Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 57 (2014) 2167 – 2175

Energy Procedia

2013 ISES Solar World Congress

Design of semi-static solar concentrator for charcoal production

G. Ramos[a *] and David Pérez-Márquez[a]

a Instituto Politécnico Nacional, CICATA-IPN, Cerro Blanco 141, Col. Colinas del Cimatario, 76090 Querétaro, QRO, México

Abstract

Charcoal is a relative cheap source of energy for stoves and cauldrons, having the advantage of being neutral with respect to CO_2 emissions. The conventional process to produce charcoal is through methods such as earth pits or brick kilns, in which the energy required to produce the carbonization is obtained from the combustion of a part of the wood, which leads to a considerable decrease in the net production of carbon, combined with lack of control of the temperature of the process, leading to products of lower quality and a maximum yield of 200-300 kg per ton of wood used.

In this paper we present the design of a solar oven capable of producing charcoal out of wood, together with its construction and evaluation. The design does not require solar tracking throughout the all-day.
The prototype built has a collection surface of 1.37 m^2, and can obtains 70 g of charcoal out of 180 g of wood, in approximately five hours, in a sunny day and with a typical irradiance of 800 W/m^2, which corresponds at an efficiency of 380 kg per tonne.

Selection and/or peer-review under responsibility of ISES.

Keywords: Solar energy, Charcoal,

1. Introduction

Charcoal is a very convenient fuel, since it produces a long lasting hot fire with almost no smoke. No longer being an important cooking fuel in many countries, is also well appreciated as fuel for grilling meat in open-air barbecues [1]. Production of firewood and charcoal in Mexico and has raised about 50% between 1990 and 2001, of which aprox. 64% was consumed in rural areas and the rest in urban areas [2].

* Corresponding author. Tel.: +52 4421587466;
E-mail address: gramos@ipn.mx

Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2014.10.183

Nomenclature

α_S	Solar altitude angle.
γ_S	Solar azimuth angle
γ	Surface azimuth angle
ϕ	Latitude of the geographical location
δ	Declination
ω	Hour angle
α_P	Profile angle

In the central area of Mexico charcoal is produced mainly in earth pits, piling up the wood in a previously cleared area, covering it with leaves and soil, lighting it and allowing it to burn slowly during typically week [3]. The energy needed for the thermo-chemical conversion is provided by part of the wood, reducing the maximum attainable conversion efficiency. Additionally, the combustion temperature cannot be controlled and sometimes rain interferes with the combustion process leading to additional energy losses and lower quality product. With good processing conditions an efficiency of 250 to 300 kg of charcoal per tonne can be achieved [4]. This production method has another drawback as it affects the soil under the pit site reducing the microorganisms responsible for the nitrogen cycling [3]

In the literature we can find a renewed interest in charcoal production, its environmental impact and sustainability [5-8]. In order to overcome some of the inconveniences we have developed and evaluated a semi-static system to produce charcoal out of wood.

2. Wood to Charcoal conversion

Lump charcoal is obtained heating whole pieces of wood above 300 °C with a limited supply of oxygen (air) [9], while other references indicate a lower temperature 275 °C [10]. In our case we selected the species *Vachellia farnesiana*, locally known as "*Huizache*" for the experiments, as it is a naturally growing plant, abundant in the mexican semi-desert. The density of this wood is aprox. 1.08 g/cm^3 according to our measurements. First we performed laboratory experiments to determine the wood to charcoal transition temperatures and processing times for our wood species.

Fig. 1 shows the thermogravimetric spectrum (TGA) of *Vachellia farnesiana* saw dust obtained with a heating speed of 0.5 °C/min in nitrogen atmosphere. A first mass loss can be observed around 100 °C which can be correlated with loss of residual water. Up to roughly 200 °C no further mass lost is visible. At 210 °C the onset of mass loss can be observed. The maximum rate of loss seems to be achieved at 300 °C. At temperatures above 340°C the ratio of mass loss diminishes rapidly. At 275°C (indicated with a vertical dashed line) the rate of mass loss is already important. After the experiment only carbonized ashes could be recovered. Form the TGA curve suggests, that the conversion to charcoal starts at 210°C, having different conversion rates at higher temperatures.

