DESIGN, MANUFACTURE AND EXPERIMENTAL INVESTIGATION OF LOW COST PARABOLIC SOLAR COOKER

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Abstract

In this paper theoretical and experimental study was performed on a parabolic solar cooker. A Simply designed and low cost parabolic type solar cooker was manufactured and tested. In order to reduce the cost of the cooker, the parabola cage is made from bamboo, which is a locally available material. Experiments were conducted to determine different figures of merit of the cooker. Temperature of pot contents, Ambient Temperature, Radiation data during the test and Wind Speed were measured and analyzed to determine Standard Sensible Heating Power, Standard Heating Time and Instantaneous Energy and Exergy efficiencies of the cooker. Besides, the experimental results for temperature distribution between pot content and ambient were compared with analytical result. Economic Analysis was also performed by comparing the solar cooker with equivalent energy supply from kerosene stove. The Payback period and net present value were determined by considering different economic parameters and overall cost of the cooker.

1 INTRODUCTION

The fast growing energy requirements, depleting traditional sources of energy and environmental pollution have forced Scientists to explore alternative energy sources of energy. Solar energy is a best substitute for other sources of energy due to its decentralized nature.

Ethiopia is situated in the horn of Africa around the equator between latitudes of 3^oN and 15^oN and longitudes of 33^oE to 48^o E and characterized by an abundant sunshine for the most periods of the year. The annual average daily solar radiation in Ethiopia is 5.6 kWh/m^2. More than 80% of the population lives in rural areas. Access to adequate modern energy resources for lighting as well as for cooking is among the critical problems in Ethiopia (Zenebe, 2007). According to Mulugeta (2009), about 94% of the energy consumption in Ethiopia comes from biomass energy sources, and 89% of the biomass energy supply is used by households for daily basic needs. Women and girls suffer extra health hazards from gathering fuel wood, caring heavy loads and indoor smoke from using low quality biomass fuels for cooking. Solar cooking liberates women from the back-breaking effect of collecting fuel wood, and from cooking each day for hours over smoky fires which damages eyes and lungs. Hence, they experience improved health and have more time to pursue education, increase food production and carry out income generating activities. Therefore, solar cookers help to promote gender equality and empower women.

According to solar cookers international (2009), Ethiopia is ranked at number four in the world and number one in Africa with regard to obtaining potential benefits from solar cookers. This ranking is based on total annual average solar radiation, national cooking fuel shortages or net energy imports, estimated population of the country by 2020, and an estimated percent of population by 2020 living with ample solar radiation and fuel shortages [11].

The application, designing and thermal performance of solar cookers studies have been carried out by many researchers (Habeebullah et al., 1995; Balzar et al., 1996; Clark, 1996; Funk, 2000; Algifri and Al-To-waie, 2001; Ahmad, 2001). In this paper concentrating type point focusing solar cooker is considered. A Point-focusing solar cooker consists mainly a paraboloid, a pot supporter, a reflector supporter, a regulating and tracking device and cooking utensils [12]. The use of concentrating type collector permits all operations, such as boiling, stewing, steaming, roasting, frying, and baking with relatively higher capacity [4]. The point focusing solar cooker makes the use of the optical characteristics of a paraboloid which concentrates direct solar radiation falling on a large area onto a smaller area and raises the intensity of the radiation, thus providing a heat focus for cooking [12]. The development of the parabolic shape is expected to be accurate to get best reflection for the collection of the incoming radiation to the focal point. But to some extent, the deviation of the reflected rays from the focal point does not affect the process rather required for even distribution of heat at the bottom surface of the pot.

Patel and Philip (2000) conducted stagnation temperature, water- heating and cooking tests to evaluate performance of three concentrating type domestic solar cookers. Habeebullah et al. (1995) presented work related to a parabolic concentrating type cooker using bare receiver and an insulated pot with a glazed insulation window. They showed that the oven – type receiver is highly efficient when compared with the bare type. The energy and Exergy efficiencies of low-cost parabolic type solar cooker have been determined by Ozturk (2004) using water heating test.

