Design, Construction and Testing of Hybrid Solar-Biomass Cook Stove

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Abstract. Many investigations have been conducted in biomass stoves to improve performances and minimize unfavorable effect on both human health and global climate. Solar cookers are also great area of investigation which can cook food without burning any wood. But a solar cooker cannot replace the traditional energy source completely; even in the sunniest regions there will be days and hours the sun doesn't provide enough power to cook meal. Recent researches and investigations are focused on improving the efficiency of existing only biomass or only solar cookers and there is a research gap in combining solar and biomass for cooking. A combined cook stove is another research dimension for intervention with an intention of using the benefit of the free solar energy to save biomass fuel. In this work, design, fabrication, and testing of portable solar-biomass combined cook stove have been done. The test was done by using only biomass, only solar and combined energy sources for cooking. The results show that the biomass stove with reflectors under the sun gives a 5% thermal efficiency rise and 6 g/L reduction in fuel consumption when compared to the only biomass stove. When only solar box oven used the first figure of merit was found to be 0.12 and second figure of merit found to be 0.55.

Keywords: Solar-biomass combined cook stove · Water boiling test · Figure of merit

1 Introduction

Traditional and inefficient ways of cooking using biomass have harsh effect on both human health and global climate. Also too much dependence on biomass energy minimize agricultural productivity, crop residues and animal wastes which can supplement soil nutrition. Similarly, scarcities of wood has become more serious; rural household who depend on collecting free wood have to travel long distances to obtain wood fuel which causes loss of human availability for productive work. Especially, in regions where biomass is scarce, time and effort spent to gather firewood can be a significant burden on households, particularly children and women. Furthermore, wood fuel depletion will promote deforestation and lead to a general degradation. The energy

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problem in Ethiopia is not much use of non-renewable energy sources; instead the problem is one form of energy reliance which is on wood fuel being consumed at an unsustainable rate. People in developing countries like Ethiopia burn biomass fuel to meet home energy needs for heating and cooking. In Ethiopia majority of the population cooks their food and bake the most popular food called Injera on an open fire inside or outside of their homes by burning various forms of biomass such as wood, charcoal, crop residues and dung. Burning each of these biomass fuels emits dangerous chemicals and large amounts of particulates, which have adverse effect on human health, global climate and regional ecosystems [1].

The government and non-governmental organizations have been struggling to provide people with cleaner and more efficient cook stoves as an alternative to traditional cooking methods. Great improvements have been made in cook stove technology. Examples of such improvements include reducing fuel usage of the stove by increasing thermal or heat transfer efficiency and reducing harmful particulate matters by increasing the combustion efficiency. All these improvements have allowed stove designers and manufacturers to provide more effective improved cook stoves to the people who need them. Despite, these considerable and appreciable improvements in cook stove performance many households in developing countries like Ethiopia still rely on inefficient stoves and procedures to cook their food because they cannot afford an improved stove imported. An effective way to provide people with better cooking options is designing cooking technologies that are appropriate for local socioeconomic conditions and cooking culture and seeking an opportunity to transform them into valuable assets.

Improved cook stoves can be designed and constructed depending on the local conditions. A comprehensive review of 50 different cook stove models tested by MacCarty, and found that, the fuel use was reduced by 33%, in comparison to the three-stone fire [2]. Other different studies conducted to assess the performance and use of household biomass cook stoves under field conditions in Africa, Asia and southern America [3–6]. Generally current investigations are intended to improve combustion and heat transfer to the pot, with the aim of improving stove efficiency and reducing pollutant emissions [7]. Solar cookers can be an alternative for the limitations of biomass cookers which is a device that cooks food using only sun energy in the form of solar radiation without consuming fuels or heating up the kitchen. However, the sale and distribution of solar cookers seems did not get off the ground because of its limitation. Different studies conducted to evaluate the performance and usability of solar cookers [8–12].

This study was motivated to use both the benefit of biomass stove and solar reflectors to add up their gain through combined performance and use interchangeably when appropriate to use only biomass or only solar energy. Current researches are focused on improving efficiency of existing cook stoves. A combined cooking system is another research dimension for intervention. In this study the basic features of solar box and biomass cooker investigated to combine them for cooking, which will enable to save dry fuel by using the benefit of the free solar energy.

