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Design and Testing of a Solar Torrefaction Unit to Produce Charcoal

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Abstract

With increasing crude oil prices, fuels like kerosene and cooking gas have become unaffordable for many ordinary people in developing countries. For millions of Africans who need heat energy to cook their food, biomass like wood remains the easiest and cheapest source of fuel. Charcoal remains the most popular choice compared to wood since it can cook food much faster with very little smoke. Torrefaction of biomass is a mild form of pyrolysis at temperatures typically between 200˚C and 300˚C to produce charcoal. Torrefaction changes biomass properties to provide a much better fuel quality for combustion applications. A simple parabolic trough solar collector to produce charcoal by torrefaction process using solar energy has been designed from first principles. The device was fabricated and various locally available wood species were tested. The yield was found to be 21% to 35% with a production time of 90 minutes. The paper details the design procedure and the test results.

Keywords

Torrefaction, Charcoal Production, Solar Parabolic Trough, Design, Testing

1. Introduction

Charcoal is in high demand in many parts of Africa, since it contains double the energy of ordinary firewood and burns much better [1]. Charcoal is produced by several methods [2]. These are mostly batch processes like i) Earth pits and mounds (yield > 10%), ii) Brick, concrete, and metal kilns (yield 20% - 25%) and iii) Retorts (yield 30%). In all these processes the heat for the process is provided directly as the heat of reaction or by the flue gases from combustion to the reactor or through the reactor wall.

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Use of solar energy for the charcoal production process has the following advantage: Reaction temperature can be maintained between 200˚C to 300˚C enabling torrefaction of the biomass. Torrefied biomass has several advantages like higher energy density, more homogeneous composition, hydrophobic behaviour (water repulsion) and elimination of biological decomposition like rotting [3].

2. Description of Solar Torrefaction Unit

A solar concentrator captures solar radiation over a large aperture as illustrated below in **Figure 1** [4]. The aperture is covered with a highly reflective material to allow light to be reflected on the focal point. The solar radiation energy is concentrated on a small tube area (receiver tube) containing biomass. The process of concentrating solar energy enables the heating of biomass in the tube to produce charcoal.

Since the sun appears to be moving from east to west daily and north to south annually, the dish must also move in the same direction and at the same speed of the sun so as to face the sun.

To maintain the trough facing the sun all the time during usage, a sun tracking system is required. However for the present unit a manual sun tracking system is incorporated. The Parabolic Trough y-axis was aligned to be parallel to the sun light by turning the tracking mechanism at an interval of 15 degree per hour. The Unit is positioned in such a way that its angle can be changed according to the latitude of the location, for example Windhoek's latitude is 22˚33'*S*, 17˚4'*E*.

The receiver tube is made from low emissivity borosilicate glass (glass with a very low iron content that has superior durability and heat resistance) with an all-glass seal and Aluminum-Nickel selective coating. Further, the tubes are evacuated and have a barium getter (vacuum indicator) which changes color from silver to white if a tube's vacuum has been compromised.

The evacuated tube has high thermal efficiency in bright sunshine as well as overcast or diffuse sunlight conditions. An examination of the tubes shows that the outside is actually 2 layers of glass and a vacuum has been created between them.

3. Design Basis

The biomass considered for design is wood with a moisture content of *m*%. Hence, 1 kg of wood with *m*% moisture content consists of $(1-m)/100$ kg of dry wood and *m*/100 kg of water. It is assumed that the moisture content is totally removed when the wet wood is heated from ambient temperature to 100˚. Hence the energy required for drying 1 kg of wet wood is given by:

$$E_{drying} = (1-m)\times C_p \times (100-t_i) + m\times C_{pw}\times(100-t_i)+L \tag{1}$$

t_i = ambient temperature; C_p = specific heat of wood = 1.76 kJ·kg·K.

C_{pw} = specific heat of water = 4.186 kJ·kg·K; L = heat of vaporization = 2265 kJ/kg.