In this paper a simply designed parabolic type solar cooker was manufactured and tested. In order to lower the production cost, the parabola cage is made from bamboo which is locally available material. This new and inexpensive type of solar cooker represents a promising technology because of the following advantages it has: (i) it can be produced from locally available materials, (ii) it doesn't require a skilled person to operate (iii) it is environmentally friendly (iv) it doesn't require auxiliary controls hence low maintenance is required. The speed of cooking is practically independent of the heat rate, once the contents of the vessel have been sensibly heated up to the cooking temperature (Lof,1963), therefore, the testing procedure for the present work is based on the sensible heating of a known quantity of water up to the boiling point.

2. DESCRIPTION OF THE SYSTEM

2.1 The Parabola Cage

The parabola cage for this cooker is made from bamboo, which is a locally available material. In order to get parabolic pattern of the bamboo, an iron skeleton was made from angle iron using appropriate dimensions of the parabola and focal length. After completing the skeleton, the bamboo matt is developed on it. The bamboo matt is kept on the skeleton by fastening with thin Aluminum wires. The matt is kept on the skeleton until it dries well and maintains the required parabolic shape. It is then removed from the iron skeleton after it dries well. Finally the bamboo maintains the required parabolic shape which looks like the image shown in Fig. 1 below.

Fig. 1 Shape of Parabola Cage developed Using Bamboo

In order to mount the reflectors on the bamboo matt, it is first lined with gypsum, and stick paint is glued on the gypsum to mount reflector strips. Totally 36 small sizes of Aluminum strips were used to obtain the required parabolic shape on the surface of the bamboo matt. The increase in number of the Strips helps to approximate the required shape of the parabola. That is, as the size of the strips becomes smaller and smaller (fine) the parabola shape will be more approximated.

Fig. 2 Shape of parabola cage after mounting reflector strips

2.2 The Solar-Parabolic Cooker

The parabolic cooker considered for this study has an Aperture diameter of 1.445 m and a focal length of 0.28m. The Reflective area of the solar cooker is 1.64 m^2. A wood support is utilized to reduce the cost of the system. Iron structures are used to support the pot at the focal point. The use of wood structure to support the pot is avoided because of danger of burning of the wood itself. Although wood is used as support of the system during this experiment (From the point of view of reducing the cost of the system), it is proposed to change to steel structure with extra cost to avoid further consumption of the wood which affects the environment. For this system, solar tracking is done manually every 30 minutes.

Fig. 3 Final Shape of the Parabolic Solar Cooker with pot

2.3 Testing Procedure and Measurements

The experiments were conducted in Gewane City of Afar Region. It is a small place between the Asab-road and the Awash-river, in the north east of Ethiopia. . It has got an altitude of 617 meters above sea level. The testing was done using ordinary cooking Aluminum pot with a capacity of 5 liters of water. The pot is painted black in the outside surface and put at the focal point without any insulation. The test was performed based on the testing conditions outlined in the international standard procedure for testing of solar cookers.

The tests were conducted for three consecutive days from 10:00 to 14:00 solar time. The following quantities were measured during the experiment. Ambient air Temperature, water temperature profiles in the cooking pot, the instantaneous solar radiation and wind speed. The temperature of the water in the pot was measured by averaging the readings of Copper –Constantan thermocouples mounted at two points. The readings were recorded every ten seconds using Delta-T data logger. The solar radiation was also measured using GS1 dome Solarimeter.

3. THERMAL FIGURES OF MERIT OF THE COOKER

3.1 Standard Sensible Cooking Power

This Parameter is taken based on the temperature change of the test load under known insolation conditions. The values are corrected to a standard horizontal insolation of 700 W/m^2. The process for calculating this figure is nearly identical to that developed by Funk et al. in ASAE S580 [2] and is given below.

The temperature change of the water shall be measured over 10-minute intervals, and cooking power shall be computed by:

$$P = \frac{m_w c_w (T_2 - T_1)}{600} \tag{1}$$

Where $m_w =$ Mass of water in cooking pot, $c_w =$ Specific heat of water, $T_2 =$ Water temperature at end of interval, $T_1 =$ Water temperature at beginning of interval. Equation 1 is divided by 600 because there are 600 seconds in each 10-minute interval. The standard sensible cooking power is obtained by normalizing the cooking power by 700 W/m^2 through eq. (2) as:

$$P_n = P\left(\frac{700\,W/m^2}{I}\right) \tag{2}$$

Where, $I =$ Horizontal insolation averaged over the 10-minute interval.

