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Experimental Study and Thermal Modelling of Cocoa Shell Convective Drying in an Indirect Solar Dryer

Siaka Touré, Adjo Christelle Ogo, Modibo Sidibé

Solar Energy Laboratory FHB University of Cocody, Abidjan, Côte d'Ivoire
Email: siakaahtoure@yahoo.fr

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Abstract

The concern of the present work is the convective drying of empty cocoa shells in an indirect solar dryer. Some drying experiments, using one sample, were carried out. During the experiments, the sample is introduced in the drying chamber. Then at steady time intervals, the sample is withdrawn from the drying chamber, for a rapid weighing. After each weighing, the sample is reintroduced in the dryer. At each time interval, the ambient temperature of the drying chamber and its relative humidity γ are measured by a thermo-hygrometer. From the experimental data, a theoretical determination of the moisture evaporated from the product was performed and a good agreement was found between the theoretical and experimental values, confirmed by the value of the RMSE. Those calculations used the constants in the Nusselt number found in literature. Then those constants were evaluated again, to get new values more suitable with the experimental data. The dimensionless numbers of Nusselt, Grashof and Prandtl were calculated. That allowed the calculation of the average value of the Nusselt number. The average convective heat transfer coefficient was determined.

Keywords

Shells of Cocoa Pods, Indirect Solar Dryer, Moisture Evaporated, Constants of the Nusselt Number, Convective Heat Transfer Coefficient

1. Introduction

An old technique used by farmers to preserve their foodstuffs is natural Solar drying. This process of course reduces the moisture content of the foodstuffs. The result is a reduction of the wastes, resulting in a decrease of the microorganism's activities. Compared with the natural air drying, the indirect solar drying has the advantage that the solar radiation does not directly impinge the drying product. Drying involves heat and mass transfers, which are linked to the specific nature of each product. Regarding cocoa pods, some drying studies have been carried out about the cocoa beans [1]. After harvesting, the empty shells are abandoned in the cocoa fields, because they are considered to be non-useful. This issue is important, because the world's production of cocoa is very important [2]. In West Africa, the production increased from about 1200.000 tons in 1961 to about 3000.000 tons in 2012. More than 50% of the world's production of cocoa come nowadays from Côte d'Ivoire and Ghana. Côte d'Ivoire is the biggest producer [3].

Drying is a physical process which involves heat and mass transfers. When heat is transferred to the product surface, water flows from inside the product to its surface. The product surface temperature also increases. As a result, moisture is evaporated from the product surface. The rate of heat used to evaporate water is linked to the heat transfer coefficient which depends on some parameters such as the product temperature, the product surrounding air temperatures and the physical properties of humid air. Those parameters allow the calculation of the rate of heat and the mass of water evaporated from the product. Those calculations are used as basis of the modelling of the drying process. Several modellings are found in literature. Some of them are based on the second law of Fick. Some other modellings don't use this Fick's law which allows the calculation of the moisture ratio [4] [5] [6] [7]. Reference [4] correlates the drying rate and the moisture content of a drying product to the water speed of transfer, by introducing some new modelling parameters. As for references [5] [6] [7], they are based on the fact that the mass of moisture evaporated is linked to the difference between the partial pressure of water vapor in the air and the partial pressure of water vapor in the saturated boundary layer just near the evaporating surface of drying product. The present paper which is relative to the experimental and theoretical study of cocoa shell drying in an indirect solar dryer, uses this idea. The experiments were carried out in Anyama, Côte d'Ivoire, using the indirect solar dryer built by the first author.

2. Materials and Methods

2.1. Materials

The materials are the electronic compact scaleSF-400C (accuracy of ± 0.01 g) used for weighing small samples of shells for drying experiments, and also materials used for temperature and solar radiations measurements and data logging. **Figure 1** shows weighing of small samples before drying.

Figure 2 shows the indirect solar dryer used for the study. It is made of two parts: the solar collector and the drying chamber.