2 Methodology

2.1 Design Considerations

Design considerations include size, material cost, durability, fuel efficiency, ease of use, cost to customer, marketability, approximate cooking time, indoor air pollution, assembly, safety, maintenance, availability of materials, solar energy potential, optical properties of the reflecting material, cooking power or overall efficiency, daily cooking time, amount of food to be cooked and type of use.

2.2 Sizing Methodology

The stove is designed to meet the cooking energy requirement of a family of six members. The stove size was estimated as follows.

Step 1: Estimation of energy needed which refers to the amount of heat that needs to be supplied by the stove to cook.
Step 2: Estimation of energy Input which indicates the amount of energy given in terms of fuel to be fed into the stove.
Step 3: Estimation of the size based on the energy requirement.

From the estimation maximum of 3600 kJ/h energy is needed for one time use of the cooker. The amount of energy needed in terms of fuel to be fed into the stove is found to be 0.5 kg biomass per hour. Next step is estimating the size of the combustion chamber which should be enough to take an enough amount of wood needed for cooking. The combustion chamber size is a function of a number of variables such as the required time to operate the burning, the burning rate and the density of biomass wood. The diameter and height of the combustion chamber or the furnace is found to be 0.12 m and 0.2 m respectively.

2.3 Material Selection Methodology

The combined stove was constructed from different materials in which number of criteria was considered for the selection of construction materials. The criterion includes affordability, strength, availability, weight, machinability, heat resistance, melting point of the material, reflectivity. For selection a numeric decision matrix is used to compare solution variants or candidate materials against one another using specific criteria that were mentioned above. Based on decision matrix, mild steel sheet is selected to construct the combined stove's body. Portland cement is selected to construct the combustion chamber insulation, and aluminum is selected for a reflector. Mild steel is also selected for fuel grate and glass wool for solar box insulation.

2.4 Combustion Air Requirement

The quantity of air to be supplied for the combustion process is determined by the chemical composition of eucalyptus tree. For an actual air supply which is 20% in excess of stoichiometry, actual air-fuel ratio is found to be 6.96 kg air/kg fuel. The area of air opening of the stove for combustion air inlet was checked.

2.5 Design Description

The stove has one opening and the fuel is putted over the grate, after cooking ash can be collected under the grate. The biomass stove is circular consisting of combustion chamber in which surrounded by insulating material to prevents heat losses (Fig. 1).

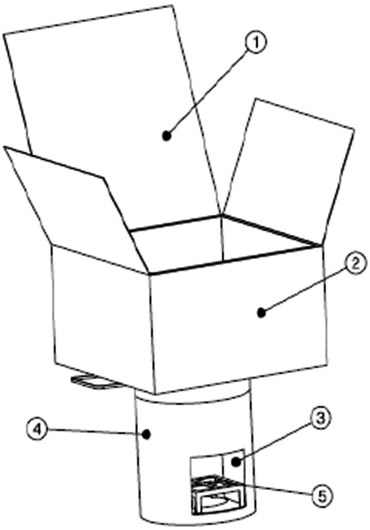

Fig. 1. Pictorial drawing of the combined stove (1- Reflector, 2- Box, 3- Combustion chamber insulation, 4 - Stove body, 5 - Fuel grate)

When the biomass is used fully the reflector can be dropped down to each sides. But the box is used to retain some heat.

2.6 Heat Transfer

It is known that huge amount of heat is lost to the ambient environment conduction, convection, and radiation. Therefore, to minimize the losses and maximize the useful heat transfer to the cooking vessel a careful analysis of heat transfer mechanisms is very important to predict the losses and to minimize the losses through modifications. Each heat transfer modes have losses and gains. The losses are associated with heat that is transferred into the stove body or out to ambient while the gains are associated with heat that is transferred to the cooking vessel. Heat Transfer contribution with losses and gains quantified and Summarizes in Fig. 2.

