim})} \qquad (Eq. 1)$$

However this calculation is for ideal situations. Since there exists a huge manufacturing error, the absorber tube should be made large enough to capture as much of the reflected solar energy from the collector surface as possible. Opposing this is the need to minimize absorber diameter to increase the concentration ratio of the collector and cut thermal losses. Sizing the absorber thus becomes a compromise between conflicting requirements.

2.2.2. Ray Tracing Tests

Parallel rays, from laser beam pointer, were emitted to the mirrors on the trough. The aim of this test was to investigate the volume where most of the reflected rays concentrate around the focal line. From this test it was found out that a 30 mm diameter pipe was an optimum size for the absorber pipe. Copper pipe, painted ABRO black, was chosen as the absorber pipe for its high thermal conductivity. Unfortunately a 30 mm diameter copper was not possible to find in nearby places hence the experiments were conducted using copper pipes of smaller diameters, 16 mm and galvanized steel pipe of diameter 22 mm.

Another set of experiment has been also done. This time the 16 mm copper pipe was impinged on a corrugated aluminum sheet as shown in figure 4. The sheet is folded 3 cm up and 3 cm down at both sides so that the reflected rays which lie above and below the 16 mm copper pipe would be captured.

Figure 4. Folded aluminum plate, coated with ABRO black.

2.2.3. Storage Tank and Cooking Stove Modifications

The cooking unit and storage tank were redesigned and manufactured in such a way that the volume and height of the cooking pot was reduced and made the oil level to just touch the lower part of the cooking pot as shown in figure 5 thereby, unlike the previous setup, maximum temperature was possible to get at the bottom of the cooking unit. Also copper pipes that were welded to the bottom of the cooking stove and the corrugated aluminum plate were found to aggravate heat losses, hence these all were removed in this final setup.

3. RESULTS

3.1. Initial Test Results

Temperature readings were taken at the inlet, outlet and the mid-absorber pipe, the inlet and outlet of storage tank, the cooking pot, and the ambient temperature. Figure 6 shows the schematics of the main components and temperature measuring points. Temperature and radiations measurements were taken using K type thermocouple and SP LITE Silicon pyranometer respectively. USB TC-08 temperature and voltage logger have been used for logging the temperature while METRON handled display is for logging the irradiance. Figure 7 shows the USB TC-08 data logger and irradiance measuring instruments.

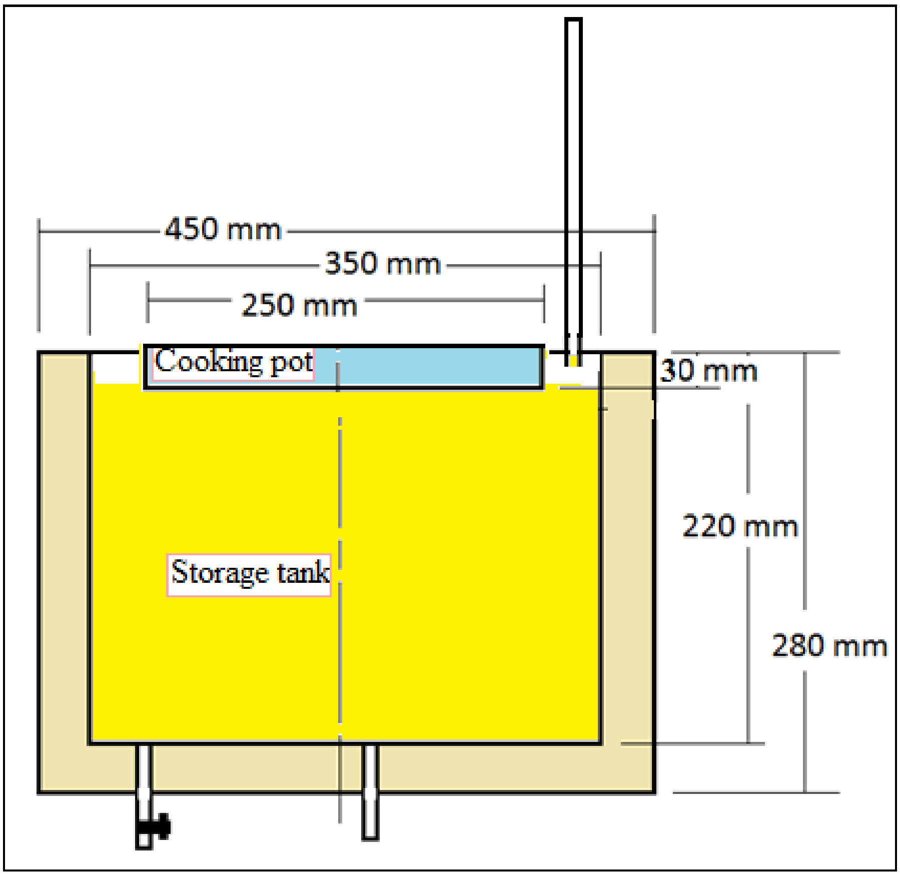

Figure 5. The modified storage tank and cooking pot.

figure 8 is an experimental result taken on 19 October 2010. 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 utmost. Maximum temperatures of 126^0C and 86^0C have been recorded at the mid absorber plate and cooking pot respectively.