The solar radiation-absorbing surface, *i.e.* the absorber, of the solar collector is a rectangular steel plate, with dimensions of 0.705 × 1.77 (width × length) painted back. The absorber is covered by a transparent flat glass plate, 4 mm

Figure 1. Weighing of samples of shells by an electronic compact scale SF-400C.

Figure 2. The indirect solar dryer used for the drying experiments.

thick. It has an area of 1.248 m^2. There are nine fins soldered along the absorber, 2 m long, which create ten channels. The collector has a rectangular entrance through which the ambient air enters following the ten channels under the absorbing surface and receives thermal energy from the absorber. This thermal energy is transferred in the drying chamber. The drying chamber is made of steel plates. It is insulated with plywood sheets, 10 mm thick. The dimensions of the drying chamber are 0.45 × 0.77 × 0.85 m (width × height × depth). There are six trays inside the drying chamber. The drying chamber is fitted with a chimney 24 cm high. A schematic representation of the solar dryer is given in **Figure 3**. **Figure 3(a)** shows the structure of the drying chamber, showing the six trays, the entrance of the hot air coming from the solar collector and the chimney. **Figure 3(b)** and **Figure 3(c)** are cross sections of the solar collector.

2.2. Methods

2.2.1. Drying Method

For the drying experiments, one sample was used. The sample has a square shape with dimensions 3 cm × 3 cm. Its initial mass was 11.24 g.

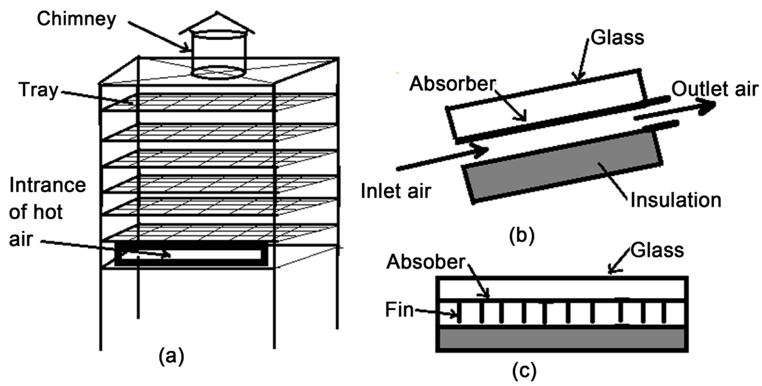

Figure 3. Schematic representation of the indirect solar dryer.

During the experiments, the sample is introduced in the drying chamber of the dryer. Then at steady time intervals Δt = 10 min, the sample is withdrawn from the drying chamber, for a rapid weighing. After each weighing, the sample is reintroduced in the dryer. At each time interval Δt, the ambient temperature of the drying chamber and its relative humidity γ are measured by a thermo-hygrometer. The results gotten from the experiment of March 3rd 2022 are given in this paper.

2.2.2. Thermal Modelling Theory

The convective heat transfer coefficient h_c is, in general, linked to the physical properties of humid air. Those physical properties are very often gathered to get some dimensionless numbers. Moreover, the theoretical moisture evaporated from a drying product is correlated to the convective heat transfer coefficient, and also to the difference between the partial pressure of water vapor in the air and the partial pressure of water vapor in the saturated boundary layer just near the evaporating surface of the product.

The Nusselt number Nu is one of the dimensionless numbers involved in the evaluation of the convective heat transfer coefficient. It is expressed by the following relation

$$Nu = \frac{h_c L}{k_f} \tag{1}$$

Then one gets

$$h_c = \frac{k_f}{L} Nu \tag{2}$$

L is the characteristic dimension which is here L = 0.03 m.