Torrefaction is an endothermic process requiring about 600 - 1000 kJ/kg. The energy which torrefaction reaction absorbs is assumed to be 800 kJ/kg [5]. Hence energy required for torrifying 1 kg of dry wood is given by

$$E_{torr} = (1-m)\times C_p \times (T_t - 100) + 800 \tag{2}$$

Therefore, total energy required by the process for 1kg of wet wood input is,

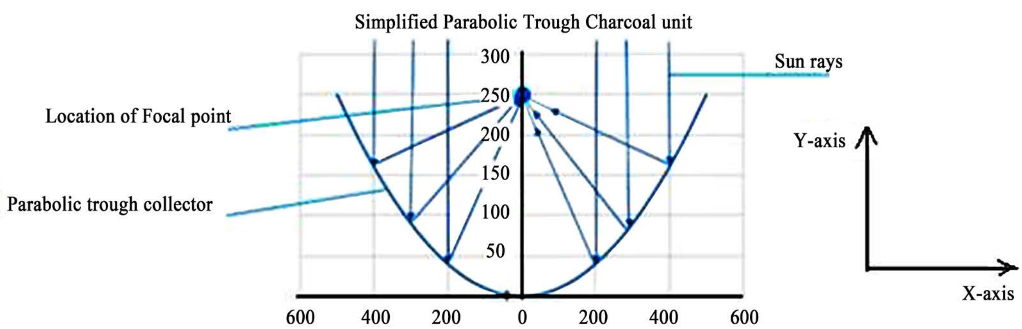

Figure 1. Indicates the focal point in the parabolic trough collector.

$$E_{total} = E_{drying} + E_{torr} \tag{3}$$

This is the heat energy to be supplied per kg of wet wood by solar energy in the Solar Torrefaction unit. $\therefore E_{total} = E_{sol}$.

Referring to the solar collector (**Figure 2**), rim angle of 90˚ is adopted to give wider exposure as indicated in **Figure 2**. For 90˚ rim angle, the ratio of focal length/diameter (f/d) = 0.25 as indicated in **Figure 2**.

Referring to the parabolic solar collector, the total radiation incident on the parabolic solar collector is given by

$$E_{sol} = \text{Collector Area} \times \text{Average Solar Radiation} \times \text{Collector Efficiency}$$

$$E_{sol} = \text{Collector Area} \times \text{Average Solar Radiation in } \mathrm{J/s \cdot m^2} \times t \times \text{Collector Efficiency}$$

(Average Solar Radiation is expressed in W/m^2 (= $J/s \cdot \mathrm{m}^2$) and t is the time taken for the process) then solar energy available = $E_{sol} = (E_{tot} \times 1000)$, since E_{tot} is in *kilo Joules*.

$$\therefore \text{Collector Area} = \frac{(E_{tot} \times 1000)}{\text{Average Solar Radiation in } \mathrm{J/s \cdot m^2} \times t \times \text{Collector Efficiency}} \tag{4}$$

The Collector area of parabolic trough is given by

$$A = \left[\frac{d}{2}\sqrt{1+\frac{d^2}{16f^2}} + 2f\ln\left(\frac{d}{4f} + \sqrt{1+\frac{d^2}{16f^2}}\right)\right] \times l, \text{ where } l = \text{length of the trough} \tag{5}$$

Equation (4) can be used to calculate the Collector area for torrefaction of 1 kg of wood. If the rim angle and aperture diameter are fixed, the length of the collector can be calculated from Equation (5).

4. Sample Calculation

Assumptions:

Moisture in wood = 10%; Rim angle of 90˚; Aperture diameter, d = 1 m, process time, t = 1 h = 3600s.

Focal length f = 0.25 since (f/d) = 0.25 for rim angle of 90˚.