As shown in figures 8 and 9 the temperature profiles have the same trend; the time response was very fast that is, the temperature increased sharply to its maximum within a short time then remained steady for much of the testing time until in the afternoon around 13:00 where it started to rise again to its maximum temperature.

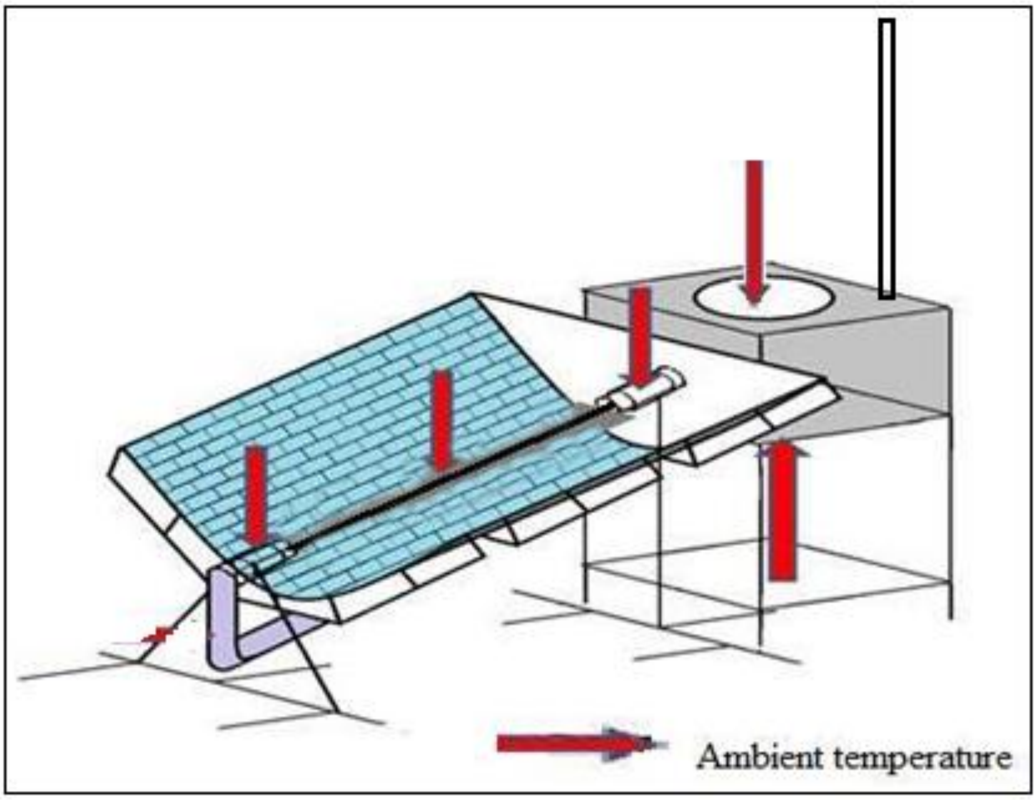

Figure 6. A schematic of the main components and temperature measuring points.

