

# Thermal and optical analysis of selective absorber coatings based on soot for applications in solar cookers

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**Abstract.** The thermal and optical properties of selective absorber coatings of a solar cooker have been investigated. Coatings have been prepared using soot from pine resin, wood stove and sugarcane, previously separated by size. Results show that the cooking power and the overall efficiency of these pots are higher than others painted with black primer. Besides, by using an integrating sphere, the diffuse reflectance of absorbers has been obtained. Lower values of the reflectance have been measured for the pots covered with soot, showing a high correlation with the results achieved from the thermal tests, considering the measurement errors.

## 1. Introduction

Solar cookers are devices that use solar radiation to cook food and are an alternative to fires fueled by wood in rural areas. The most common types of solar cookers are box cookers, panel cookers and parabolic cookers. Parabolic solar cookers use a reflector to focus the sunlight directly onto a cook pot. Parabolic geometry allows reach much higher temperatures than the other types of solar cookers. Taking into account the portability of the system, the compound parabolic collector (CPC), is a suitable alternative [1]. Designs based on CPC collectors have been implemented in rural communities regarding the simplicity of the stove design so that it can be built by the user [2].

One of the most important parameter in a solar cooker is the selective solar absorber coating that allows converting the sunlight into thermal power. For efficient photothermal conversion solar absorber surfaces must have high solar absorptance for wavelengths shorter than 3  $\mu\text{m}$  and a low thermal emittance at the operational temperature [3]. Materials used in solar cookers are usually expensive and difficult to obtain for rural communities. As a result, the identification and characterization of low-cost materials allows that low-income families could have access to solar cookers. Inexpensive designs as the stove *Jorhejpatarnskua* [2] and the rural solar cooker (RSC) [4] have been reported to have thermal parameters better than to commercial cookers. These designs are constructed with a mirror aluminum foil and paint for solar applications. However, the manufacturing cost could be reduced if local materials are used. Untreated materials from rural areas such as soot from biomass combustion have been proposed as a selective absorber coating for solar cookers. In a previous work [4], the standard cooking power using different absorber coatings including soot, have been compared. It has been found that copper oxide has the best

thermal parameters. Nevertheless, this coating is toxic and is harder to get than soot. Furthermore, Thermogravimetric analysis of pine soot resin prove that low material decomposition occurs up to 600°C; thus, showing the high resistance of soot coatings to sun heating [5].

Solar cookers performance should be evaluated according to the international standard procedure which was proposed at the Third World Conference on Solar Cooking [6]. The methodology includes rigorous procedures to determine thermal parameters such as standard cooking power ( $P_s$ ) and the overall efficiency ( $\eta$ ).  $P_s$  has to be measured by exposing the pot or container to sunlight with suitable climatic conditions for several hours.

In this work the standard cooking power of the stove *Jorhejpatarnskua* is obtained for different pots coated with absorbers based on soot from pine resin, wood stove and sugarcane. The effect on  $P_s$  as a function of the soot particle size is also evaluated. Furthermore, diffuse reflectance technique was successfully employed as an alternative to characterize the thermal performance of the coatings.

## 2. Metodology

### 2.1. Diffuse Reflectance Spectroscopy

The Reflectance is defined as the ratio of reflected irradiance,  $I_r$ , to incident irradiance,  $I_i$ , and could be used to analyze opaque samples. There are two reflectance components for a surface: *specular* and *diffuse*. Reflection light of smooth surface (such as a mirror) follows the law of reflection and the specular reflectance is the principal component. On the other hand, diffuse reflectance takes place when the surface is microscopically rough and the light is reflected and scattered in many different directions. The roughness degree of the surface will define which component will have a greater contribution to the overall reflectance [7].

Reflectance measurements are typically performed with an integrating sphere and a diffuse reflectance standard. The cavity of the sphere is covered with a diffuse white reflective coating to obtain a uniform scattering or diffusing effect with a few small ports. Multiple scattering reflections from the sample and the cavity will be equally distributed to all points inside the sphere and the scattered light is collected by a spectrophotometer or a photomultiplier. Reflectance is usually measured relative to a reference standard settled at the sample port, which is taken to be 100%.

Thus, the sample reflectance  $R(\lambda)$  can be calculated by

$$R(\lambda) = \frac{I_c(\lambda) - I_b(\lambda)}{I_w(\lambda) - I_b(\lambda)}, \quad (1)$$

where  $\lambda$  is the wavelength,  $I_c(\lambda)$  and  $I_w(\lambda)$  are the detected intensity corresponding to the coating and reference standard, respectively.  $I_b(\lambda)$  is the background intensity obtained with the lamp off.

