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Natural Solar Drying and Charcoal Production by Pyrolysis of Empty Shells of Cocoa Pods Using a Carbonisation Stove Fitted with a Chimney

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Abstract: The world's production of cocoa highly has grown since 1960. In West Africa, the production reached about 3,000,000 tons in 2012. More than 50% of the world's production of cocoa comes nowadays from Côte d'Ivoire and Ghana and Côte d'Ivoire is the biggest producer. After harvesting, the empty shells, considered as non-useful wastes, are abandoned in the fields where they become a source of pollution. That yields millions of tons of biomass that can be converted into charcoal, instead of being sources of pollution. In the present work, the drying kinetics of the empty wet shells were studied. Then, charcoal production by pyrolysis of those empty shells of cocoa pods was performed, using a carbonisation stove fitted with a chimney. The study showed that the empty shells have a high moisture content. The different phases of the drying were observed. The study compared the drying rates and the diffusion coefficients of a small sample and a big sample. Two experiences of carbonisation of the empty shells were successfully carried out. For the first experiment, the pyrolysis temperatures were recorded and the charcoal mass efficiency calculated. For the second experiment, the temperatures were higher and the result was colored charcoals. The colorations disappeared after some hours.

Key words: Shells of cocoa pods, solar drying, diffusion coefficient, charcoal production, carbonisation stove.

1. Introduction

The world's production of cocoa highly has grown since 1960. The production has of course increased from 1,200,000 tons in 1961 to 1,700,000 tons and 5,000,000 tons respectively in 1980 and 2012 [1].

In West Africa, the production increased from about 1,000,000 tons to about 1,400,000 tons in 1980 and to 3,000,000 tons in 2012. More than 50% of the world's production of cocoa comes nowadays from Côte d'Ivoire and Ghana and Côte d'Ivoire is the biggest producer [2].

Fig. 1 shows the cocoa tree with its matured pods. After harvesting, the empty shells, shown in Fig. 2, considered as non-useful wastes, are abandoned in the fields where they become a source of pollution.

That yields millions of tons of biomass that can be converted into charcoal, which is an energy source, instead of being sources of pollution.

A previous work on the pyrolysis of cocoa shells was made by David Léonce Kouadio et al. [3]. The pyrolysis made at 450 °C in a stove, was carried out on shells previously crushed and impregnated with orthophosphoric acid, to yield activated coal. The aim of this work was to produce activated coal for depollution.

In the present work, the drying kinetics of the empty wet shells were studied. Then, charcoal production by pyrolysis of those empty shells of cocoa pods was performed, using a carbonisation stove fitted with a chimney. The experiments were carried out in Anyama, Côte d'Ivoire, using the systems (dryer and carbonisation stove) built by the first author.

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Fig. 1 Cocoa trees with their matured pods.

Fig. 2 Empty shells of cocoa abandoned in a field after harvesting.

2. Materials and Methods

2.1 Materials

2.1.1 Materials for Solar Drying

The materials are the electronic compact scale SF-400C (accuracy of ±0.001 g) used for weighing small samples of shells for drying experiments, the scale used for weighing dried shells before carbonization experiences, and also materials used for temperature measurement and data logging. Fig. 3a and 3b show weighing of small samples before drying. Fig. 4 shows the scale used for weighing dried shells (accuracy of ±0.5 g).

A hurdle dryer was used for natural solar drying. It is fitted with a wooden frame and a wire netting bottom. The surface of the hurdle is laid on four supports. The hurdle-dryer is shown in Fig. 5.

(a) (b)

Fig. 3 (a) Weighing of small samples; (b) Weighing of a quarter shell of shells 3 cm × 3 cm.

Fig. 4 The scale used for weighing dried shells.

Fig. 5 The hurdle-dryer used for natural solar drying.

Fig. 6 The EPPLEY type pyranometer.

Global solar radiation measurements were performed each 10 min. The radiation received by the hurdle was measured using an EPPLEY type pyranometer shown in Fig. 6. The pyranometer yields an electromotive force *U* proportional to the received radiation given by the following relationship:

$$E = \frac{U}{K} \quad (1)$$

where:

E is the solar radiation (W/m²);

U is the electromotive force (mV);

K is the conversion coefficient (10.41 mV/W/m²).

The error on the illumination is ±10 W/m².

