Cocoa Beans Microwave Pulse Drying: Characterization of the Moisture Transfer

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ABSTRACT---- *The aim of this study was to characterize the moisture transfer during microwave pulse drying of cocoa beans. Experiments were carried out on fermented cocoa beans using a domestic microwave oven. Three microwave power levels (450 W, 600 W and 700 W) were used. The moisture transfer characterization was made using the estimation of mass transfer parameters and a modeling. The estimated mass transfer parameters were the Biot number (Bi), the diffusivity (D) and the mass transfer coefficient (k_m). They were given by the analytical method of Dincer. The 2^{nd} Fick's law was used for the moisture transfer modelling. The results obtained showed that for the whole microwave powers, the Bi values were included between 0.57 and 0.62. The D values, for the various microwaves powers (450 W, 600 W and 700 W), were respectively 6.01×10^{-9} m².s^{-1}, 10.27×10^{-9} m².s^{-1}and 11.94×10^{-9} m².s^{-1}. The k_m values varied between 9.87×10^{-7} m.s^{-1}and 21.33×10^{-7} m.s^{-1}. The Fick's model application showed a good adequacy between the experimental values and those simulated. R² of the Fick's model for the whole microwave power levels, was higher than 0.998.*

Keywords--- Drying, Microwave, Mass transfer, Cocoa

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1. INTRODUCTION

Drying is one of the oldest techniques of food preservation. It is a removing moisture technique which implies simultaneously a heat and mass transfer. Drying is an operation very significant in the post-harvest processing of cocoa beans. It reduces moisture content in cocoa beans (from 55 % to 7.5 %) and acidity and makes them easier to store [1]. Sun and hot air drying are the two main techniques used by cocoa farmers [2]. In spite of their advantages, these techniques have various drawbacks. For instance, unpredictable weather pattern, labour intensive, prolonged drying duration, low production rate and product spoilage are various drawbacks which are associated with sun drying. Meanwhile, the high energy cost, low thermal efficiency and low flavour quality (high acidity) are drawbacks usually associated with hot air drying. So, these drawbacks outline the need for innovating and searching more efficient drying devices.

The use of microwave drying techniques can constitute an interesting alternative way for cocoa beans. Indeed, microwave drying technique is a promising alternative to reduce drying time [3], [4], [5]. It can be also a thermal technique for microorganism's destruction [6], [7]. Moreover, it can be used for lipases inactivation, especially, triacylglycerol lipase responsible for the fat content degradation [8]. The use of microwave rays, as main supply energy in dryer for cocoa beans, requires a mass transfer mechanisms knowledge, which takes place in the product during drying. The mass transfer, in transient state, plays a significant role during drying [9]. Several transport mechanisms exist: diffusion, capillarity, evaporation-condensation etc. [10].

To understand mass transfer mechanisms, in transient state, it is needed to determine the main mass transfer parameters (diffusivity, mass transfer coefficient) and to analyze, matter distribution profile. Several determination methods of the mass transfer parameters, particularly diffusivity, exist [11], [12**]**, [13] and [14]. However, method developed by Dincer and Dost [12], [13**]**, allows to obtain these parameters easily. In transient state, mass distribution profile analysis, is possible from theoretical model simulation. Among theoretical models, diffusion one, is widely used because of its simplicity.

This study aimed to characterize and model moisture transport mechanism, during cocoa beans microwave pulse drying. Thus, Dincer and Dost method used to determine mass transfer parameters i-e Biot number (Bi), diffusivity (D) and the mass transfer coefficient (k_m), and then the 2nd Fick law used for moisture transfer modelling.

2. MATERIAL AND METHODS

2.1. Sample preparation

Fermented cocoa bean (*Forastero, ''Mercedes cocoa"*), used in these experiments, were obtained from Yamoussoukro (a city in the center of Ivory Coast, West Africa). They were stored at a temperature of - 4 ± 0.5 °C until drying experiment. A preheating of sample (200 g) was carried out in a microwave oven for 5 min at 100 W prior to be exposed to room temperature for 1 hour. The final temperature before the experiment was 28 ± 0.5 °C.