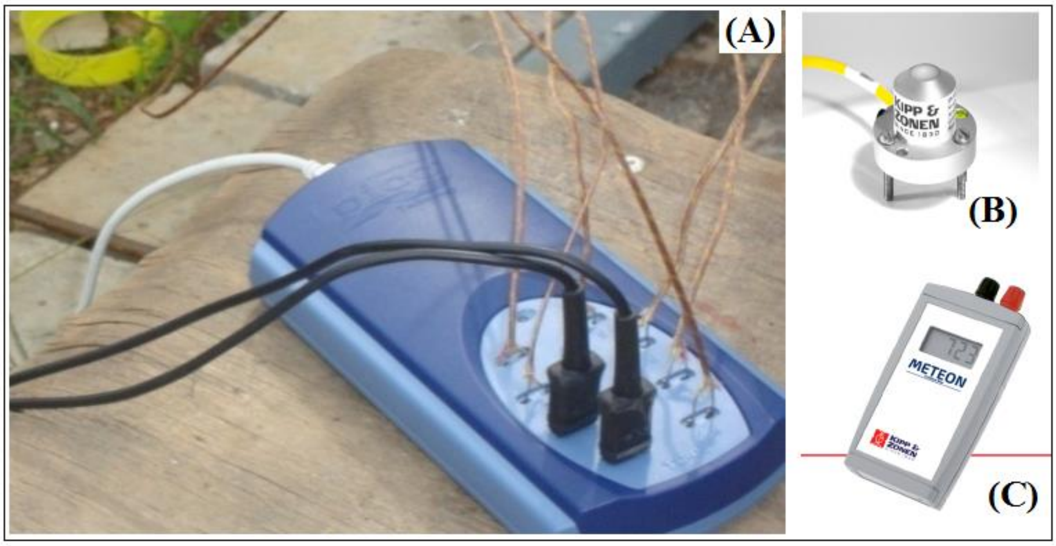

Figure 7. A) USB TC-08 data logger, B) SP LITE Silicon Pyranometer and C) Radiation data logger.

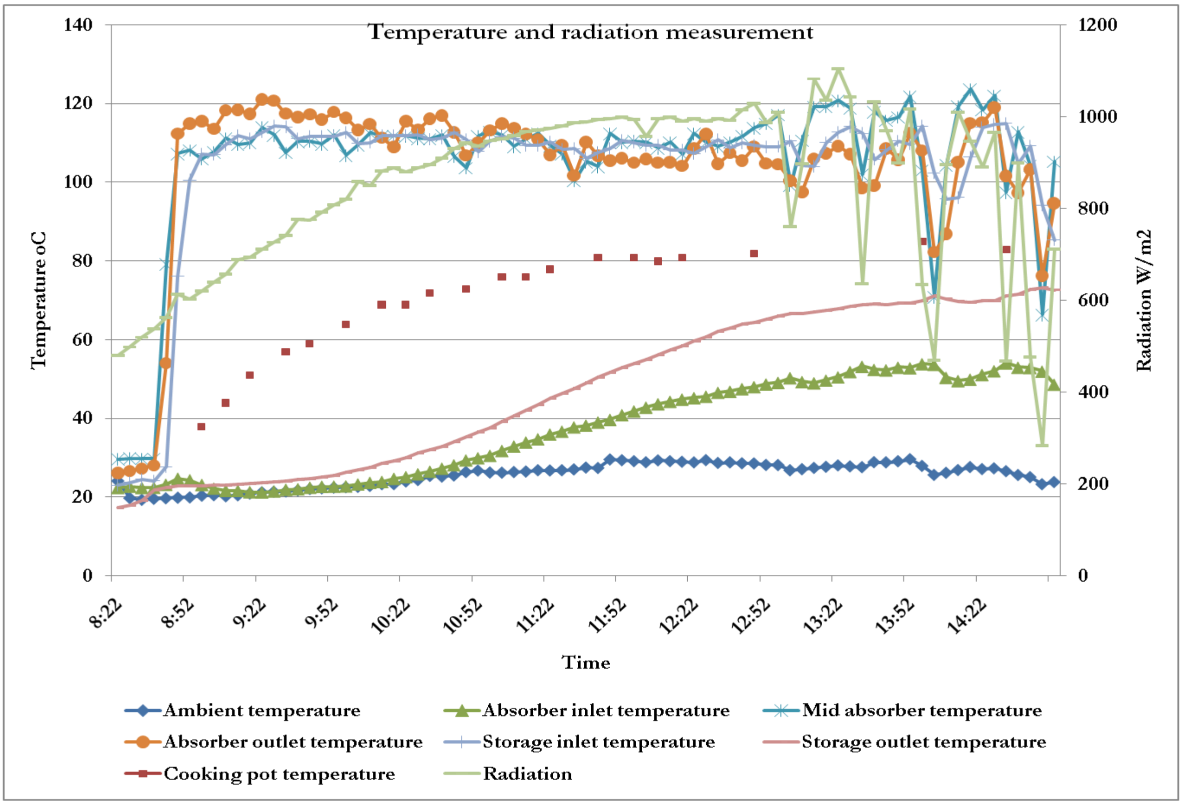

Figure 8. Radiation and temperature measured on 19th October 2010.