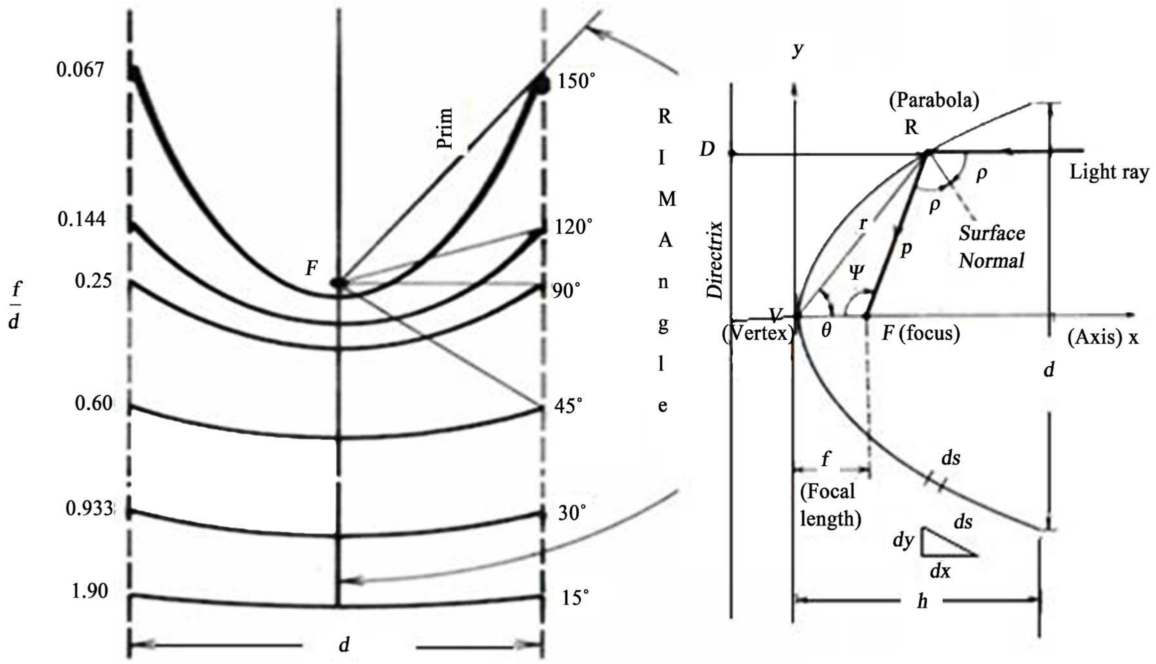

Figure 2. The critical points in the parabolic collector.

From (1)

$$E_{drying} = 0.9\times1.76\times(100-20)+0.1\times\left[4.186\times(100-20)+2265\right]=126.72+259.99=386.71\ \text{kJ}/kg$$

From (2)

$$E_{torr} = (0.9)\times\left[1.76\times(300-100)+800\right]=1036.8\ \text{kJ}/\text{kg}$$

From (3)

$$E_{total} = E_{drying} + E_{torr} = 386.71+1036.8 = 1423.5\ \text{kJ}/\text{kg}$$

With an average solar radiation of 675 W/m^2 (= $\text{J}/\text{s}\cdot\text{m}^2$) in Windhoek, Namibia [6], and collector efficiency of 70%, substituting in Equation (4), the collector area required works out to,

$$\therefore \text{Collector Area} = \frac{(E_{tot}\times1000)}{\text{Average Solar Radiation in } \text{J}/\text{s}\cdot\text{m}^2\times t\times\text{Collector Efficiency}}$$

$$=1423.5\times\frac{1000}{600\times3600\times0.70}=0.836\ \text{m}^2$$

This is the collector area required for torrefaction of 1 kg of wood in 1 hour.

The Collector area of parabolic trough is given by (5) as,

$$A=\left[\frac{d}{2}\sqrt{1+\frac{d^2}{16f^2}}+2f\ln\left(\frac{d}{4f}+\sqrt{1+\frac{d^2}{16f^2}}\right)\right]\times l \quad \text{where } l = \text{length of the trough.}$$

Substituting the values,

$$A=\left[\frac{1}{2}\sqrt{1+\frac{1^2}{16\times0.25^2}}+2\times0.25\times\ln\left(\frac{1}{4\times0.25}+\sqrt{1+\frac{1^2}{16\times0.25^2}}\right)\right]\times l=1.148\times l\ \text{m}^2$$

Required length l is given by, $1.148\times l=0.836\rightarrow l = 0.728$ m.