2.1.2 Materials for Charcoal

Before pyrolysis, the dried shells were weighed using the scale shown in Fig. 4. During the pyrolysis process, temperatures were measured using type K thermocouples shown in Fig. 7.

During the experiments, the temperature data were recorded using data loggers USB-TC08 connected to a computer, as shown in Fig. 8.

A carbonisation stove fitted with a chimney was used for the pyrolysis of the dried empty shells. It is shown in Fig. 9.

Fig. 7 K type thermocouples used for the temperature measurements.

Fig. 8 Temperature data recording using a data logger USB-TC08 connected to a computer.

Fig. 9 The carbonization stove used for the pyrolysis of the shells.

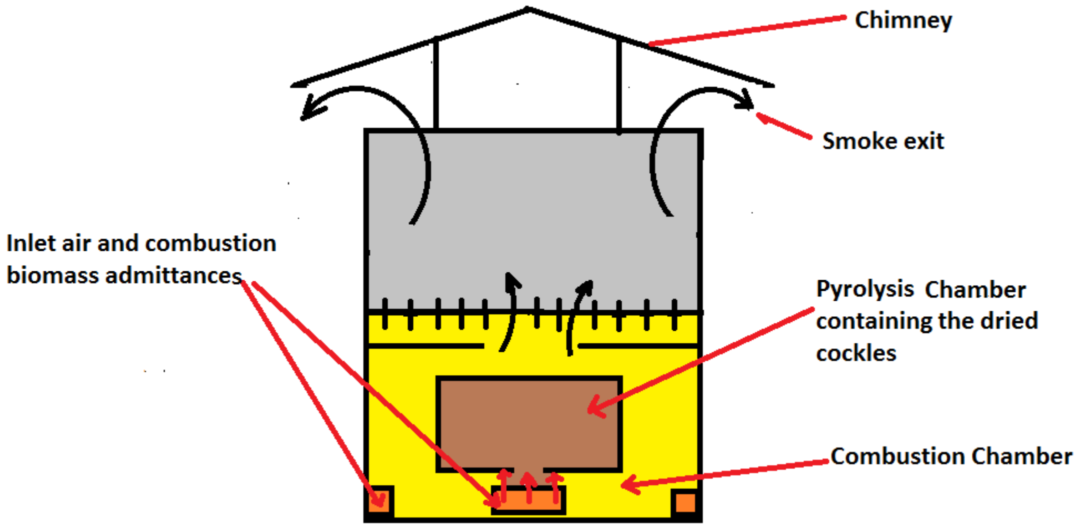

Fig. 10 Schematic representation of the carbonization stove.

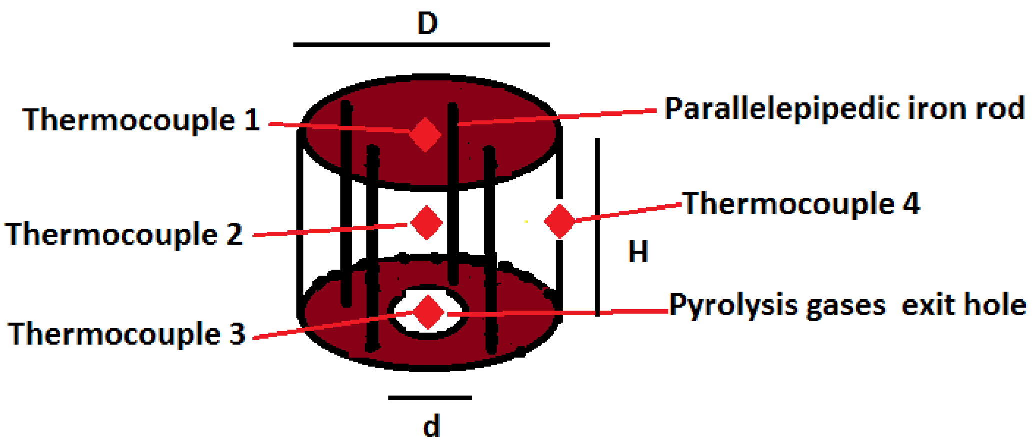

Fig. 11 Location of the thermocouples in the pyrolysis chamber.

Its schematic representation is shown in Fig. 10. It is fitted with four openings used for inlet air and combustion biomass admittances, a pyrolysis chamber installed in the combustion chamber and containing the dried shells. A chimney is used for the smoke exit.

The thermocouples are installed in the pyrolysis chamber as shown in Fig. 11.