Finally, these equations must be reduced to a single measure of performance. This is done by plotting P_n against ΔT and performing a linear regression, where ΔT refers to T_{water}-$T_{ambient}$ (recorded for each interval). Based on the regression fit (R^2 >0.75) the standard sensible cooking power is taken at ΔT = 50 °C.

3.2 Standard Heating Time

Sensible heating time is more important to the user than power and temperature. It is normally the time taken to perform a cooking function. Therefore, this figure of merit indicates how long it will take the cooker under investigation to heat a known quantity of water to 50°C above ambient temperature under a horizontal insolation of 700 W/m^2.

The sensible heating time is given by:

$$t = \frac{m_w c_w \Delta T}{\eta_0 A I} \tag{3}$$

Where η_0 is the combined optical and heat transfer coefficient.

The standard sensible heating time is obtained by normalizing eq. (3) and given by:

$$t_0 = \left(\frac{I \Delta T_0}{I_0 \Delta T}\right) t \tag{4}$$

Where I_0 is 700 W/m^2. and ΔT_0 is 50°C.

4. ENERGY AND EXERGY EFFICIENCY OF THE SOLAR COOKER

Energy efficiency of a solar cooker can be defined as the ratio of energy output (only the increase of the water energy due to temperature growth) to the energy input (the energy of solar radiation) [8]. Thus the instantaneous energy efficiency of the cooker is given as:

$$\eta_I = \frac{mc_p \lfloor T_{fw} - T_{iw} \rfloor}{IA\Delta t} \tag{5}$$

Where m is the mass of water in the pot, T_{fw} and T_{iw} are the final and initial temperatures of water in the time interval Δt, c_p is the specific heat of water and A is the area of the reflector.
Petala (1964) examined for the first time the Exergy of solar radiation, and concluded that thermal radiation from the sun is relatively rich in Exergy. Bejan (1987) presented a unified theory. $Ex_{in,solar}$ or Exergy of solar radiation per unit collection area reaching the ground is [5]:

$$Ex_{in,solar} = I\left[1 - \frac{T_a}{T_s}\right] \qquad (\mathrm{W/m^2}) \tag{6}$$

Where I is the mean solar radiation intensity between consecutive reading and T_a is the ambient temperature.T_s is the temperature of the sun and is taken equal to 5600 K.

The second law efficiency or Exergy efficiency is defined as the ratio of cooker output Exergy (increase of Exergy of water due to temperature rise) to the Exergy input (Exergy of solar radiation). Thus the instantaneous Exergy efficiency is given by:

$$\eta_{II} = \frac{mc_p\left[\left(T_{fw} - T_{iw}\right) - T_a \ln\frac{T_{fw}}{T_{iw}}\right]}{I\left[1 - \frac{T_a}{T_s}\right]A\Delta t} \tag{7}$$

5. ANALYTICAL FORMULA FOR SOLAR COOKER DESIGN

In order to design a parabolic solar cooker a few basic equations are sufficient. Normally a parabolic solar cooker is a storage collector without any power transported out of the system. The energy balance of this system with the equation of the cooker efficiency is:

$$mc\, {d\theta}/{dt} = \left(\eta_0 I - K\theta\right)A \tag{8}$$

Where: m is the mass of the water in kg, c is the specific heat capacity of water in KJ/kg.k, θ is the temperature difference between pot content and ambient, η_o is the optical efficiency of the solar cooker, I is the solar radiation in W/m^2, K is the thermal loss coefficient in W/m^2.k and A is the cooker aperture area in m^2.

The thermal loss coefficient can be calculated from the data of the heat-loss test and given by [10]

$$K = \frac{mc}{t_{end} - t_{start}} \ln\left(\frac{\theta(t_{start})}{\theta(t_{end})} \right) \tag{9}$$

After simplification, eq. (8) can be written in simplified form as:

$$\theta(t) = \frac{K_1}{K_2}\left(1 - e^{-K_2 t}\right) \tag{10}$$

Where K_1 and K_2 are constants to be evaluated as:

$$K_1 = \frac{\eta_0 IA}{mc} \quad and \quad K_2 = \frac{KA}{mc} \tag{11}$$

6. ECONOMIC ANALYSIS OF THE SOLAR COOKER

Solar processes are generally characterized by high first cost and low operating costs. Thus, the basic economic problem is comparing an initial known investment with estimated future operating costs. Solar energy equipment is bought today to reduce tomorrow's fuel bill. The objective of the economic analysis can be viewed as the determination of the least cost method of meeting the energy need, considering both solar and non solar alternatives. Here the method of discounted cash flow analysis is used rather than the straight payback period.