Moreover, the Nusselt number Nu is linked to the Grashof number Gr and the Prandtl number Pr by the following relation

$$Nu = C\left(GrPr\right)^n \tag{3}$$

In the above Equation (3), C and n are experimental constants. Some values of C and n are given in literature. Jannot, Y (2012) [8] gives the following values for a plate: C = 0.59 and n = 0.25 for a product $GrPr$ in the range 10^3 - 10^9. In a first step, those values were used in our calculations. Then C and n were recalculated, to get values in better accordance with our experimental data.

Finally, the convective heat transfer coefficient h_c is expressed as

$$h_c = \frac{k_f}{L} C\left(GrPr\right)^n \tag{4}$$

The dimensionless numbers Gr and Pr are expressed as indicated below

$$G_r = \frac{g\beta L^3 \rho_f^2 \left(T_i - T_p\right)}{\mu_f^2} \tag{5}$$

T_p is the temperature of the product surface; T_i is defined as: $T_i = \frac{T_p + T_a}{2}$. T_a is the temperature of the drying air above the product surface; β is the coefficient of volumetric expansion; ρ_f is the density of humid air; μ_f is the dynamic viscosity of humid air

$$Pr = \frac{\mu_f C_f}{k_f} \tag{6}$$

C_f is the specific heat of humid air, k_f is the thermal conductivity of humid air.

The rate of heat used to evaporate moisture from the drying product is expressed as [8]

$$Q_{ev} = 0.016 h_c \left[P\left(T_p\right) - \gamma P\left(T_i\right)\right] \tag{7}$$

$P(T)$ is the partial vapour pressure at temperature T; γ is the relative humidity. From Equations (4) and (7), one gets

$$Q_{ev} = 0.016 \frac{k_f}{L} C\left(GrPr\right)^n \left[P\left(T_p\right) - \gamma P\left(T_i\right)\right] \tag{8}$$

The theoretical moisture evaporated from the product, at time t, is expressed as

$$m_{th} = \frac{Q_{ev} A t}{\lambda} \tag{9}$$

A is the area of the product; λ is the latent heat of evaporation of water. From Equations (8) and (9), one gets

$$m_{th} = 0.016 \frac{k_f}{L\lambda} C\left(GrPr\right)^n \left[P\left(T_p\right) - \gamma P\left(T_i\right)\right] At \tag{10}$$

In a first step, the values of C and n used were those found in literature: $C = 0.59$; $n = 0.25$.

The evaluation of the physical properties of humid air, found in the above equations, was performed, at the temperature T_i, by using the following equations [9]:

$$C_f = 999.2 + 0.1434 T_i + 1.101 \times 10^{-4} T_i^2 - 6.7581 \times 10^{-8} T_i^3 \tag{11}$$

$$k_f = 0.0244 + 0.7673 \times 10^{-4} T_i \tag{12}$$

$$\rho_f = \frac{353.44}{T_i + 273.15} \tag{13}$$

$$\mu_f = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} T_i \tag{14}$$

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273.15}\right] \tag{15}$$

The latent heat of evaporation is expressed as [10]

$$\lambda = -2.419 T_p + 3164 \tag{16}$$

In Equation (16), T_p is expressed in K.

The temperature T_p of the product was not measured, but estimated. Some previous works show a link between T_p and T_a, the temperature of the drying air above the product surface [11]. From those works, a good approximation is T_a - T_p = 2.6˚C.

From those equations, the theoretical moisture evaporated from the product m_{th} was estimated step by step, for each time interval. The calculations were made by choosing, for the constants C and n, C = 0.59; n = 0.25.