2.2 Methods

2.2.1 Methods for Solar Drying

For the drying experiments, two samples were used. The big sample is a quarter of pod. It has an oval shape. Its initial mass was 59.7 g. As for the small sample, it has a square shape with dimensions 3 cm × 3 cm. Its initial mass was 11.55 g.

During the experiments, samples are introduced in the dryer. Then at steady time intervals of 10 min, the samples are withdrawn from the dryer, rapidly weighed, and then reintroduced in the dryer. In the meanwhile, the ambient temperature and the global solar radiation are recorded.

Several experiments were made. The results of March 16th, 2022 are given in this paper.

From the measurement of the sample mass at instant t, the moisture content $X(t)$, on dry basis is calculated according to the following equation:

$$X(t) = \frac{m(t) - m_s}{m_s} \qquad (2)$$

where $m(t)$ is the sample mass at instant t during the drying; m_s is the dry mass.

The drying rate is defined as:

$$-\frac{dX}{dt} = -\frac{x(t+\Delta t) - x(t)}{\Delta t} \quad (3)$$

The moisture ratio is defined as:

$$X_r = \frac{X - X_{eq}}{X_{cr} - X_{eq}} \quad (4)$$

where X_{eq} is the equilibrium moisture content. X_{cr} is the critical moisture content. The moisture ratio may also be expressed as [4]:

$$X_r = \frac{(X - X_f)}{(X_{cr} - X_f)} \quad (5)$$

where X_f is the final moisture content.

The Fick's diffusion law is used in several models. It is expressed as [5]:

$$\frac{dX_r}{dt} = D\frac{d^2X_r}{dr^2} \quad (6)$$

In Eq. (6), $r(m)$ is the diffusion path, t is the time. The diffusion coefficient D (m ?/s) (or effective diffusivity) is constant. The analytical solution of Eq. (6), given par Crank [6], is expressed as [7]:

$$X_r = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp[-(2n+1)^2\frac{\pi^2 Dt}{4L^2}] \quad (7)$$

L is the half thickness of the drying product. For a drying time large enough, the other terms of the series are considered to be negligible as compared with the first term for which $n = 0$. Eq. (7) is therefore expressed as:

$$X_r = \frac{8}{\pi^2}\exp(-\frac{\pi^2 Dt}{4L^2}) \quad (8)$$

The diffusion coefficient D is considered as constant during all the drying process. The drying kinetics of several foodstuffs have been successfully modeled by using The Fick's diffusion model.

From Eq. (8), one can write:

$$\text{Log}(X_r) = \text{Log}(\frac{8}{\pi^2}) - \frac{\pi^2 D}{4L^2} * t \quad (9)$$

Let us write:

$$\text{Log}(\frac{8}{\pi^2}) = a \text{ and } \frac{\pi^2 D}{4L^2} = b$$

One finally gets:

$$\text{Log}(X_r) = a - bt \quad (10)$$

The experimental determination of the slope b allows the calculation of the diffusion coefficient D by using the following equation:

$$D = \frac{4bL^2}{\pi^2} \quad (11)$$

2.2.2 Methods for Charcoal Production

Pyrolysis is a thermal degradation process without the presence of oxygen. The output is made of:

- condensable gases, tars;
- combustible gases such as H_2, CH_4, CO, CO_2;
- solid carbon-containing residue.

Several studies have been made about carbonisation [8].

Some carbonisation studies have been made on tropical products using metal kilns [9, 10].

The metallic stove used for the present study is shown in Fig. 9. It is made of two barrels. The downmost barrel contains the pyrolysis chamber and also the combustion chamber which is located under the pyrolysis chamber. The combustion chamber contains four parallelepipedic-rod fins. The upper barrel is the chimney. At the beginning of the experiment, the mass of dried shell is weighted and introduced in the pyrolysis chamber. Then the combustion is started in the combustion chamber, using firewood. Finally, the combustion chamber is introduced and the pyrolysis begins. At the end of the pyrolysis, the pyrolysis chamber is withdrawn and its temperature is let move downwards, before the withdrawing of the charcoal.

3. Results and Discussions

3.1 Results of Solar Drying

3.1.1 Mass Evolution with Time

The mass evolutions of the two samples with time are shown in Figs. 12 and 13. A decrease of mass of the two samples is observed during the drying process. The mass of the small sample decreases from 11.55 g to 9.08 g.