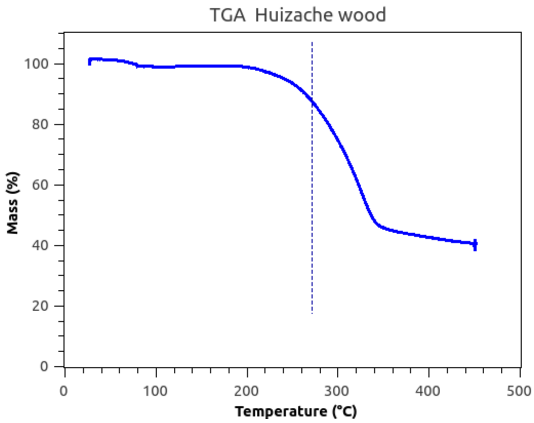

Figure 1. Thermogravimetric analysis of saw dust of Vachellia farnesiana.

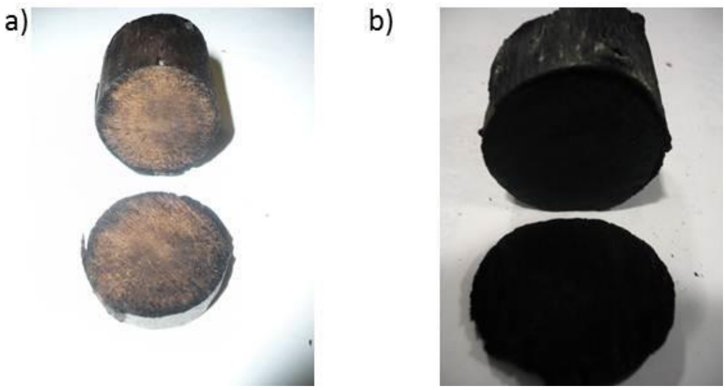

Figure 2. Pictures of Samples a) after 2 hours and b) 6 hours of carbonization at 275°C.

Next we performed carbonization experiments using an electric oven in order to determine the time need to complete the conversion at 275°C. Samples, of different diameters were placed in a metallic closed reservoir and baked at 275°C with different times. Afterwards cross-sections of the samples were analyzed optically to determine if the carbonization was homogeneous throughout the sample. At this temperature 6 hour were required to carbonize our samples having diameters up to 3.4 cm as is illustrated in Fig. 2. In a separated experiment it was determined, that a minimum energy of 3.5 Wh/g was required to complete carbonization.

3. Design and construction of the Solar Concentrator

Throughout this paper OptiCAD software [11] is used in for the calculations. This software can perform raytracing and radiometric evaluations. The details of the model used to simulate the solar radiation are explained elsewhere [12].

3.1.Conceptual design

Preliminary measurements were performed using a commercial solar parabolic concentrator, that required adjustment every 15 minutes, which proved to be impractical. That led us to look for a configurations that does not require sun tracking. One of the design considerations was, that the prototype should not require realignment during a day, at he most realignments form day to day After having reviewed different configurations that could be suitable, we decided to start with a parabolic through configuration in east-west orientation. The receptor would be a hollow cylinder used as container for the wood to be processed. The design is configured to process 400 g of wood per day, considering a maximum solar irradiance of 900 W/m^2 at noon. Fig. 3 shows a render of the conceptual design..

3.2 Ray tracing and Radiometric modeling

For the simulations OptiCAD software was used. The sun was simulated as a source of energy, without any account for the spectral irradiance, only total energy was considered. The receptor with cylindrical geometry in the conceptual design was simulated in the CAD as two mutually perpendicular flat surfaces (ribbon) that collect the energy. In order to account for losses the mirror was assumed to have a reflectivity of 80% and the receptor was assumed to have a flat absorption of 90%.

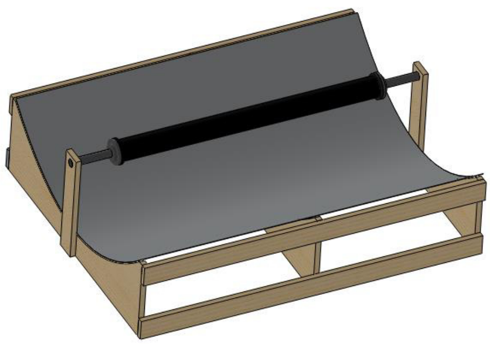

Figure 3. 3D render of the conceptual design of the semi-static solar concentrator.

While the energy required to process 400 g of wood is aprox. 1.4 kWh the collecting area was dimensioned for twice the energy for clear days having an irradiance of 900 W/m^2 at noon. The volume of the receptor was designed to easily accommodate the wood to be processed, resulting in a cylinder with 96 cm length and 6.2 cm of diameter. With this the collecting area was set.