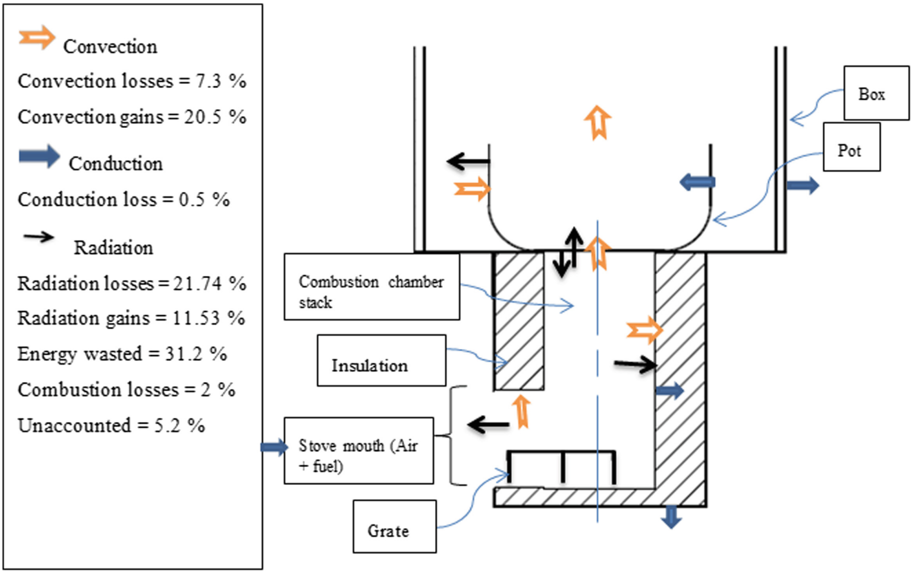

Fig. 2. Schematic of stove cross-section with heat transfer modes contribution.

2.7 Method of Fabrication

The following steps were implemented to construct the combined stove.

- Dimensions were specified for all components and material selected according to the function as it was discussed in the material selection.
- Parts/components were fabricated separately in metal shop.
- Parts were assembled in the way that disassembly is possible.
- Painting and other esthetic was completed.

Table 1. Process and tool required to construct the combined stove

Process	Tooling required
Shearing bulk stock to size	Sheet metal shearing press
Blanking of inlets/fuel opening	Sheet metal blanking press
Rolling into tube form	Sheet metal bend roller
Seaming of edges to form finished tube	Sheet metal vertical seaming machine
Permanent attachment	Welding machine
Attachment of top box to the stove	Force fit and Rivet Gun
Attachment of reflectors to the box	Hinge and lock
Painting	Spray

2.8 Experimental Methods

The water boiling test was done to measure performance metrics when only biomass was used and when biomass is used with the reflectors under sunshine. The amount of same type fuel wood was weighed for each series of tests. The cooking vessel and thermocouple were weighed before a measured amount of water was poured to the pot to determine the final weight of the water after test. The weighed fuel wood was introduced into the combustion chamber and kerosene was sprinkled for ignition. The pot was placed on the stove and the time, the ambient temperature and the initial temperature of the water were recorded. The temperature of the water was recorded at intervals of five minutes until the water reached the boiling point of Bahir Dar which is around 94 °C. The pot was then removed from the stove, and the fire instantly putted out. The final weight of the remaining water, charcoal, wood and the final temperature of water were then measured and recorded. The hot start test followed after the cold start high power test with same procedure. The test was repeated three times for each case. During experimental work different measuring instruments were used like K-type thermocouple (accuracy ± 1.0 °C, resolutions 1.0 °C), digital weight measuring device, contact type thermometer, digital infrared thermometer and stopwatch (Table 1 and Figs. 3, 4).

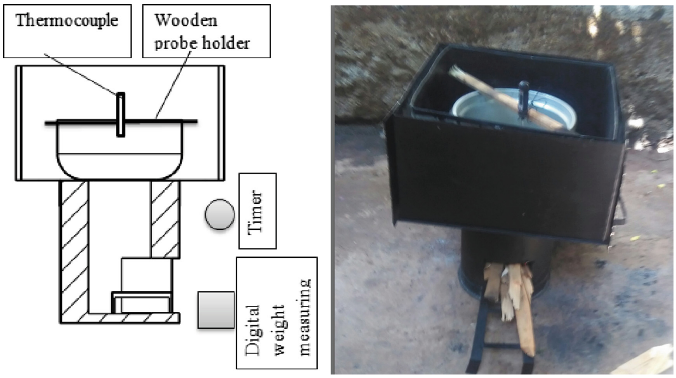

Fig. 3. Water boiling test set up without reflectors (only biomass)