In order to evaluate the goodness of fit between the theoretical moistures evaporated m_{th} end the experimental values m_{ex}, the Root Mean Square Error (RMSE) is determined according to the following formula

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(m_{ex} - m_{th}\right)^2\right]^{1/2} \tag{17}$$

Then, a new calculation of C and n was performed, by using the following procedure [12]. Let Z defined as:

$$Z = 0.016\frac{k_f}{L\lambda}\left[P\left(T_p\right) - \gamma P\left(T_i\right)\right]At \tag{18}$$

Then, from Equation (10), one can write

$$\frac{m_{th}}{Z} = C\left(GrPr\right)^n \tag{19}$$

When the logarithm of the two sides of Equation (18) is taken, one gets:

$$\ln\left(\frac{m_{th}}{Z}\right) = \ln C + n\ln\left(GrPr\right) \tag{20}$$

Let Y, X, m and b be defined as:

$$Y = \ln\left(\frac{m_{th}}{Z}\right) \tag{21}$$

$$X = \ln\left(GrPr\right) \tag{22}$$

$$m = n \tag{23}$$

$$b = \ln\left(C\right) \tag{24}$$

Then one gets the following linear equation

$$Y = mX + b \tag{24}$$

From the slope m of the regression straight line, one gets the constant n.

Then from the intercept b of the line, one gets $C = e^b$.

3. Results and Discussions

From the experimental weighing of the sample at steady time intervals Δt = 10 min, the evolution of the sample mass with time is gotten. It is shown in Figure 4.

Then the calculations of the the theoretical moistures evaporated m_{th} was carried out, using the temperature and relative humidity data. The results are given in Table 1 which shows the values of m_{th} and m_{ex}.

Figure 5 shows the comparative evolutions of the experimental and the theoretical moistures evaporated from the product.

On the whole, there is a good agreement between the experimental and the theoretical moistures evaporated from the product. Significant differences between the experimental and the theoretical moistures evaporated occur for only two points, for which T_a = 52.9˚C and T_a = 51.6˚C. It should be noted that those two points are characterised by a sudden rise of the temperature T_a of the drying air above the product surface, resulting in more moisture evaporated that the model takes into account. The good agreement between the experimental and the theoretical moistures evaporated was confirmed by the value of the Root Mean Square Error. It was found RMSE = 0.0307 g.

The data were also used for the calculation of the constants C and n of the Nusselt number, using the procedure described from Equation (18) to Equation (24). Figure 6 shows the plotting of Y against X.

The equation found is:

$$Y = 0.2425 - 0.5473X \tag{25}$$

From Equation (25), one gets C = 0.5785 and n = 0.2425.

The values of the Nusselt number, the Grashof number, the Prandtlnumber and convective heat transfer coefficient were calculated.

The Grashof number varies from 6.544 × 10^3 to 8.645 × 10^3. As for the Prandtl number, it varies from 0.6946 to 0.6974. For the Nusselt number, the following average value found was: Nu = 4.4938. The average value of the convective heat transfer coefficient was: h_c = 4.2252 W/m^2˚C.

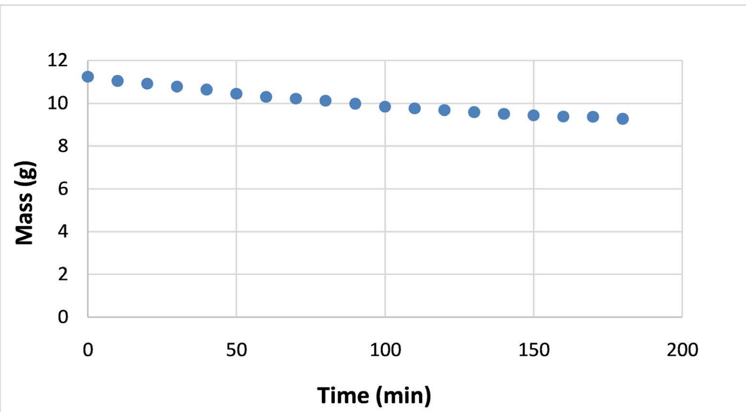

Figure 4. Evolution of the sample mass with time.

Table 1. Results of the calculations of the moisture evaporated.