2.2. Microwave drying equipment and drying procedure

Cocoa beans drying experiments were carried out using a domestic microwave oven (*Samsung MW712K*, Malaysia), with technical feature of 800 W at 2.45 GHz. The microwave cavity dimensions were 330×211×309 mm. The microwave oven has ventilation opening on the left side. Microwave drying with 6 fold pulsing ratio (PR) was adopted in order to limit overheating. Pulsing ratio (PR) was defined as following expression [15]:

$$PR = \frac{CPon\ time + CPoff\ time}{CPon\ time} \qquad (1)$$

With

CP on time: Cycle power on time (60 s);

CP off time: Cycle power off time (300 s);

The experiments were drawn with 3 microwave power levels (i.e. 450 W, 600 W and 700 W). Each sample (200 g) was put on the rotating disc placed at the microwave oven center. The average initial moisture content of cocoa beans was 57.38 % ± 0.13 % (wet basis). Microwave energy was applied intermittently, until sample mass reached a level corresponding to a moisture content of 7.5 % (wet basis) which was regarded as the preservation moisture content. Samples moisture loss was recorded using a digital balance (*RADWAG* PS 2500/X, Poland) whose precision was *0.01g* an interval of 6 min. For each power level, experiments were carried out 9 times.

2.3. Drying kinetics

Sample moisture content at any time was transformed into moisture ratio [16]. The moisture ratio (MR) was calculated according to the equation (2)

$$MR = \frac{m_t - m_e}{m_0 - m_e} \qquad (2);$$

Where m_t, m_0, m_e are respectively sample moisture content at any time (kg of water/kg of dry matter), initial moisture content (kg of water/kg of dry matter) and equilibrium moisture content (kg of water/kg of dry matter). The moisture ratio was simplified in equation (3) because m_e is relatively negligible compared to m_t and m_0 [17].

$$MR = \frac{m_t}{m_0} \qquad (3);$$

Drying rate of samples was obtained from equation (4)

$$DR = \frac{m_t - m_{t+dt}}{dt} \qquad (4);$$

where DR is the drying rate (kg of water/kg dry matter) and m_{t+dt} the moisture content at specific time *t+dt* (kg of water/kg dry matter);

2.4. Moisture transfer parameters estimation

Mass transfer parameters such as Biot number (Bi), diffusivity (D) and mass transfer coefficient (k_m) were given using the analytical model suggested by Dincer and Dost [13]; the following assumptions were considered:
- initial concentration in moisture was uniform;
- thermophysical properties were constant;
- cocoa bean was comparable with an infinite plate;
- moisture diffusion was supposed to be one-way in direction thickness of cocoa bean.

Dincer and Dost model application assumes that moisture ratio distribution follows an exponential law:

$$MR = J_1 \exp(-S \times t) \quad (5);$$

where J_1 is dimensionless lag factor and S the drying coefficient (s^{-1}). Then, dimensionless moisture ratio values were regressed against drying time in the exponential form of Eq. (5). Thus, lag factors (J_1) and drying coefficients (S) values were determined by minimizing the mean square error with the least squares curve fitting method. The fitting were drawn using Matlab R2012a (MathWorks Inc., Massachusetts, USA) software.
The lag factor J_1 for an infinite slab is given by the following equation [12], [13]:

$$J_1 = \exp\left(\frac{0.2533 \times Bi}{1.3 + Bi}\right) \quad (6);$$

By determining J_1 values, the dimensionless Biot number (Bi) was calculated from Eq. 7

$$Bi = \left(\frac{0.2533 - \ln j_1}{1.3 \times \ln j_1}\right) \quad (7);$$

Then, moisture diffusivity was calculated by using Eq 8 as follows:

$$D = \left(\frac{S \times L^2}{\mu_1}\right) \quad (8);$$

where D is the diffusivity coefficient ($m^2.s^{-1}$); L is the characteristic dimension (slab half-thickness) : L= 0.035 m.
The value of μ_1 is calculated according following expressions [12], [13]:
for 0.1< Bi < 100

$$\mu_1 = \tan^{-1}(0.640443 \times Bi + 0.38097) \quad (9);$$

for Bi > 100

$$\mu_1 = \frac{\pi}{2} \quad (10);$$

Finally, moisture transfer coefficient ($m.s^{-1}$) was obtained by using equation 11

$$k_m = \frac{Bi \times D}{L} \quad (11);$$

2.5. Moisture transfer modelling

Diffusion was regarded as moisture transport mechanism inside cocoa bean. The geometric model replied the average dimension of the cocoa beans used for experiments. The average dimensions were as follows: length = 2 $\times 10^{-2}$ m, thickness = 7 $\times 10^{-2}$m. Bean meshing was carried out automatically via COMSOL Multiphysics 4.3 (Comsol Inc Burlington, MA) software.
The diffusion is governed by Fick's model (Eq.12), according to which the moisture flux is proportional to the concentration gradient though the moisture diffusivity (D), which was given by Eq (8). Also, moisture diffusivity (D) was considered time and space independent.