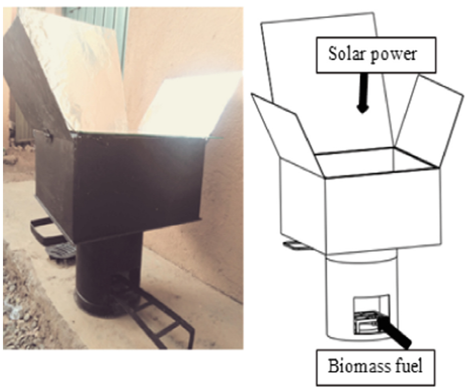

Fig. 4. Water boiling test with reflector

3 Result and Discussion

Variables that are directly measured

f_{hi} Weight of fuel before test (grams)
P_{hi} Weight of Pot with water before test (grams)
T_{hi} Water temperature before test (°C)
t_{hi} Time at start of test (min)
f_{hf} Weight of wood after test (grams)
c_h Weight of charcoal and container after test
p_{hf} Weight of Pot with water after test (grams)
T_{hf} Water temperature after test (°C)
t_{hf} Time at end of test (min)

Variables that are calculated are listed below [7].
Temperature adjusted time to boil pot

$$\Delta t_h^T = (t_{hf} - t_{hi}) \times \frac{75}{(T_{hf} - T_{hi})} \tag{1}$$

Thermal efficiency

$$h_h = \frac{4.186 \times (p_{hi} - p) \times (T_{hf} - T_{hi}) + 2260 \times (w_{hv})}{f_{hd} \times LHV} \tag{2}$$

Burning rate (grams/min)

$$r_{hb} = \frac{f_{hd}}{t_{hi} - t_{hf}} \tag{3}$$

Specific fuel consumption (grams/grams water)

$$sc_h = \frac{f_{hd}}{p_{hf} - p} \tag{4}$$

Temperature corrected specific consumption

$$sc_h^T = \frac{f_{hd}}{p_{hf} - p} \times \frac{75}{(T_{hf} - T_{hi})} \tag{5}$$

Firepower (W)

$$FP_h = \frac{f_{hd} \times LHV}{60 \times (t_{hi} - t_{hf})} \tag{6}$$

Where, LHV is net calorific value (dry wood) (MJ/kg), P is dry weight of empty pot (grams), w_{hv} Water vaporized (grams), f_{hd} is equivalent dry wood consumed (grams).

3.1 Performance Merit Tests When Biomass Is Used with and Without Solar Reflector

The average test results of the stove when only biomass is used is shown in Table 2 and both biomass and solar used with the help of a reflectors is shown in Table 3. The results show that the biomass stove has an average thermal efficiency of 36.9%, temperature corrected specific energy consumption of 886 kJ/L and temperature corrected specific fuel consumption of 47 g/L in cold start high power water boiling test when only biomass is used.

Table 2. Summary of average boiling test results when only biomass is used.

Test phase High power WBT	Unit	Cold start average	Hot start average
Time to boil pot	min	18	17
Temp-corrected time to boil	min	19	18
Burning rate	g/min	7	7
Thermal efficiency	%	36.9	39
Specific fuel consumption	g/liter	46	42
Temp-corrected specific fuel consumption	g/liter	47	44
Temp-corrected specific energy cons.	KJ/liter	886	835
Firepower	Watts	2126.4	2083

Table 3. Summary of average water boiling test results when biomass is used with the help of solar reflectors.

Test phase High power WBT	Unit	Cold start average	Hot start average
Time to boil Pot	min	17	15
Temp-corrected time to boil	min	18	16
Burning rate	g/min	6	7
Thermal efficiency	%	41.9	43
Specific fuel consumption	g/liter	40	38
Temp-corrected specific fuel consumption	g/liter	41	40
Temp-corrected specific energy cons.	KJ/liter	772	751

The water boiling tests was done by raising the reflector under sunshine intended to measure performance metrics and compares it with previous water boiling test when biomass is only used. The results show in Table 3 that the biomass stove with reflector under sun has an average thermal efficiency of 41.9%, temperature corrected specific energy consumption of 772 kJ/L and temperature corrected specific fuel consumption of 41 g/L in cold start water boiling test. This indicates 5% rise in thermal efficiency and average 6 g/L fuel consumption saving when compared to when only biomass is used separately.