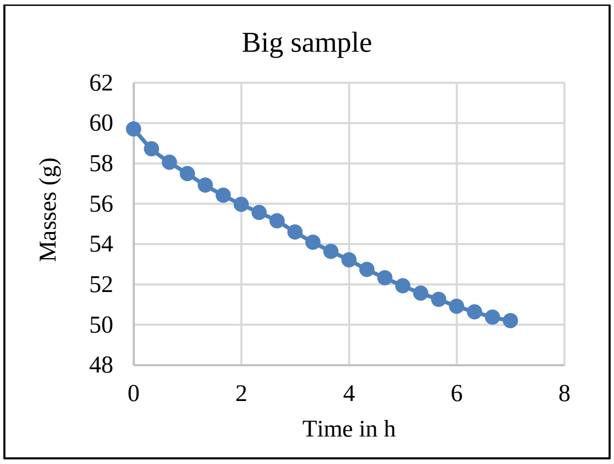

Fig. 12 Experimental mass variation with time of the big sample.

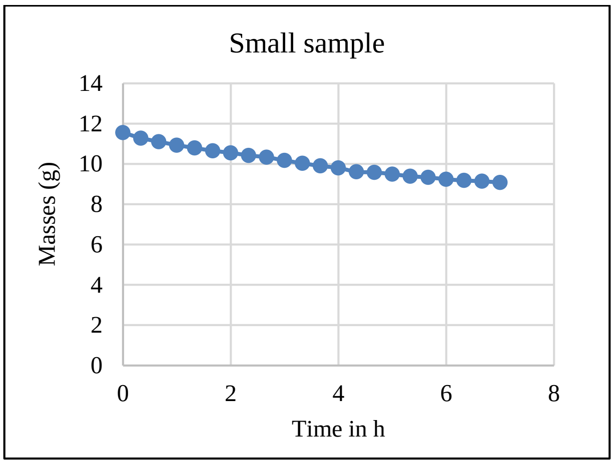

Fig. 13 Experimental mass variation with time of the small sample.

As for the big sample, its mass varies from 59.7 g to 50.19 g. The results show that the big sample has lost 15.93% of its water content, during the period of experimentation, while the small sample has lost 21.38% of its water content. One can say that the small sample dries quicker than the bigger one. This result has already been observed in some previous studies, looking for the influence of the size and the shape of the product during its drying process [11, 12].

3.1.2 Evolution of the Drying Rate with Time and with the Moisture Ratio

The drying rate was calculated for each sample, using Eqs. (2) and (3). The evolutions of the drying rate, for the two samples, are given in Figs. 14 and 15. It is worth noting that the dry masses are the followings: $m_s =$ 15.99 g for the big sample and $m_s =$ 3.15 g for the small sample. They were determined after drying in an oven at temperature maintained at 105 ℃. The two curves reveal the different phases of drying. The first phase, characterised by a high increase of the drying rate, corresponds to the warming up of the product, then follows a very short period of constant drying rate. In this phase, the surface of the drying product is considered to be a free water surface. The third period is the falling rate period, characterized by a decrease of the drying rate. In this third period, there is a short period of high decrease of the drying rate, followed by a period of slow decrease. Fig. 16 gives a comparison of the drying rates of the two samples.