### 2.2. Thermal Parameters

Thermal parameters are useful tools to compare different solar cookers designs. The most important parameters to evaluate the performance of solar cookers are the standard cooking power  $P_s$  and overall efficiency  $\eta$ . According to the American Society of Agricultural and Biological Engineers standard (ASAE S580) [8],  $P_s$  could be obtained from:

$$P_s = P_c \frac{700 \text{ W/m}^2}{I}, \quad (2)$$

where  $P_c$  is the cooking power and  $I$  is the insolation falling on cooker aperture in  $\text{W/m}^2$ . The  $P_c$  can be calculated through:

$$P_c = mC_p \frac{dT}{dt},$$

where  $m$  is the mass of water,  $C_p$  is the specific heat of water and  $T$  is the water temperature at a given time  $t$ .

The other relevant thermal parameter is the *overall efficiency*,  $\eta$ . This parameter takes into account the amount of solar heat reaching the cooker. This can be defined by [9]:

$$\eta = \frac{mC_p(T_{wf}-T_{wi})}{A \int I dt}, \quad (3)$$

where  $T_{wf}$  and  $T_{wi}$  is water final and initial temperatures and  $A$  is the collector area.

### 3. Experimental Section

#### 3.1. Materials Preparation

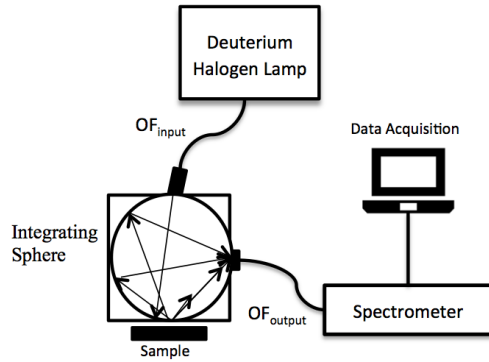
Soot from pine resin, wood stove and sugarcane have been investigated to employ as a solar radiation absorber. Soot is composed of particles of different size, which is then separated by a vibratory sieve shaker (Reisch AS 200). Samples have been separated according to the particle size: less than 32  $\mu\text{m}$  and between 150 to 250  $\mu\text{m}$ . Afterward, the coatings were prepared with a mix of 50 wt% of soot and 50 wt% of black primer paint. The paint was applied to a pressure aluminum pot by means of an air spray gun. Additionally, to compare the performance of soot coatings, two cooking pots were painted with commercial black paint and black primer paint.

#### 3.2. Measurement of Diffuse Reflectance

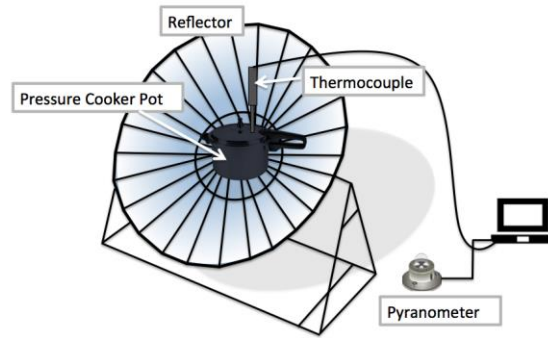
Figure 1 shows a schematic of the used device to measure the reflectance of the coated samples. The system consists of a Deuterium Halogen lamp (DH2000-DUV, from Ocean Optics), emitting in 190-2500 nm range; a 50 mm diameter integrating sphere (ISP-50-8-REFL, from Mikropack); and a miniature spectrometer (USB4000-XR1-ES- Ocean Optics), which spans the 200-1025 nm wavelength range with an optical resolution of 1.5 nm. Two 600  $\mu\text{m}$  fused-silica optical fiber bundles were used to direct the light from the lamp to the integrating sphere and the spectrometer. Reflectance was obtained by using the Eq. (1) using a Polytetrafluoroethylene (PTFE) sample as the reference standard for the whole investigated wavelength range. Measurements of the cooking pots were performed at 30 different sample positions and the obtained values were averaged.

#### 3.3. Measurement of thermal parameters

Measurements of thermal parameters were performed by using the procedure proposed by Funk [8]. The experimental arrangement is shown in figure 2. The solar cooker employed a pressure cooker pot coated with the prepared paint with soot and a black paint. Initially, the pot was filled with 3.5 l of water. The test was performed by exposing the solar cooker to the sun at 10:00 solar time. Two thermocouples type K have been used to register the temperature inside and outside of pot. The incident radiation was measured with a pyranometer (LP02-LI-19). All experimental parameters, such as water temperature within the pot, ambient temperature, wind speed and solar flux radiation were measured every 5 min until the water reaches 90°C.