The performance test of the constructed box type solar cooker was tested using two major testing standards for evaluating a solar cooker throughout the world. Which are American Society of Agricultural Engineering Standard and the Bureau of Indian Standard [13]. Bureau of Indian Standard highlighted two methods of test: a stagnation test (test without load), and a load test [14]. Stagnation temperature and the rise in temperature inside the cooker were recorded without load. The stagnation temperature, ambient temperature and absorber plate temperature were measured for different time of the day. The tests with load were done by placing a water-filled vessel in the cooker. The absorber plate temperature, ambient temperature, water temperature, solar radiations were measured.

3.2 Performance Measures

The performance evaluation of the solar box cooker involve estimation of the following parameters: First figure of merit (F_1), Second figure of merit (F_2) and cooker's efficiency. The first figure of merit (F_1) of a solar box cooker is defined as the ratio of optical efficiency and the overall heat loss coefficient (U_L).

$$F_1 = \frac{\eta_0}{U_L} \tag{7}$$

Experimentally,

$$F_1 = \frac{T_{PS} - T_{as}}{H_S} \tag{8}$$

Where T_{ps}, T_{as} and H_s are stagnation temperature, average ambient temperature and solar radiation intensity respectively.

The second figure of merit (F_2) is evaluated under full load condition and can be expressed by the expression as follows:

$$F_2 = \frac{F_1(m_w C_w)}{A_t} \ln\left\{\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)}\right\} \tag{9}$$

Where F_1 is first figure of merit (Km^2w^{-1}), m_w is the mass of water as load (kg), C_w is the specific heat capacity of water (J/kg°C), T_a is the average ambient temperature (°C), H is the average solar radiation incident on the aperture of the cooker (W/m^2), T_{w1} is the initial water temperature (°C), T_{w2} is the final water temperature (°C), A is the aperture area (m^2) and t is the time difference between T_{w1} and T_{w2} (s).

3.3 Cooker Efficiency

The overall thermal efficiency of the solar box cooker is found mathematically as follows:

$$\eta_U = \frac{m_w Cw \Delta T}{I_{av} A_{c\Delta t}} \tag{10}$$

Where η_u denotes the overall thermal efficiency of the solar cooker; m_w, mass of water (kg); C_w, Specific heat of water (J/kg/^{o}C); ΔT, the change in temperature between the maximum temperature of the cooking fluid and the ambient air temperature; Ac, the aperture area (m^2) of the cooker; Δt, time required to achieve the maximum temperature of the cooking fluid; I_{av}, the average solar intensity (W/m^2) during time interval Δt (Fig. 5).

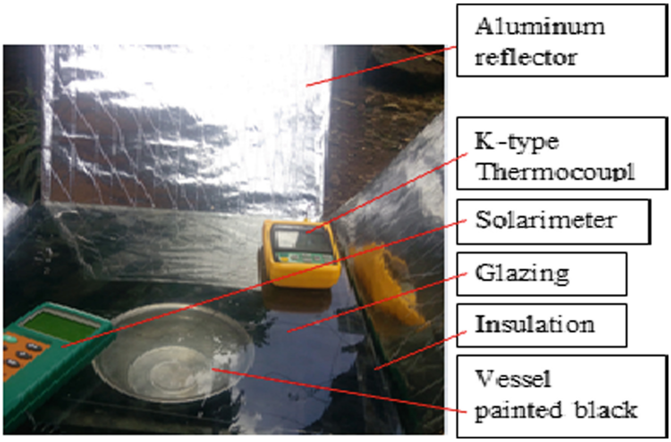

Fig. 5. Solar box cooker performance set up

Stagnation temperature tests, thermal load test or heat up condition test and cooking power estimation was performed based on procedure for testing the solar cookers developed by American Society of Agricultural Engineering (ASAE) Standard S580 and the Bureau of Indian Standard [13]. The stagnation temperature, ambient temperature and absorber plate temperature were measured from different time of the day. The box-type solar cooker was placed in the open sun without load; Type "k" thermocouples were attached to the solar cooker to measure both the cooker and ambient temperatures consecutively at a given interval until the stagnation condition was gotten. Intensity of total solar radiation on horizontal surface was measured, and recorded at a regular interval using digital radiation solarimeter. Also loading test was done by placing a water-filled pot in the cooker. The absorber plate temperature, ambient temperature, water temperature, solar radiations were measured.

3.4 Stagnation Temperature Test

The stagnation temperature test was conducted to evaluate the first figure of merit (F_1) of solar cooker. The test was started at 10:00 a.m. local time until the maximum plate temperature (128 °C), which occurred at 1:00 pm as shown in the Fig. 6. F_1 is calculated to be 0.12 where this value should be greater than 0.12 to be marked as A-Grade solar cooker [15]. The lower value of first figure of merit is because of convection and radiation losses from the bottom side of the cooker and leakage between the single glazing and ambient.