For a parabolic through mirror all the light from sources located on the focal plane will be concentrated on the focal line. For a perfect mirror with the sun in the focal plane the radiation will be concentrated not to a line but to a ribbon due to the apparent angle of 0.5° subtended by the sun rays due to the dimensions of the solar disc. Orienting the collector west-east will cause, that early in the morning only a few rays will reach the receptor. The best collection time will be at noon. Two situations are simulated, at the equinox and at the solstice. For sake of simplicity all the simulations are done for a latitude $\Phi=0$ corresponding to the Equator and calculations are only performed between 8 a.m. and noon as, due to the symmetry, these results can be used for the afternoon hours.

The Solar altitude was calculated according to [13]:

$$\alpha_S = \sin^{-1}\left(\cos\varphi * \cos\delta * \cos\omega + \sin\varphi * \sin\delta\right)$$

In our case $\gamma = 90°$ since we are orienting the concentrator in west-east direction.

Additionally it is important to calculate the profile angle [13]:

$$\alpha_P = \frac{\tan(\alpha_S)}{\cos(\gamma - \gamma_S)} = \frac{\tan(\alpha_S)}{\sin(\gamma_S)}$$

In the equinox the values of α_P do not vary during the day and the radiation is projected to a line. Figure 4 shows a series of radiometric simulations of radiation falling onto the receptor at 8 am, 10 am and at noon, in false color representation. It the morning at 8 am, only a fraction of the receiver is collecting solar energy; at 10 am the energy is better distributed and at noon the receivers is homogeneously illuminated. The radiation, in all cases is falling onto a narrow line..The radiation falling onto the horizontal and vertical surfaces simulating the absorber were the same in each case.

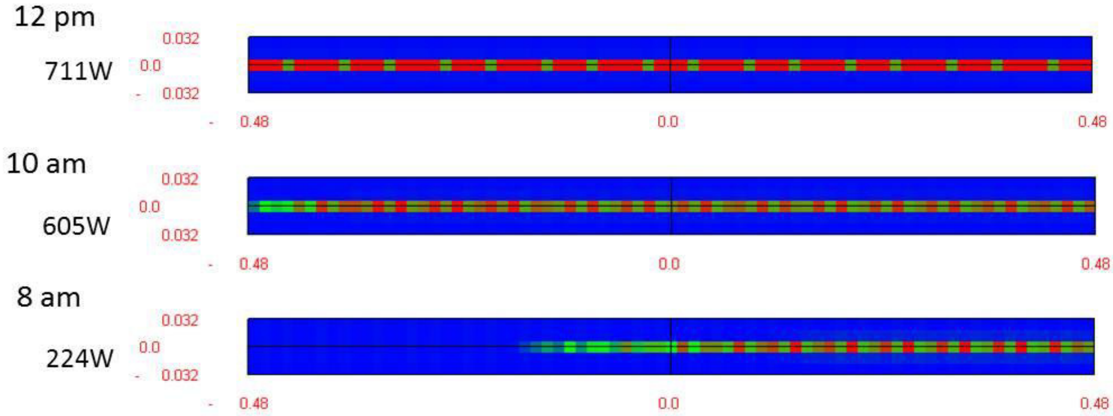

Figure 4 False color representation of the radiation falling onto the receiver (red indicates the highest intensity) for 8 am, 10 am and 12 m during the equinox.

In the solstices the calculated profile angles show variation during the day, which is also reflect in the radiometric simulations. Fig 5 shows the radiometric calculations at 8 am, 10 am and 12 m orienting the collector to maximize collection. At 8 am (Fig. 5 , 8 am, left) the radiation falling onto the horizontal ribbon simulating the receptor is shifted to one side with a total power of 16 W. The radiation at 10 am falls in the central area of the receptor, totaling a power of 573 W. The total energy collected by the receptor has to be calculated from the contributions of vertical an horizontal ribbons. Due to this effect, we had to make sure that all the radiation during a solstice day could be collected. In order to achieve this, the focal length and the position of the receptor had to be chosen properly. For the final design we had a parabolic through collector with a collecting area 0.96 x 1.32 m^2 a focal distance of 0.27 m with the receptor placed in the focal line. Figure 6 shows the expected instant power collected by this configuration at the equinox and solstice assuming a clear sky with 900 W/m^2 of irradiance at noon. of This implies, that the solar radiation will not be projected onto the same plane along a day. Figure 5 shows the false color representation of the radiation falling onto the receiver , again for 8 am , 10 am and noon, in the case of a solstice trying to orient the device to include the sun in the focal plane.