**Figure 1.** Experimental setup employed to measure the reflectance of coated samples.

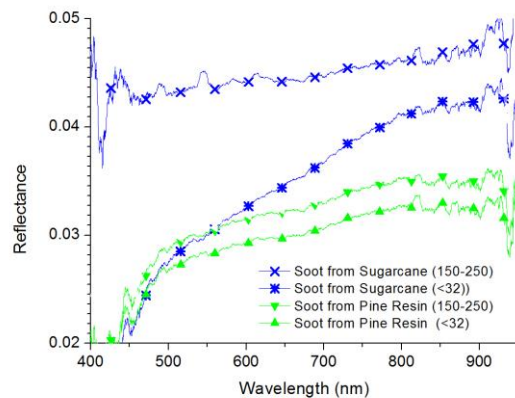


**Figure 2.** Solar Coker implemented to measure the thermal parameters.

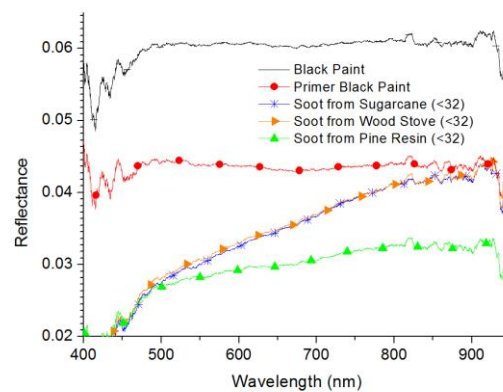
## 4. Results

### 4.1. Diffuse Reflectance

Figure 3 depicts the dependence of the reflectance for particle sizes in the range 150-250  $\mu\text{m}$  and less than 32  $\mu\text{m}$ , for coatings of soot from sugarcane and pine resin. The estimated experimental error is about 13% which was obtained from the relative standard deviation from 30 different sample regions. Result shows that reflectance is greater for larger particle sizes. Also, reflectance values are higher for coating of soot obtained from sugarcane than the produced from pine resin. In Figure 4 the dependence of the reflectance for the different investigated coatings is presented. It was observed that coatings of black paint and black primer paint have higher reflectance values in relation to the other tested coatings, with values of 6% and 4.4% on average, respectively. The lower reflectance value (3%) was obtained for coating of soot from pine resin.



**Figure 3.** Reflectance for coatings with different particle size ( $\mu\text{m}$ ) of soot from sugarcane and pine resin.



**Figure 4.** Reflectance for different types of coatings.

### 4.2. Thermal Parameters

The performance of coatings was analyzed by its thermal parameters. The design of solar cooking outlined in Figure 2 was used for thermal test. Three solar cookers were used to simultaneous test the different investigated coatings. The standard cooking power and overall efficiency were determined with equations (2) and (3), respectively. Here, the obtained experimental error has

determined to be ~10%. Results of  $P_s$  and  $\eta$  show that coatings of soot with particle size less than  $32\ \mu\text{m}$  have better thermal performance than coatings of particle size of 150-250  $\mu\text{m}$ .

Table 1 shows a summary of thermal parameters and reflectance for coatings of soot and primer paint.

**Table 1.** Summary of thermal and optical parameters.

| Coatings Parameters                  | Sugarcane | Wood Stove | Pine Resin | Sugarcane | Wood Stove | Pine Resin | Primer |
|--------------------------------------|-----------|------------|------------|-----------|------------|------------|--------|
| Soot particle size ( $\mu\text{m}$ ) | <32       | <32        | <32        | 150-250   | 150-250    | 150-250    | -----  |
| $P_s$ (Watts)                        | 79        | 75         | 74         | 63        | 69         | 66         | 59     |
| $\eta$ (%)                           | 27.6      | 24.8       | 25.6       | 22.9      | 23.4       | 23.5       | 20.5   |
| Reflectance (%)                      | 3.6       | 3.5        | 2.9        | 4.4       | -----      | 3.2        | 6.1    |

## 5. Conclusions

The thermal efficiency and the cooking power of different selective solar absorber coatings based on soot have been investigated. The coatings with soot show better thermal parameters than the tested black paints. Besides, diffuse reflectance has also been used to characterize the samples and the preliminary results show a high correlation between the optical properties and the thermal parameters, considering the experimental errors. Soot from pine resin has the lower reflectance which is translated into higher absorptance and a higher cooking power. This method has the advantage that could be implemented in the Laboratory regardless of the ambient weather conditions.

Although the efficiency of coatings with smaller particle size is higher, this difference is about 15%; thus, unprocessed materials could be used as absorber coatings without sacrificing its thermal efficiency.

## Acknowledgments

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