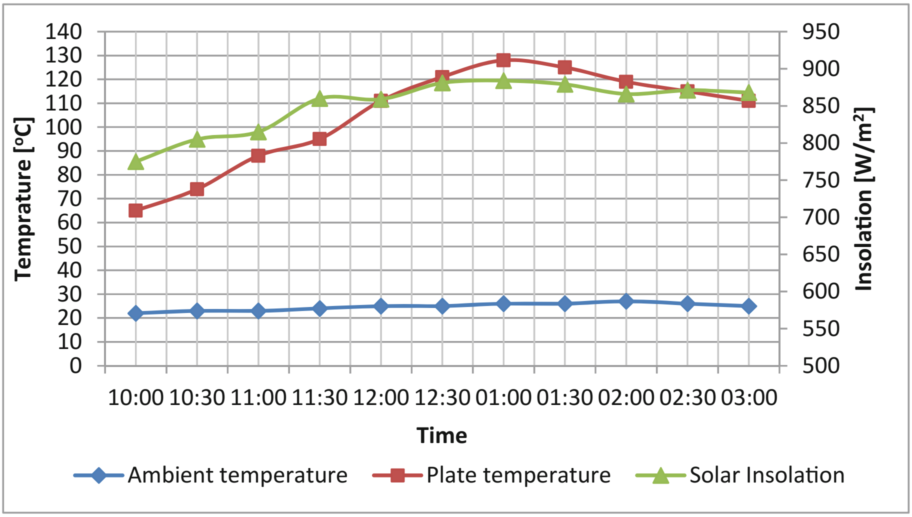

Fig. 6. Stagnation temperature test result of solar cooker.

3.5 Thermal Load Test or Heat up Condition Test

The thermal load test was conducted to determine the second figure of merit F_2 and evaluated under full-load condition. The solar box cooker was loaded with 2 kg of water which can be used for small cookers in an aluminum cooking vessel painted black; the water temperature was initially above the ambient temperature. Results are shown in the Fig. 7. It is clearly seen that the water temperature increases towards the noon period, then decreases towards evening. The figure shows that the maximum water temperature (reaches the boiling point) was achieved during mid-day around 1:30 PM. The variation of temperature throughout the day is due to the fact that the solar radiation is not constant throughout the day and reaching maximum at noon.

Second figure of merit was calculated using Eq. 9 for the water temperature between T_{w1} = 65 °C and T_{w2} = 95 °C; average solar insolation found is 839 W/m^2 and the average ambient temperature was 25.5 °C. Second figure of merit was computed to be 0.55 which is greater than recommended standard value of 0.40 [7]. It shows that there is a good heat transfer to the contents in the vessel.

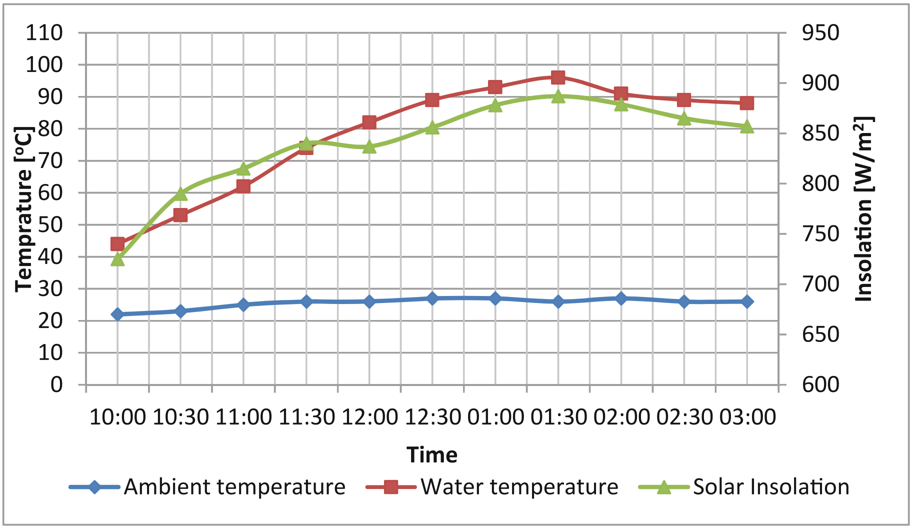

Fig. 7. Water heat up test of solar cooker for second figure of merit (F_2)