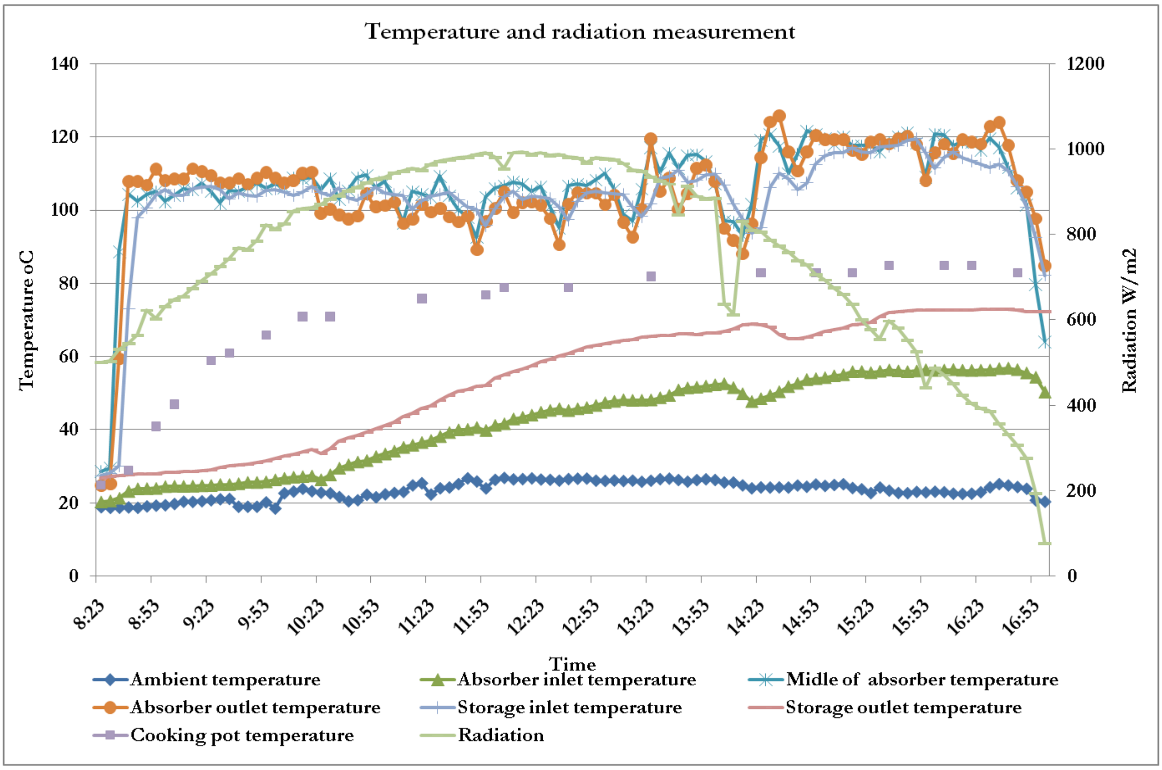

Figure 9. Radiation and temperature measured on 21st October 2010.

3.2. Final Test Results

3.2.1. Standard Stagnation Temperature (SST) Using 16 mm Copper Pipe as an Absorber

The *SST* test was done on February 19, 2011. Radiation and temperature readings recorded are shown in figure 10. The test started at 9:20 and continued until 14:24 for about five and half hours.

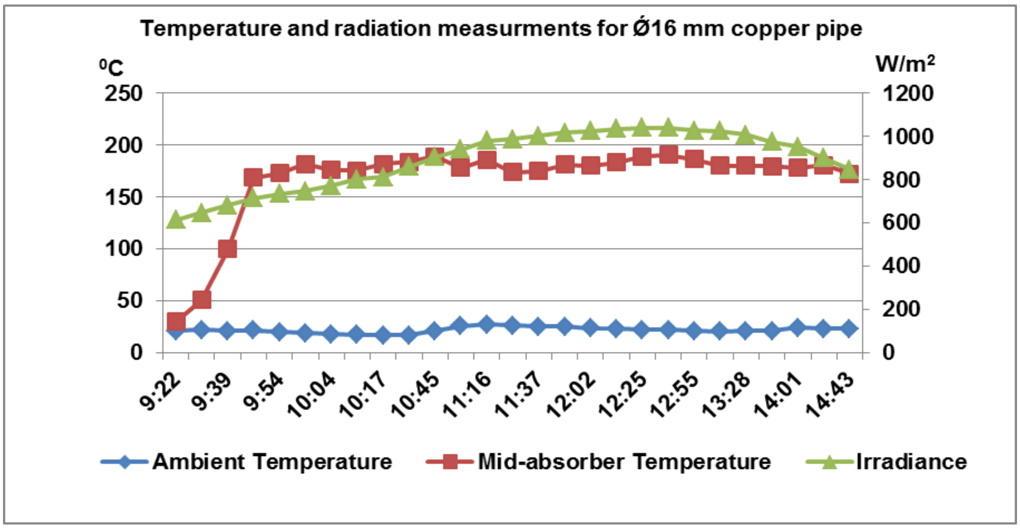

Figure 10. Radiation and temperature measured on 19th February, 2011.