5. Test Results

A solar torrefaction unit based on the above design was constructed and tested [7]. **Figure 3** shows the unit.

Figure 3. The unit.

The Parabolic Trough y-axis was aligned to be parallel to the sun light by turning the tracking mechanism at an interval of 15 degree per hour. Three types of wood (Acacia, Berchemia discolor and White oak) were placed inside the tube for testing and time taken for torrefaction was recorded. The receiver tube inside temperature was of the order of 300˚C - 320˚C.The tube inside temperature recorded at regular interval starting at 9 AM is given in **Figure 4**.

After the completion of the process, the charcoal from the three types of wood was weighed, and charcoal yield was calculated. Charcoal yield was calculated by the following:

$$\text{charcoal yield}(\%) = \frac{\text{weight of charcoal}(\text{kg})}{\text{oven dry weight of wood material}(\text{kg})} \times 100\%$$

The results are tabulated below.

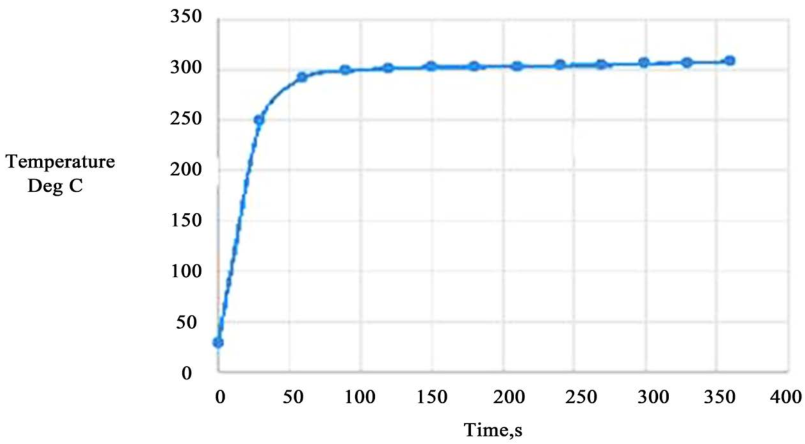

Figure 4. The tube inside temperature recorded at regular interval starting at 9AM.

Figure 5. Shows the different woods tested and the charcoal obtained.

Type of wood	Time for charcoal production (h)	Charcoal yield %
White Oak Charcoal	01; 30	21
Berchemia discolor	01; 30	35
Acacia	01; 30	28

The time taken for these types of wood is the same **Figure 5**. The yield ranges from 21% - 35% depending on the wood. It is observed that the charcoal of white oak is lighter than those of Acacia and Berchemia.

6. Conclusion

Basic principles in the design of Solar Torrefaction unit have been identified and a design methodology has been developed from the first principles. The unit designed as per these procedures are found to work well. The simple design methodology developed is found to be adequate.

Acknowledgements

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References

[1] Africa's Addiction to Charcoal—Everything You Need to Know about This Billion-Dollar Business! http://www.smallstarter.com/

[2] Czernik, S. (2008) Fundamentals of Charcoal Production. *IBI Conference on Biochar, Sustainability and Security in a Changing Climate*, Newcastle, 8-10 September 2008.

[3] (2014) Torrefaction—A New Process in Biomass and Bio Fuels. New Energy and Fuel. November 19, 2008. Retrieved February 29, 2012 Vol. 2014

[4] Stine, W.B. and Geyer, M. (2001) Power from the Sun. http://www.powerfromthesun.net/index.html

[5] Syu, F.-S. and Chiueh, P.-T. (2012) Process Simulation of Rice Straw Simulation. *Sustainable Environmental Research*, **22**, 177-183.

[6] Namibia Weather (2013) Windhoek Weather Station History. http://weather.namsearch.com/wdhhighlow.php

[7] Nandjembo, F.N.P. (2015) Design and Manufacture of an Improved Solar Charcoal Unit. Polytechnic of Namibia, B. Tech Project.