3.6 Cooking Power Estimation

The Cooking power experiment was conducted based on international standard of American Society of Agricultural Engineers (ASAE) procedure. Experiment was conducted for the load of 2.0 kg of water. The average cooking power P is the rate of useful energy available during heating period. It may be determined as a product of the change in water temperature for each interval and mass and specific heat capacity of the water. Dividing the product by the time (10-min intervals according to American Society of Agricultural Engineers) contained in a periodic interval yields the cooking power in Watts:

$$P = \frac{(mC_w)(T_2 - T_1)}{600} \tag{11}$$

Where P is interval cooking power (W), T_1 is initial water temperature (°C), T_2 is final water temperature (°C), M is mass of water (kg), and C_w is specific heat capacity (4186 J/kgK).

To determine the standardizing cooking power, P_s, from the cooking power, P, each interval is corrected to a standard insolation of 700 W/m^2:

$$P_S = \frac{P \times 700}{I_S} \tag{12}$$

Where Ps is standardized cooking power (W), P is interval cooking power (W), and I_s is interval average solar insolation (W/m^2).

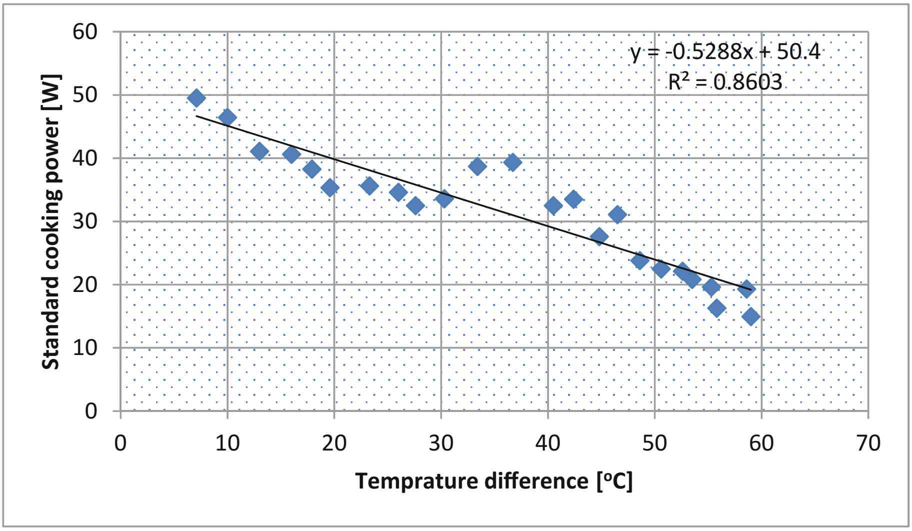

Fig. 8. Standard cooking power plotted over temperature difference.

The Solar cooker was exposed to the sun at 10:00 a.m. to 2:00 p.m., initial and final temperature of water, ambient temperature, and solar insolation were recorded at 10 min interval. Standard cooking power (P_s) is plotted against the difference between water temperature and ambient temperature (T_d) as shown in Fig. 8. The value of the coefficient of determination (R^2) of the regression equation is 0.86 which is greater than the recommended standard value 0.75. The cooking power at 50 °C temperature difference was calculated using the regression equation, P_{50} is to be 24 W.

3.7 Over All Cooker Thermal Efficiency

The overall thermal efficiency of the solar box cooker was calculated to be 34.6% (m_w, mass of water is 2 kg; C_w, Specific heat of water is 4186 J/kg^{0}C; ΔT, temperature difference between the maximum temperature of the cooking fluid and the ambient air temperature is 68.5 °C; A_c, the aperture area is 0.16 m^2; Δt, time required to achieve the maximum temperature of the cooking fluid is 12,600 s; I_{av}, the average solar intensity is 828.5 W/m^2 during time interval Δt.

4 Conclusion

The study shows that the solar- biomass combination system for cooking promotes lower daily fuel consumption by using the benefit of the free solar energy and season independent cooking since biomass can act when the solar is not enough. The biomass stove with reflector under the sun gives a 5% thermal efficiency rise. Improving the existing model and modifications could be made in the future studies.

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