The maximum temperature obtained on the mid absorber pipe was 191^{0}C. This temperature was recorded at 11:16 when the radiation reached 980 W/m^2. Looking at figure 10, it can be seen that the temperature of the mid-absorber pipe remained in the range 165^{0}C to 191^{0}C for quite long time and took less than 30 minutes to reach this range.

SST test gives the temperature to which the absorber will rise under a horizontal insolation of 850 W/m^2 and is given by (Petros, 2011):

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

Where T_s is maximum temperature of the mid absorber pipe (191^{0}C), T_a is the ambient temperature (25^{0}C) and $I_{measured}$ the radiation which corresponds to the maximum temperature (980 W/m^2). The SST for this test was then found to be 144^{0}C.

3.2.2. SST Using 16 mm Copper Pipe on a Corrugated and Folded Aluminum Plate as an Absorber Pipe

Temperatures were measured at the same points as the previous tests. Figure 11 shows the results. With this set up the maximum temperature obtained at the mid absorber pipe was175^{0}C; hence lower than the previous bare 16 mm copper pipe. This temperature was obtained at 14:24 when the radiation was 901 W/m^2.

It relatively took longer time to reach the maximum temperature than the previous set up.

SST = 142^{0}C

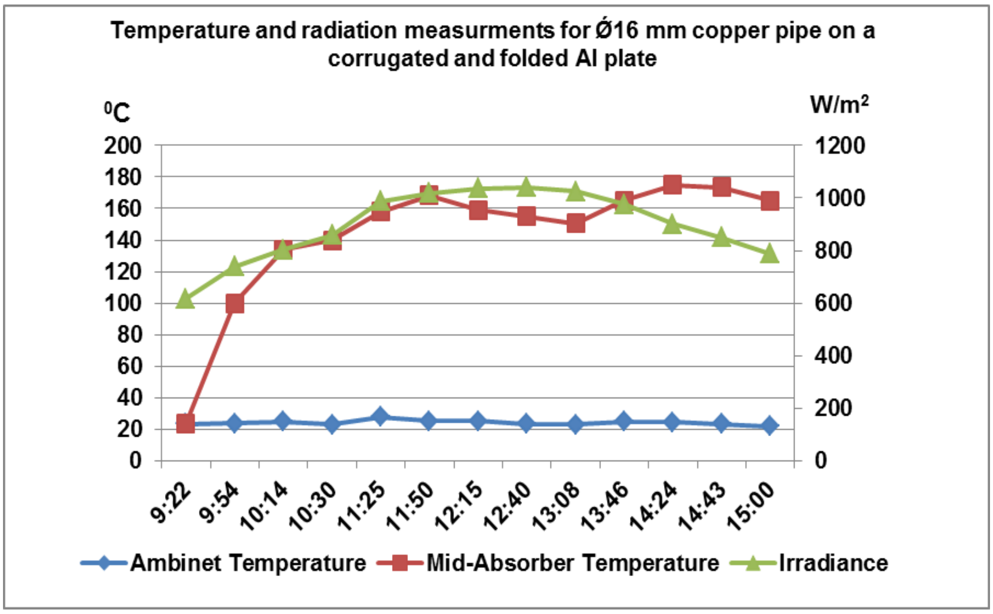

Figure 11. Radiation and temperature measured on 20th February, 2011.

3.2.3. SST Using Galvanized Steel as an Absorber Pipe

At this time the copper pipe was replaced by a galvanized steel of diameter 22 mm. Galvanized steel has lower thermal conductivity (18 W/m^2-K) than copper. The same points have been checked for the temperature. The results obtained are presented in figure 12.

The temperature on the mid-absorber pipe took more than 30 minutes to reach its average value. The maximum temperature obtained on the mid-absorber pipe was 178^{0}C. This was at 14.30 hours, and the corresponding radiation reading was 916 W/m^2. Had this absorber pipe been copper of same diameter, the maximum temperature would have been higher than 178^{0}C; because copper has higher thermal conductivity than galvanized steel. So this result is another indication to use copper pipe of greater diameters for the absorber pipe. The time taken to reach this maximum temperature was around 5 hours. As compared to the copper pipe test, this test has lower maximum temperature and it took relatively longer time to reach its maximum value.

SST = 143^{o}C

Of all these tests, the SST was found the highest, 144^{o}C, for the Ǿ 16 mm copper pipe.