6.1. Net Present Value

The net present value NPV of an investment is the difference between the total present value of the future savings and the capital cost of the investment. i.e.

$$NPV = \sum PV - C_I \quad Where \;\; C_I \;\; is \; the \; initial \; investment \tag{12}$$

By applying the above equation for each year of the life span of the solar system for all future payments on maintenance and for all future energy savings, the total present worth can be determined. If the calculated net present value is positive, then money will have been made by installing the solar system.

6.2 Pay Back Period

The payback period (PBP) for the investment is the number of years for which the net present value (NPV) is zero, or it can be defined as the time needed for the cumulative savings to equal the initial investment.

$$pay \;\; back \;\; period = n_p = \frac{\ln\left[1 + \frac{C_I\,(i_e - i)}{C_e}\right]}{\ln\left[\frac{1 + i_e}{1 + i}\right]} \tag{13}$$

Where C_e is the first year energy saving, C_I is the initial investment, i is the interest rate on the money, i_e is the inflation rate of the saved energy cost, n_p is the life span of the project.

7. RESULTS AND DISCUSSION

As mentioned before, the experiments were conducted in Gewane City of Afar Region. It has latitude of 10.2°N, Longitude of 40.7°E and altitude of 617 meters above sea level. Different tests were conducted between 10:00 and 14:00 solar time. The measured values for ambient temperature, wind speed and beam radiation satisfy the required measurement standards. Test results were analyzed and the thermal figures of merit of the cooker were determined based on the previous equations. The calculated energy and exergy efficiencies are also displayed here.

7.1 Water Heating Test

Figure 1 shows the change of water temperature in the pot as a function of time for one of the tests. During the experiment the solar radiation increased from 467 W/m^2 to 596 W/m^2 and the water temperature in the pot increased from 309K to 364K. The maximum temperature was reached approximately after 1 hour. During this time the ambient temperature varies between 306K and 307K.