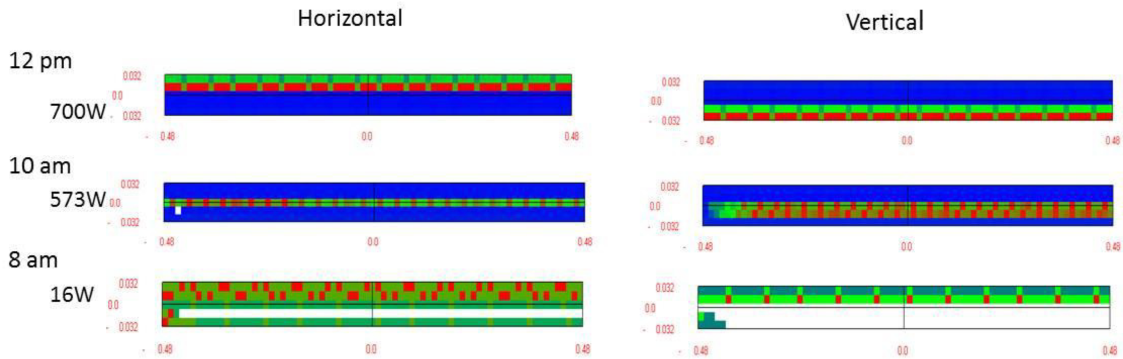

Figure 5 False color representation of the radiation falling onto the receiver (red indicates the highest intensity) for 8 am, 10 am and 12 m during the solstice.

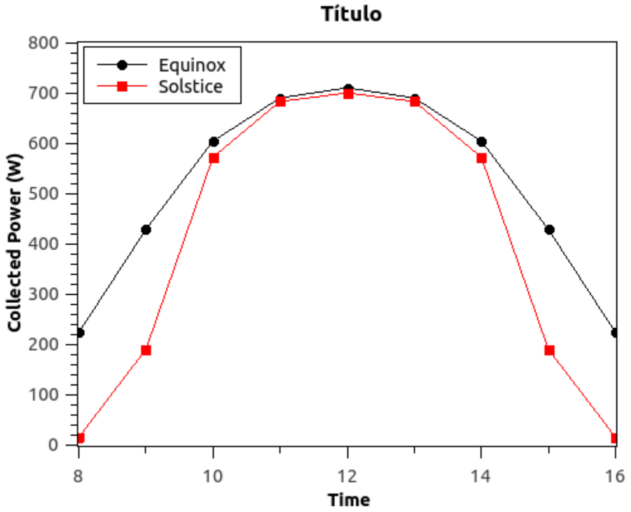

Figure 6 Instant collected power for the designed receiver, assuming a clear day with 900 W/m^2 irradiance at noon , (black) for the equinox, (red) for the solstice.

With this radiation pattern CAD simulations with Solidworks were performed to calculate the expected temperature. First calculations assumed a black copper receiver without transparent cover and natural convection. The maximum temperature was limited to 130 °C, which was to low for the purpose. Only a design incorporating evacuated tube isolation resulted in mean temperature of 309 °C, as shown in figure 7 for the simulation at noon. It can bee observed that the temperature distribution is approximately homogeneous along the receiver.

It proved to be difficult in our market to find evacuated tubes of different diameters o a factory that could prepare one for our purposes. We had to take a single ended evacuated tube used for solar water heaters to provide the isolation. Only a copper tube of 1 inch O.D. fitted in the interior of the evacuated tube, which limited our volume of wood that could be processed. Figure 8 shows the final setup with the evacuated and copper tubes in place.

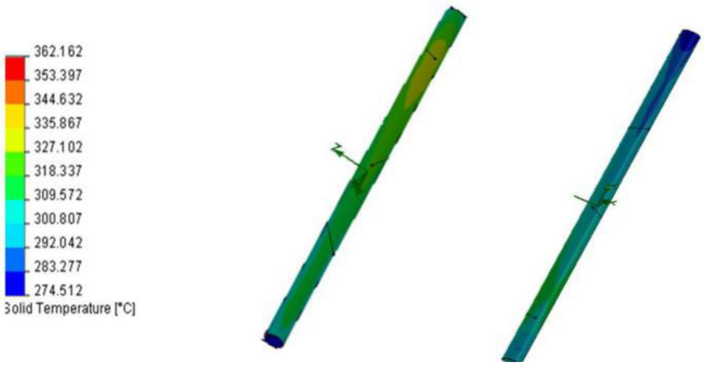

Figure 7 Temperature distribution as calculated for a copper receiver with evacuated turbe cover assuming a heating power of 900 W uniformly distributed.