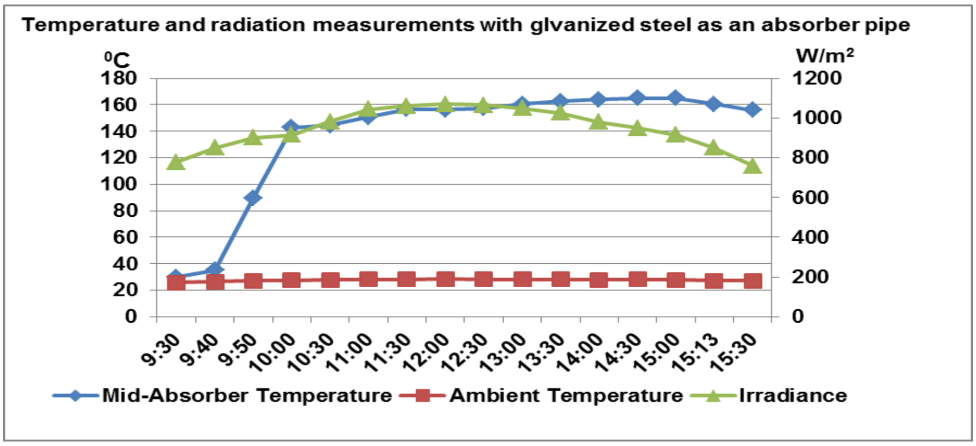

Figure 12. Temperature and radiation measured on 10th April, 2011.

3.2.4. No Load Test with the Heat Transferring Oil

This time an amount of 17.5 litres of the soya bean oil was filled- with the effects mentioned in section IV above - into the storage tank and piping systems. The standard stagnation test revealed that the Ǿ 16 mm copper absorber pipe gives the highest temperature; thus these next two experiments were conducted using this absorber pipe. Figure13 shows that maximum temperature of 126^{0}C was recorded at the cooking pot at around 14:30 hours when the radiation was 920 W/m^2.

It took two and half hours to reach 100^{0}C (water boiling temperature) at the cooking pot but the temperature started to increase fast from this temperature until it reached its maximum (126^{0}C) value. The cooking pot temperature stayed at an average temperature of 118^{0}C for quite a long time; thus the cooker can efficiently cook from 11:00 to 16:30; hence lunch, snack and in some places dinner can be well prepared with this solar cooker.

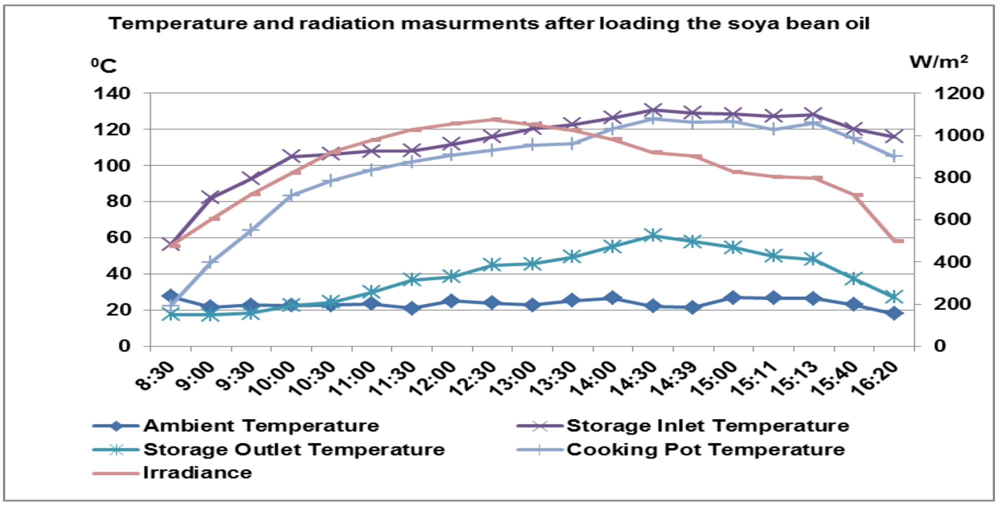

Figure 13. Radiation and temperature measured on 22nd March 2011.

3.2.5. Simulated Load Test Using 16 mm copper Pipe as an Absorber Pipe

The objective of this test was to see the highest temperature that could be obtained on the water in the cooking pot. This test was carried out on 25th March, 2011 from 9:06 to 15:30 for more than six hours. After few minutes, one liter of water originally at 25^0C was added to the cooking pot. When the water temperature reached 100^0C, eggs and potatoes were added to the cooking pot. Then the water temperature dropped sharply to 65^0C but after 20 minutes it again went on increasing and reached 100^0C. As it can be seen from figure 14, the cooking stove temperature remained steady for few minutes but later started to increase until it reached its maximum reading of 119^0C at 15:05.