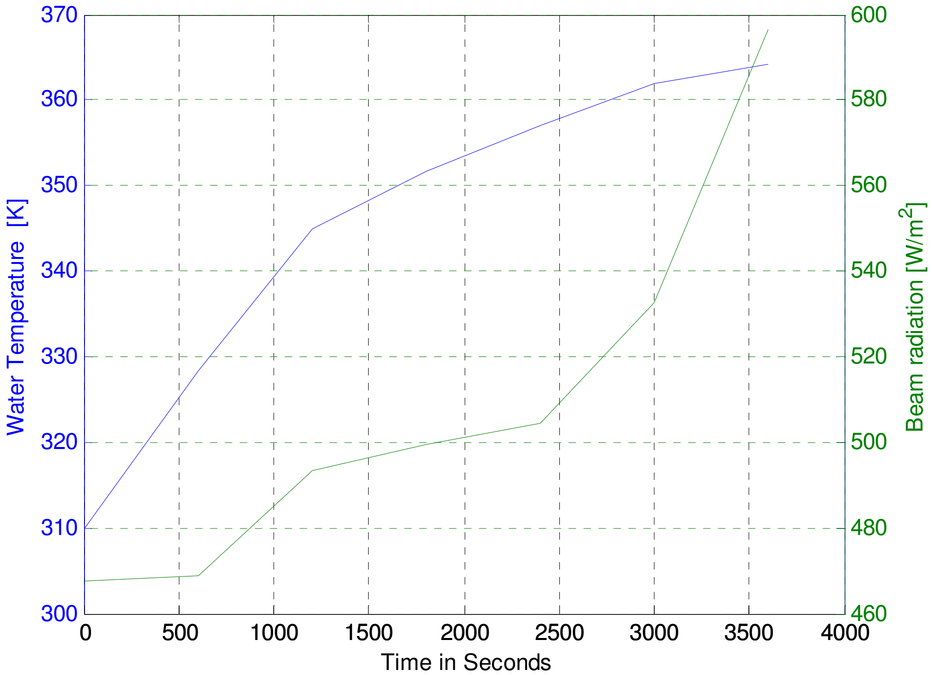

Fig. 4 Variation of water temperature and solar radiation with time

7.2 Standard Sensible Cooking Power

The standard sensible cooking power provides an insight as to the cooker's ability to cook food but it also allows for devices tested under the proposed standard to be compared to devices tested under any other standard. In order to get this figure, the sensible cooking power was determined using eq. (1) from test results for three consecutive days and normalized using eq. (2). A plot of normalized sensible cooking power (P_n) with temperature difference between water in the pot and ambient air (ΔT) was made as shown in Fig. 5.

The data was analyzed using linear regression. R^2 values of 0.88, 0.969 and 0.927 were obtained for test1, test 2 and test 3 respectively. These values are above the lower limit of the recommended regression coefficient for tests (R^2>0.75). The standard sensible cooking power of the three tests was determined using at ΔT values of 50 ^oC for all the three tests and has values of 169.77 W, 196W and 223 W for Test 1, Test2 and Test 3 respectively.

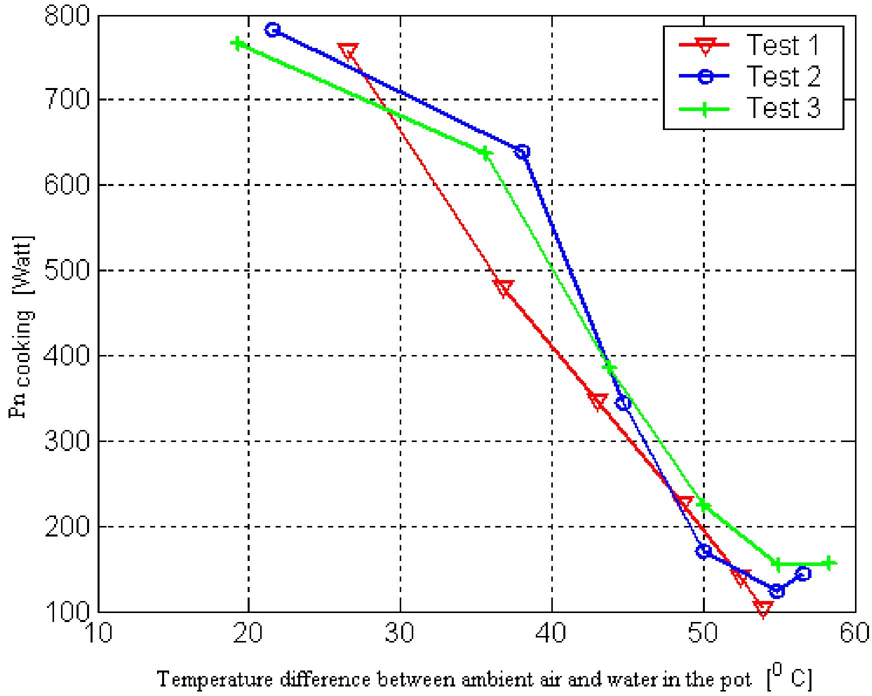

Fig.5 variation of sensible cooking power with temperature difference

7.3 Standard Heating Time

The standard heating time was calculated from the sensible heating test. It takes approximately 40 minutes for water temperature to increase by 50 ^oC above ambient air. Taking average value of 550 W/m^2 of radiation and employing eq. (4) standard heating time of 40.44 minute was obtained. Hence after approximately 40 minutes, the water temperature in the pot increased by 50 ^oC.

7.4 *Energy and exergy Efficiency of the cooker*

The variation of instantaneous energy and exergy efficiencies as a function of time is presented in fig. 6. The energy efficiency varied from 15.25% to 49.2%. The exergy efficiency varies from 2.3% to 4.4%. Instantaneous energy decreases continuously with time due to less heat energy gain as the temperature of water increases. Whereas, the instantaneous exergy efficiency of the cooker increases reaches a peak value and then decreases with time, which shows that for maximum instantaneous exergy efficiency, the instantaneous initial temperature must be optimum.