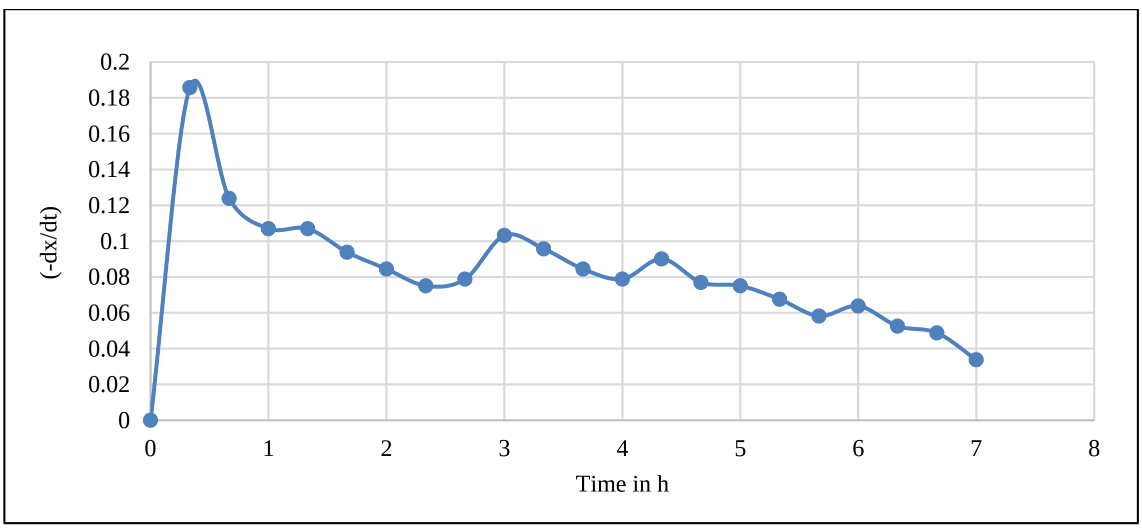

Fig. 14 Variation of the big sample drying rate with time.

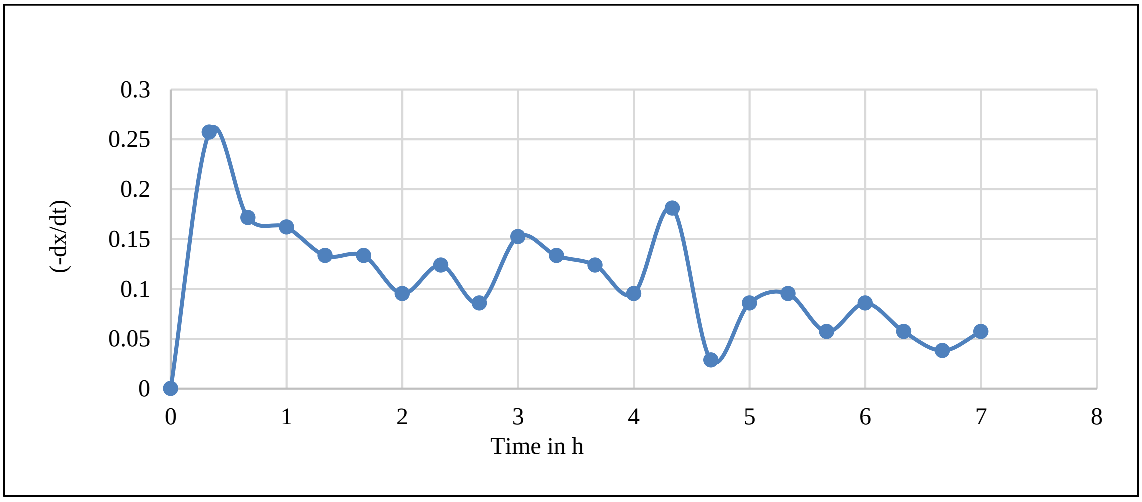

Fig. 15 Variation of the small sample drying rate with time.

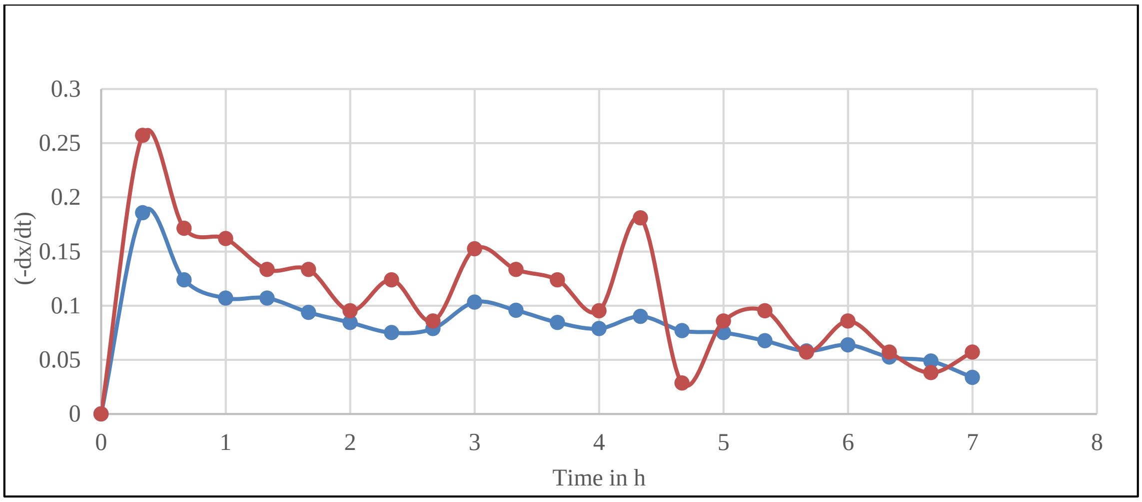

Fig. 16 Comparison of the drying rates of the big (the blue curve) and the small samples (the red curve).