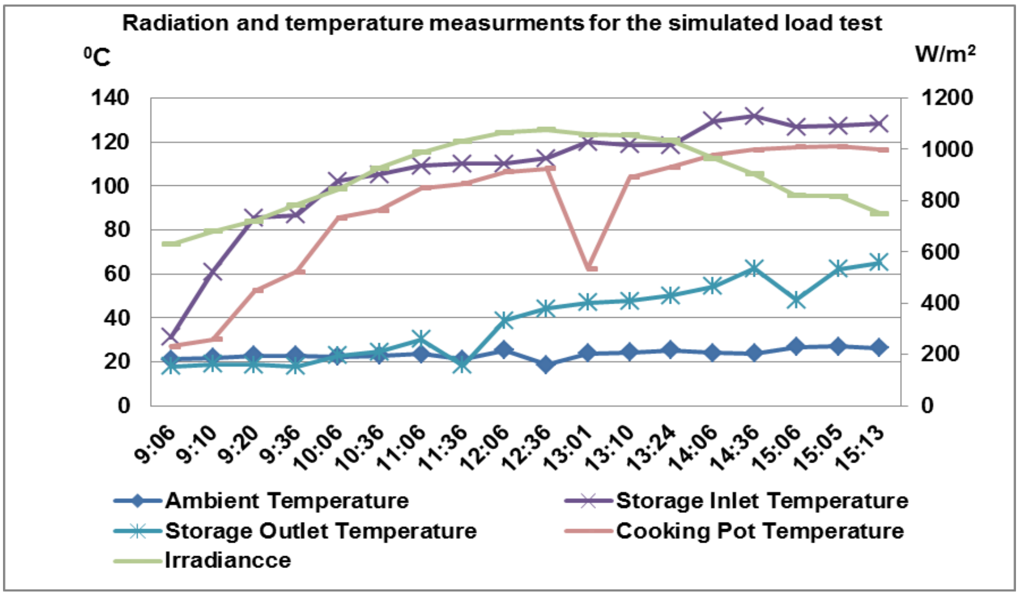

Figure 14. Temperature and radiation measured on 25th March, 2011.

3.2.6. No Load Test and Using Galvanized Steel as an Absorber Pipe

This test was conducted on April 12, 2011 from 9:30 to 14:45. At the beginning, the temperature on the mid-absorber pipe was the highest as compared to the other points (absorber outlet, storage inlet, cooking stove, storage outlet and absorber inlet) but as the oil temperature inside the pipes increases, the temperatures on the absorber outlet and storage inlet were higher than the mid-absorber temperature. Figure 15 shows that the maximum temperature achieved on the cooking stove was 103^0C at a radiation of 920 W/m^2. It took four hours to reach this temperature. From these experiments it was concluded that using copper pipe of diameter 16 mm for the absorber pipe results in the best performance for this solar cooker.

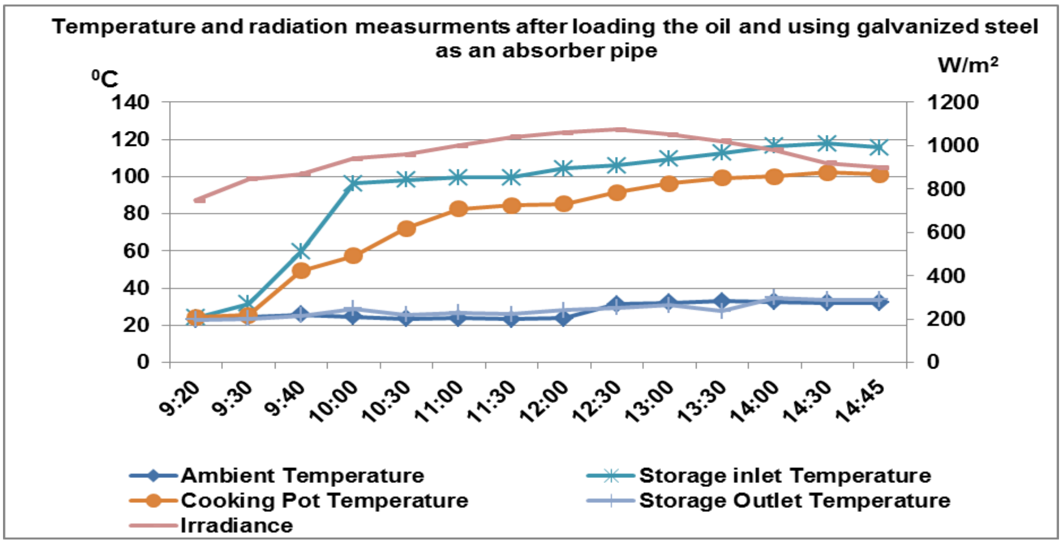

Figure15. Temperature and radiation measured on 12th April, 2011.