$$\frac{\partial MR_{num}}{\partial t} + \nabla(-D \nabla MR_{num}) = 0 \quad (12);$$

Where MR_{num}, is calculated moisture ratio at time t (s) and at spatial coordinates x and z (m).
As initial condition, initial moisture ratio were uniform.
At t = 0

$$MR_{num}(z, x, 0) = 1 \quad \forall (x, z) \quad (13);$$

At z = 0, $$\frac{\partial MR_{num}(0, x, t)}{\partial z} = 0 \quad \forall x \quad (14);$$

For boundary condition, Dirichlet's condition was used in order to avoid the moisture saturated air estimation, in the microwave. Boundary moisture ratio were assuming equal to experimental mean moisture ratio.
At z = L

$$MR_{num}(L, x, t) = \overline{MR}_{Exp}(t) \quad \forall (L, x, t) \quad (15);$$

Where $\overline{MR}_{Exp}$ is experimental mean moisture ratio.
The model was solved via finite element method using COMSOL Multiphysics 4.3 (Comsol Inc Burlington, MA) software. Modeling quality was evaluated using the determination coefficient (R^2) and the mean relative error (*MRE*). These parameters were calculated as follows:

$$R^2 = \frac{\left(cov(MR_{exp,i}; MR_{pre,i})\right)^2}{S^2_{rexp,i} \times S^2_{r\,pre,i}} \qquad (16);$$

$$MRE = \sum_{i=1}^{n} \frac{|MR_{exp,i} - MR_{pre,i}|}{MR_{exp,i}} \qquad (17);$$

$MR_{exp,\,i}$: i th experimental moisture ratio ;
$MR_{pre,\,i}$: i th predicted moisture ratio ;
Cov ($MR_{exp,\,i}$; $MR_{pre,\,i}$): Covariance of $MR_{exp,\,i}$ and $MR_{pre,\,i}$;
$S_{r\,exp\,i}$: Standard deviation of $MR_{exp,\,i}$;
$S_{r\,pre\,i}$: Standard deviation of $MR_{pre,\,i}$;
n: number of observations.

3. RESULTS AND DISCUSSION

3.1. Drying kinetics

The moisture ratio versus drying time curves for cocoa beans microwaved pulse drying are shown in figure 1. It revealed that the experimental dimensionless moisture ratio profiles fall exponentially throughout the drying period. Drying time varies from 4680 s (78 min) for 700 W to 10800 s (180 min) for 450 W (Fig 1). It decreased substantially as microwave power level was increased. Indeed, drying time obtained in the drying process using 450 W was respectively 2.30 and 7.87 fold longer than those in 700 W and 600 W. This result indicates that mass transfer is more rapid within cocoa bean sample, at higher microwave power levels. This is explained by the fact that higher microwave power leads to more heat generation inside the product resulting to a strong internal vapor pressure gradient. This observation was already mentioned by several authors [18], [19]. The drying rate curves for cocoa bean were given in figure 2. Drying rate varies during the whole drying process at the same microwave power levels. Three drying periods (figure 2), respectively heating period very quick, constant rate and falling rate ones, were observed. A similar tendency of drying rate was found in tomato hot air-microwave drying [20] and longan microwave vacuum-drying [21]. At heating period, drying rate increased quickly for the whole microwave powers levels as observed by [22]. About 70 % of moisture was removed during constant rate period. The drying rates regressed gradually during falling rate period. These results show that microwave power level influences on drying rate. Similar results were reported in several works [4], [16], [20], [23], [24].

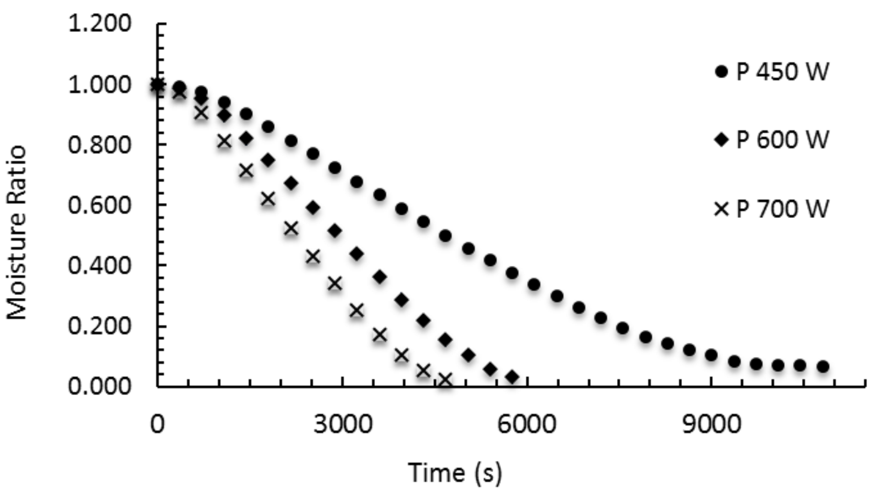

Figure 1: Variation of cocoa beans moisture ratio with drying time at different microwave powers