Fig. 16 shows clearly that the small sample has a higher drying rate than the big sample. The evolution of the drying rate with the moisture ratio was also investigated, using Eqs. (3) and (5). The results are shown in Figs. 17 and 18, respectively for the big and the small sample.

A polynomial correlation was looked for between the drying rate and the moisture ratio.

For the big sample, it was found (with a regression coefficient R^2= 0.9513):

$$(-\frac{dXr}{dt}) = 0.8561X_r^6 - 3.9454X_r^5 + 7.4339X_r^4 - 6.7186X_r^3 + 2.6675X_r^2 - 0.2001X_r + 0.1234$$

As for the small sample, it was found (with a regression coefficient R^2= 0.7117):

$$(-\frac{dXr}{dt}) = -2.1893X_r^6 + 11.752X_r^5 - 24.228X_r^4 + 24.886X_r^3 - 13.986X_r^2 + 4.5264X_r - 0.5562$$

Figs. 17 and 18 show that the drying rate is high for high moisture ratios.

Then Log(X_r) was drawn against time t. For the big sample, it was found: Log(X_r)= -0.0003t + 0.7381 with a regression coefficient R^2= 0.8717.

That gives, using Eq. (11), a diffusion coefficient D = 7.599 ×10^{-8} m^2/s.

For the small sample, it was found: Log(X_r) = -0.0001t + 0.552 with a regression coefficient R^2 = 0.9939.