T_a (˚C)	T_p (˚C)	T_i (˚C)	γ (%)	m_{th} (g)	m_{ex} (g)
49.6	47,0	48.3	0.25	0.1267	0.12
49.8	47.2	48.5	0.32	0.115	0.14
49.4	46.8	48.10	0.22	0.131	0.14
53.1	50.5	51.8	0.19	0.164	0.20
49.1	46.5	47.8	0.21	0.131	0.14
52.9	50.3	51.6	0.16	0.169	0.08
51.6	49.0	50.3	0.18	0.15	0.10
49.8	47.2	48.5	0.19	0.139	0.14
49.2	46.6	47.9	0.19	0.135	0.13
47.4	44.8	46.1	0.22	0.118	0.09
45.9	43.3	44.6	0.23	0.107	0.08
43.6	41.0	42.3	0.26	0.091	0.09
43.4	40.8	42.1	0.26	0.0907	0.09
40.2	37.6	38.9	0.36	0.065	0.07
39.2	36.6	37.9	0.32	0.066	0.06

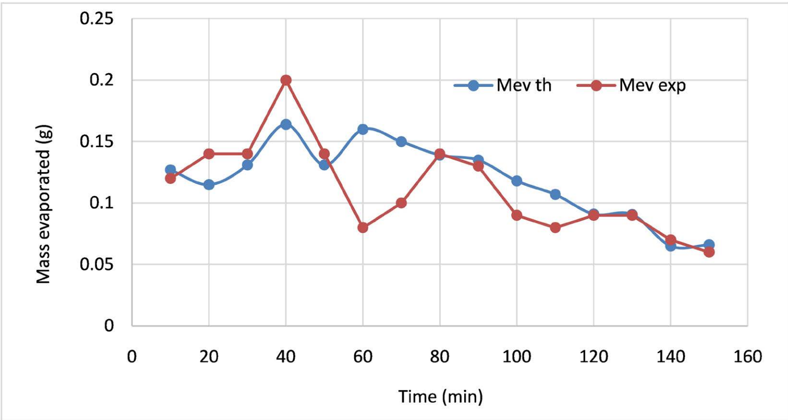

Figure 5. Comparative evolutions of the experimental and the theoretical moistures.

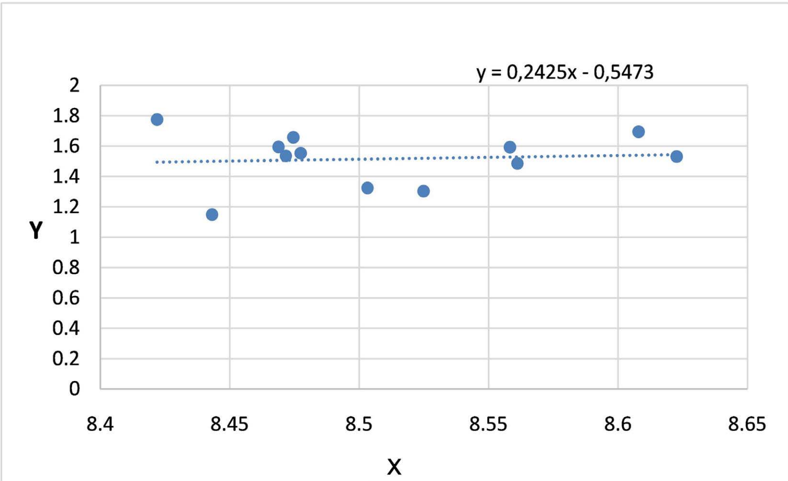

Figure 6. Plotting of Y against X.

4. Conclusion

The concern of the present work is the convective drying of empty cocoa shells in an indirect solar dryer. From the experimental data, a theoretical determination of the moisture evaporated from the product was performed. A good agreement was found between the theoretical and experimental values. Then the two constants involved in the Nusselt number were determined. It was found that $C = 0.5785$ and $n = 0.2425$. The dimensionless numbers of Nusselt, Grashof and Prandtl were calculated. The average value for the Nusselt number was: $Nu = 4.4938$. As for the convective heat transfer coefficient, its average value was: $h_c = 4.2252$ W/m^2°C.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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