Figure 8 Picture of the prototype in its final version with the evacuated tube receiver.

Figure 9 Picture of the prototype in its final version with the evacuated tube receiver.

First the prototype was tested without wood inserting a thermocouple to monitor the temperature of the interior of the copper tube and using a pyranometer with datalogger to measure the solar radiation. In about 20 minutes temperatures in excess of 380 °C were reached with a mean solar irradiance of 990 W/m^2 and a wind speed of 0.17 m/s.

A charge of 180 g of *Vachellia farnesiana* was used in the experiments, starting the carbonization at 10 am and ending at 3 pm. This time the solar irradiance at noon was about 1000 W/m^2. During the experiment the temperatures in the cylinder were above 270 °C, with wind gusts up to 3 m/s. After the process 70 g of charcoal were recovered, carbonized up to the center. This implies a conversion efficiency of 0.38% or 380 kg per tonne. Figure 9 shows the product obtained.

Conclusions

A semi- static solar concentrator for the production of charcoal was designed, build and tested. The design consists of a parabolic through concentrator oriented in east-west direction with a receiver designed to accommodate the wood to be processed.

The prototype built has a collection surface of 1.37 m^2, and can obtain 70 g of charcoal out of 180 g of wood, in approximately five hours, in a sunny day, which corresponds at an efficiency of 380 kg per tonne.

Acknowledgements

The authors will acknowledge the support of Concyteq-IPN for the realization of this work.

References

[1] Rousset P., Caldeira-Pires A., Sablowski A., Rodrigues T., LCA of eucalyptus wood charcoal briquettes. Journal of Cleaner Production 19 (2011) 1647.1653
[2] Inegi, Estadísticas económicas. Volumen de la producción forestal maderable y no maderable, según principales productos, 1999-2001,(in spanish) INEGI Mexico 2003.
[3] Gomez-Luna Blanca Estela, Rivera-Mosqueda Ma. Cruz, Dendooven Luc, Vazquez-Marrufo Gerardo, Olalde-Portugal Vıctor, Charcoal production at kiln sites affects C and N dynamics and associated soil microorganisms in Quercus spp. temperate forests of central Mexico, Applied Soil Ecology 41 (2009) 50 –58
[4] Cano M., Armendariz R., Juarez P. Carbón de encino: una alternativa de producción para las zonas forestales , INIFAP Mexico 2003.
[5] Panwara N.L., Kotharib R, Tyagic V.V., Thermo chemical conversion of biomass – Eco friendly energy routes, Renewable and Sustainable Energy Reviews 16 (2012) 1801– 1816
[6] Bailis R., Rujanavech C., Dwivedi P., Vilela A., Chang H., Carneiro R., Innovation in charcoal production: A comparative life-cycle assessment of two kiln technologies in Brazil,Energy for Sustainable Development 17 (2013) 189–200
[7] Kituyi E., Towards sustainable production and use of charcoal in Kenya:exploring the potential in life cycle management approach, Journal of Cleaner Production 12 (2004) 1047–1057
[8] Ghilardi A., Mwampamba T., Dutt G., What role will charcoal play in the coming decades? Insights from up-to-date findings and reviews, Energy for Sustainable Development 17 (2013) 73–74
[9] Emrich W. Handbook of charcoal making: the traditional and industrial methods. Solar energy R&D in the European community, Series E: Volume 7: Energy from Biomass; 1985. p. 278.
[10] FAO Forestry Department, Simple technologies for charcoal making, Mechanical Wood Products Branch, Forest Industries Division, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome, 1987
[11] OptiCAD Corporation, 511 Juniper Drive, Santa Fe NM, 87501-1323, USA
[12] David Pérez-Márquez and G. Ramos, Ray-trace evaluation of a fisheye lens as static concentrator, to be published,Energy Procedia (2013)
[13] Duffie JA., Beckman WA, Solar Engineering of Thermal Processes, John Wiley and Sons Inc. USA 2006.