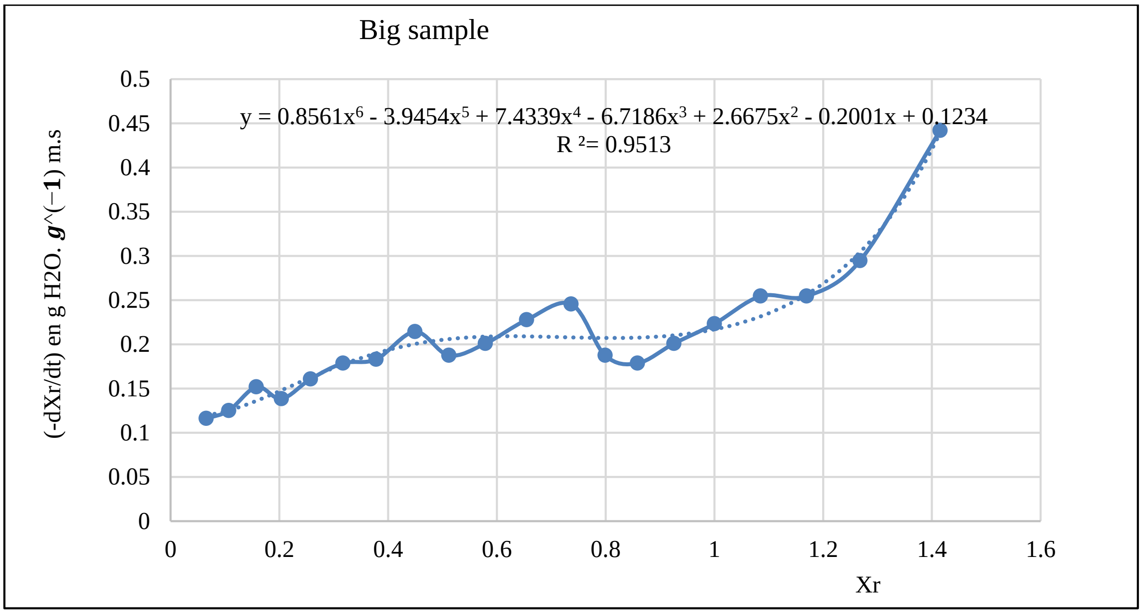

Fig. 17 **Variation of the big sample drying rate with the moisture ratio.**

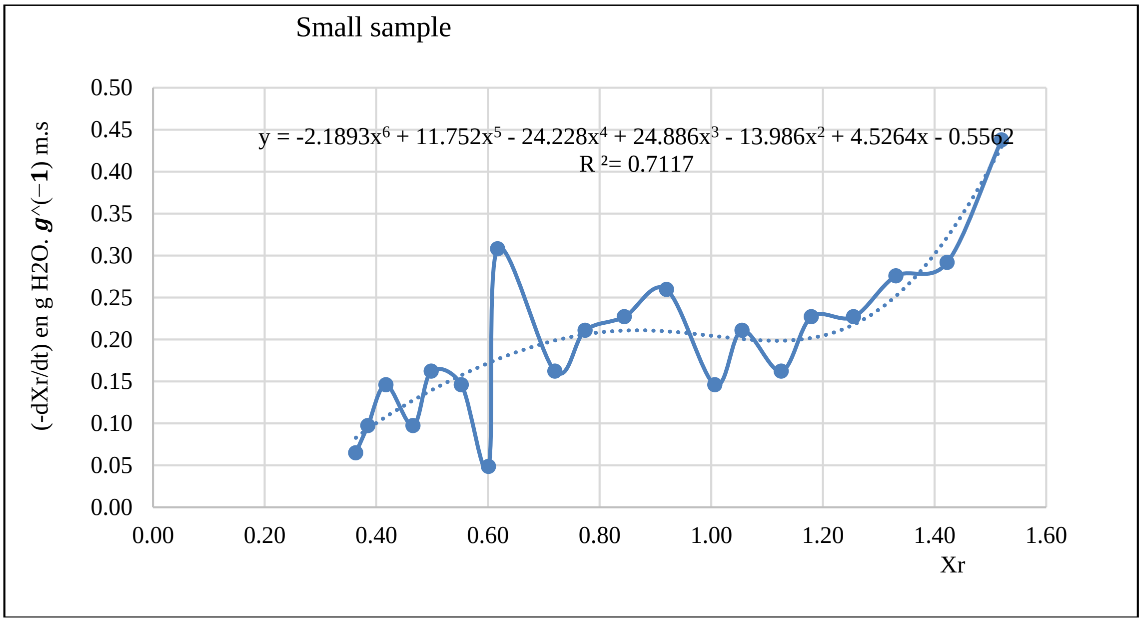

Fig. 18 **Variation of the small sample drying rate with the moisture ratio.**

Consequently, the diffusion coefficient of the small sample is $D = 9.119\times10^{-9}$ m^2/s.

Those values were compared to the diffusion coefficient of the cocoa beans determined by Aka et al. [13]. He found values varying from 1.2×10^{-10} m^2/s to 2.1×10^{-10} m^2/s.

It is worth noting that the value of the parameter *L* is 0.025 m for the big sample and 0.015 m for the small sample.

Hence the cocoa shell has higher diffusion coefficient than the cocoa beans, showing that the shells have a higher moisture than the beans.

3.2 Results of Charcoal Production

Two experiments of charcoal production were carried on September 2022. The first one lasted 1.49 h. The temperatures in the pyrolysis chamber were measured by thermocouples installed as shown in Fig.

11. A mass of 4.90 kg of empty dry shell was introduced in the pyrolysis chamber. At the end of the experiment, 2.7 kg of charcoal was obtained, which gives a charcoal mass efficiency $Rm = 0.55$. The mass efficiency is expressed as:

$$Rm = \frac{\text{dried charcoal mass}}{\text{dried shells mass}}$$

The temperatures measured by the thermocouples were recorded. Their evolutions are show in Fig. 19

Until 4,949 s, the thermocouple 3, which is near the pyrolysis gases exit hole, has the highest temperature, with a maximum temperature 312.06 ℃ at 4,651 s. After 4,949 s, the highest temperatures are recorded by the thermocouple 1, with a maximum temperature 357.92 °C at 5,107 s. The thermocouple 1 is located near the bottom of the pyrolysis chamber. After 5,107 s, all the temperatures decrease.

Fig. 20 shows the charcoal obtained, after its withdrawal from the pyrolysis chamber and cooling in the ambient air

For the second experimentation, the carbonization lasted 3 h 9 min. The initial mass of dried shell was 4.9 kg. The temperatures were not recorded because of the burning of the conduction wires of the thermocouples. After a cooling of the whole system during 30 min, the charcoal was withdrawn from the pyrolysis chamber. The mass of charcoal obtained was 1.7 kg, which gives a charcoal mass efficiency $Rm = 0.347$.