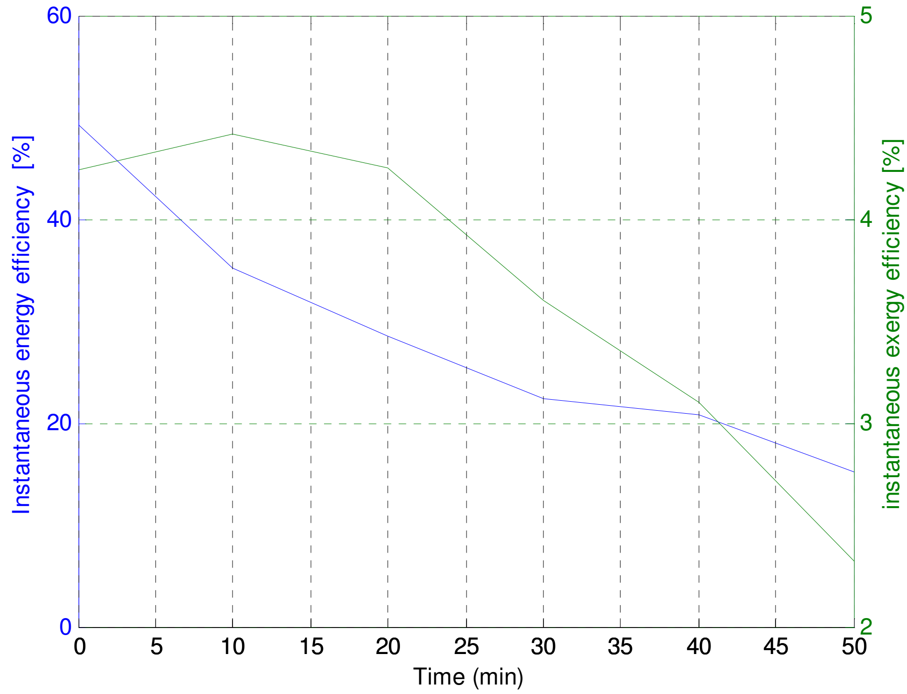

Fig 6. Variation of Energy and Exergy efficiency of the solar cooker with time.

The cooker has an average instantaneous energy efficiency of 32.2% and an average exergy efficiency of 3.35%. Energy and exergy efficiencies are mainly affected by the level of water temperature, solar radiation energy and ambient temperature. The combination of the three factors generates characteristic maximum exergy efficiency, whereas the energy efficiency keeps on decreasing during the test.

7.5 Comparison of Values obtained by Analytical equation and Experiment

Experimental results for temperature difference between pot content and ambient air were compared with Analytical equation given by eq. (10). Summary of the comparison is shown in Table 1 below.

Table 1 Summary of Comparison of analytical and experimental values

Time [second]	$\theta(t)$ obtained using equation (11) $[^0C]$	$\theta(t)$ obtained by measurement $[^0C]$	Percentage error [%]
600	24.1815	26.5500	8.9208
1200	37.5284	36.8100	1.9143
1800	44.8951	42.9700	4.2881
2400	48.9612	48.6500	0.6356
3000	51.2054	52.4700	2.4101
3600	52.4441	53.9700	2.8273

The data is plotted with time as shown in fig below. From fig. 7 (Table 1) it can be observed that, the Analytical formula gives reasonable results compared to experimental results. Hence the formula can be used to observe the time it takes to raise a given amount of water above ambient air temperature.