4. DISCUSSION

4.1. Thermal Efficiency of the Cooker

The thermal efficiency of the cooker given by equation 3 (Schwarezer et al., 2008) was calculated to be 6% and the power was found to be 288.5 W. This power rating is small as compared to LPG based cooking which is 1 KW (Singh, 2009). Thus the speed of cooking will be lower than the LPG based cooking speed.

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In this equation, **Error! Reference source not found.** is the mass of water in the cooking pot in kg, **Error! Reference source not found.** is the specific heat of water at constant pressure in J/(kg.K), t is the time in s, *A* is the area of the solar collector in m², and *I* is the flux of global solar radiation incident in the collector plane in W/m², **Error! Reference source not found.** represent the initial and final water temperatures respectively.

4.2. Economic Analysis: Simple Payback Period

Use of solar cooker can replace use of firewood, kerosene, LPG, and electric cooking. Depending on which fuel it replaces, payback period varies.

4.2.1. Energy produced by the cooker

Heat energy required for cooking for single person is 900 kJ (Chetan Singh, 2009). The parabolic cooker is designed to cook for a five head family but it can cook for, say, only 80 % of the meal (other part of the meal is considered as frying based food for most Ethiopians). Considering cooking two meals per day, the heat energy produced by the solar cooker per day is 5 x 2 x 80% x 900 = 7200 kJ/day.

Now assuming replacing an LPG, number of days required by the solar cooker to produce energy equivalent of LPG cylinder (Singh, 2009):

$$= \frac{Cylinder's\ total\ useful\ energy}{Energy\ produced\ by\ cooker\ per\ day} \qquad Eq.\ (4)$$

4.2.2. Energy content of an LPG cylinder

The calorific value of LPG (mixture of propane and butane) is 12.6 kWh/kg. An LPG cylinder typically will have 13.5 kg of gas, thus the total energy of a full cylinder is 12.6 X 13.5 =170 kWh/cylinder =612,360 kJ/cylinder. But only 60 % (Singh, 2009) of this energy is used (other part goes as waste), therefore useful energy is 612360 X 0.6 = 367,416 kJ/cylinder.

$$= \frac{367416\ kJ}{7200\ kJ/day} \qquad = 52\ days$$

A family of five members needs 7= (365/52) LPGs in a year. Cost of an LPG cylinder is 400 birr = $25.

$$Payback\ period = \frac{Cost\ of\ solar\ cooker}{Cost\ of\ energy\ saved\ per\ year = 7x400} = \frac{7{,}000}{2800} = 2.5\ years$$

The payback periods will be two and half years and assuming 20% efficiency for wood stoves this solar cooker can save 80,000 kg of fuel wood in ten years time, estimated to be the life time of the cooker.

5. CONCLUSION AND RECOMMENDATIONS

Performance tests and improvements have been made for a concentrating solar cooker. The system has two separate parts, cooker and collector. The cooking section is placed 0.5 m far from collector and these two parts were joined by a series of pipes with soya bean oil conveying the heat from the collector to the cooker. This arrangement helps to cook indoors or shaded area like the conventional cooking style.

Ray tracing together with the SST test showed that a 30 mm copper pipe is an optimal diameter for the absorber pipe.

Tests have been conducted with two sets of experimental setups. Maximum temperatures of 191^0C and 126^0C, under no load conditions, was obtained at the mid absorber pipe and cooking pot respectively when using a 16 mm diameter copper pipe as an absorber. A maximum temperature of 119^0C was achieved at the cooking pot when the cooking pot was loaded with water, eggs and potato. It was found that the cooker can efficiently cook from 11:00 to 16:30; hence lunch, snack and in some places dinner can be well prepared with this solar cooker. The payback period is two and half years and assuming 20% efficiency for wood stoves this solar cooker can save 80,000 kg of fuel wood in ten years time, estimated to be the life time of the cooker. Finally, the efficiency of the cooker has been calculated and the maximum value was found to be 6%.

The absorber pipe, heat transferring fluid, and natural circulation systems provide further areas of research. Glass envelope for the absorber pipe may reduce the heat loss from the absorber pipe – as in greenhouse effect- and hence improve the efficiency of the total system.

6. ACKNOWLEDGMENTS

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