Figs. 21a and 21b show the charcoal obtained in the pyrolysis chamber after its withdrawal from the combustion chamber and cooling at ambient temperature.

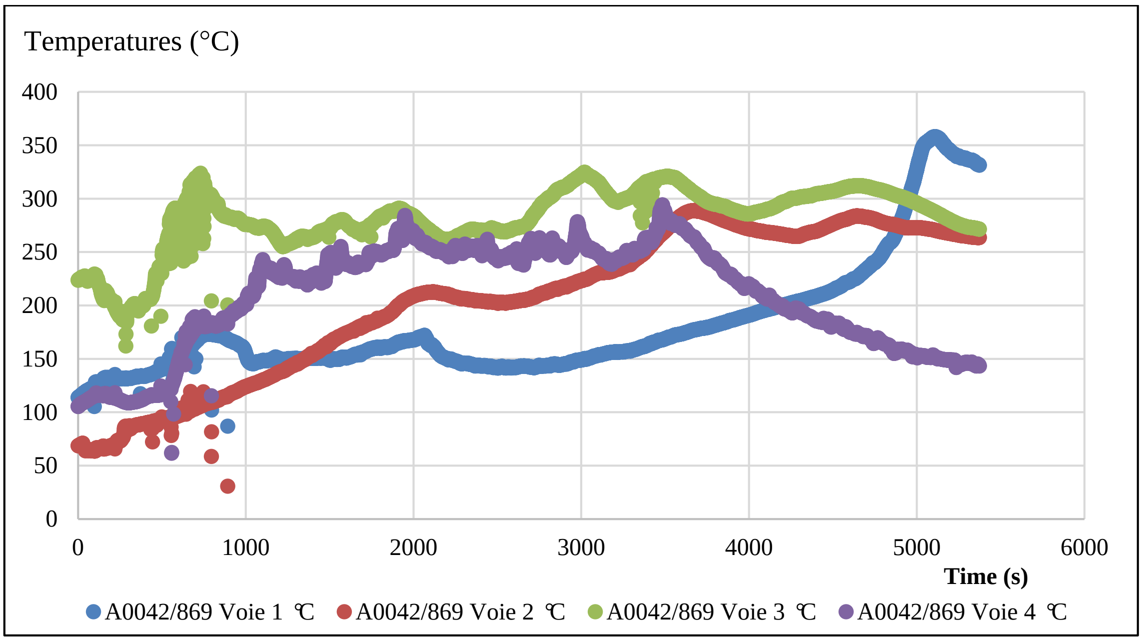

Fig. 19 Temperatures evolution in the pyrolysis chamber during the first charcoal production experiment.

The photographs in Fig. 21 show a blue color on some charcoals. They show also that some charcoals have several colors, mainly blue, yellow and violet, with a predominance of blue. But the colors disappear after some hours. The coloration may be linked to the composition of the charcoal, but also to the temperature.

The influence of the temperature on the apparition of the coloration was checked. One sample, for which the coloration had disappeared, was heated over (but not in) the flame of a gas burner, for about 50 s. A slight yellow coloration appeared, as shown in Fig. 22. The sample which is below, have been heated. It is compared with the one above it which has not been heated. The sample heated have of course taken a slight coloration.

Fig. 20 Charcoal obtained after the first experiment.

(a)

(b)

Fig. 21 Photographs of the charcoal obtained after the second experiment.

Fig. 22 Apparition of a slight coloration after heating a sample which had lost its coloration.

4. Conclusion

The study carried out in this paper was first focused on the solar drying of empty shells of cocoa pods, because drying is the necessary step before carbonisation. The study showed that the empty shells have a high moisture content. The different phases of the drying were observed. The drying rate of a small sample is higher than the one of a big sample. The diffusion coefficient was determined for the two samples. The results were compared with the diffusion coefficient of the cocoa beans. Experiences of carbonisation of the empty shells were successfully carried out. For the first experiment, a maximum pyrolysis temperature of 357.92 ℃ was recorded with a charcoal mass efficiency $Rm = 0.55$. As for the second experiment, the result was colored charcoals, with a charcoal mass efficiency $Rm = 0.347$. The colorations disappeared after some hours. An experience showed that a slight coloration reappears after heating. The experiences showed that the empty shells of cocoa pods may be used as energy source, for heat production or electricity generation.

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