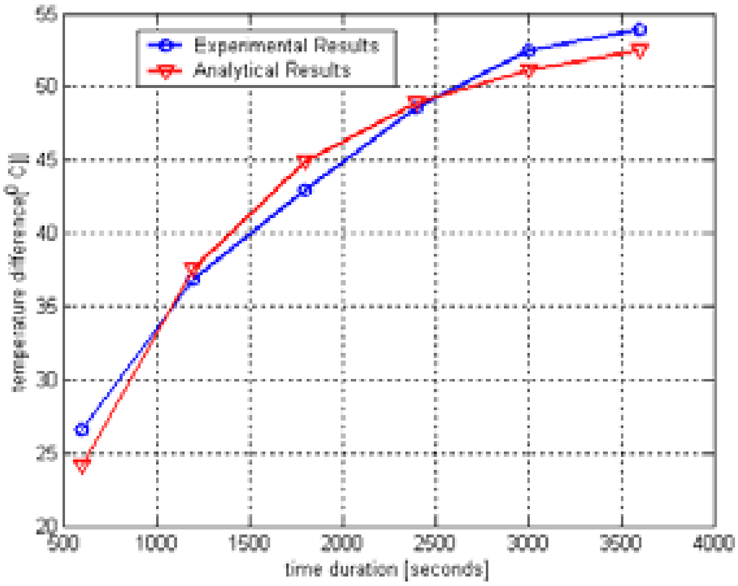

Fig. 7 Comparison of Experimental and Analytical results

7.6 Net Present Value of the cooker

The economic analysis of the cooker is performed by taking energy of kerosene stove as a base line. The net present value is computed by assuming that the initial capital is a loan which will be paid in yearly basis. It was assumed that the cooker can boil 15 liters of water per day. For kerosene stove efficiency of 30% (the efficiency of kerosene stoves used in most of the households of Ethiopia is 30%), approximately 107.2 liter of kerosene is required per year. The current price of kerosene is taken as 20 birr. Thus, the yearly cost of kerosene would be 2144 birr. The initial investment cost of the cooker is 800 birr. Maintenance cost of 200 birr, annual kerosene cost inflation rate of 10% annual maintenance cost inflation rate of 5%, annual interest rate of 10% and a five year life span of the cooker were assumed for the analysis. (1USD ~ 17.00 Birr)

The Economic parameters of the cooker are summarized in table 2 below.

Table 2 Summary of cash flow of Economic parameters of the cookers

year	Kerosene cost savings per year[birr]	Present Value of kerosene cost savings[birr]	Maintenance cost per year[birr]	Present value of Maintenance cost per year[birr]
1	2144.0	2122.8	200.0000	198.0198
2	2358.4	2311.9	210.0000	205.8622
3	2594.2	2517.9	220.5000	214.0151
4	2853.7	2742.3	231.5250	222.4910
5	3139.0	2986.7	243.1013	231.3025
Net present value		12681.60		1071.691

As summarized in table above the net present values of the Kerosene cost savings and the present value of maintenance costs are added. Hence using equation (12)

$$NPV = \sum PV - C_I \quad Where \ C_I \ is \ the \ initial \ investment$$

$$\sum PV = net\ present\ value\ of\ Kerosene\ \cos t\ savings - Net\ present\ value\ of\ Ma\text{int}\,enace\ \cos t$$

$$\sum PV = 12681.6\ birr - 1071.691 birr = 11609.909\ birr$$

$$\Rightarrow NPV = 11609.909\ birr - 800\ birr = 10809.909\ birr$$

Since the net present value is positive, money is saved by using the solar cooker and this shows that the project is Economical.

7.7 Payback period

The payback period is determined considering the discounted cash flow analysis method using eq. (13). Where the first year energy saving C_e is 2144 birr, is the initial investment C_I is 800 birr, the interest rate on the money i and the inflation rate of the saved energy cost i_e are 10% each. Based on this data a payback period of 0.4 year or approximately five months is obtained. Hence the money invested on the cooker can be returned in approximately five months period, which is very short, compared to the five year life span of the cooker.

8 CONCLUSION

The solar cooker considered in this study can effectively be applicable in most parts of Ethiopia especially in arid zones due to its low initial and running costs. The increase in number of Aluminum reflecting panels on the parabola cage allows approximating the shape accurately and this helps to increase collection efficiency of the cooker. From experimental results, it was observed that as time goes on the incoming solar radiation is used to compensate for the heat loss rather than heating the water, which results in lowering the instantaneous efficiency of the cooker. The exergy efficiency of any solar cooker is low because input solar radiation is rich in exergy and being utilized in the form of heat at low temperature. The cooker has acceptable energy and Exergy efficiency when compared to other cookers reported in literature. It was observed from the study that, there is good relationship between experimental result and results obtained using analytical formula. The economic analysis performed on the cooker indicates that the cooker has a very short payback period compared to its life span. This is due to its low initial and running costs.

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