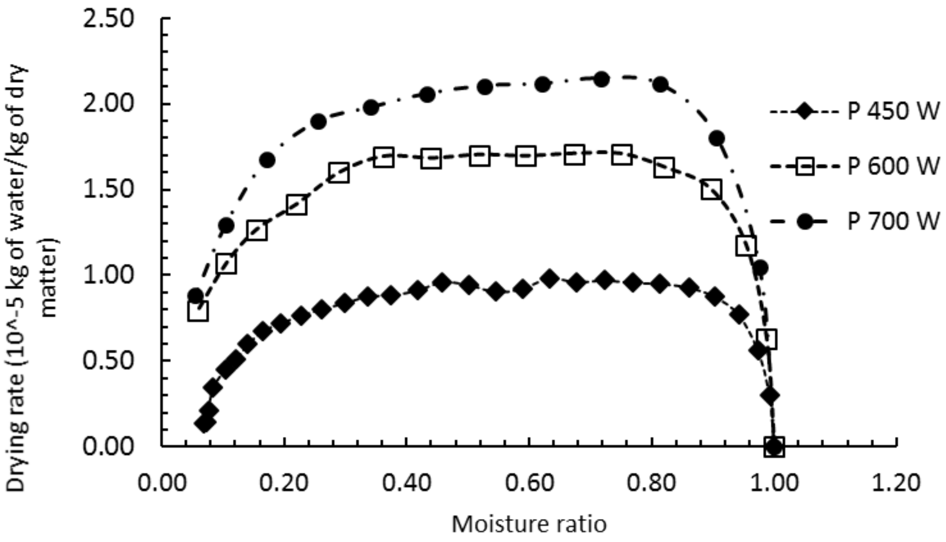

Figure 2: Variation of drying rate with moisture ratio at different microwave powers

3.2. Characterization of the moisture transfer

Table 1 presents the coefficients of determination (R^2) obtained, following to the moisture ratio distribution (MR) nonlinear regression (Eq 5). The table analysis shows that R^2 for the whole microwave powers levels (700 W, 600 W and 450 W) were respectively 0.9291, 0.9351 and 0.9570. These R^2 are superiors to 0.90 and outline a good fitting between the MR distribution and the exponential law. For the each microwave powers levels, R^2 obtained were close to those reported by many authors [25], [26] and [27]. The coefficient of drying (S) were ranging between 4.285×10^{-4} s^{-1} and 2.026×10^{-4} s^{-1} (Table 1). The S values increased with the microwave power. It highlights the water extraction amplitude. As S value was increased, the drying time was reduced. The lag factor (J_1) is an indicator of internal and external resistances to the moisture transport [12]. These values ranging between 1.150 and 1.156, indicated internal resistance to the moisture diffusion as mentioned by McMinn [28]. Moreover, when the lag factor is higher than 1, then Bi is higher than 0.1. This observation reported by [25], is explained by the relation between the lag factor and the Biot number (Eq 7). The Biot number (Bi) is a significant dimensionless parameter in drying, indicating whether internal or external resistance to mass transfer prevails [29]. In this study, Bi varied between 0.5749 and 0.6249 (Table 1). The values were all in the range 0.1 and 100. Consequently, it outlined the internal and external resistance presence to the moisture diffusion, during cocoa beans microwave pulse drying. Similar observation reported by [30], [31] and [27]**.** Internal and external resistance presence, during cocoa beans microwave drying, could due primarily to the cocoa bean structure. This explanation mentioned by [2] in the case of cocoa beans hot air drying. Indeed, the difference between the testa and the cotyledon cellular structures would be responsible of the moisture diffusivity difference within cocoa bean. Moreover, the testa hardening would contribute to slow down the moisture elimination. The cocoa beans diffusivity values varied between 6.01×10^{-9} $m^2.s^{-1}$and 11.94×10^{-9} $m^2.s^{-1}$. These values are included in the general margin (from 1×10^{-12} $m^2.s^{-1}$to 1×10^{-6} $m^2.s^{-1}$) of the foodstuffs enumerated by [32]. They showed the moisture internal transfer velocity during microwave drying. It explained by a strong internal pressure gradient due to absorption increasing of microwave energy [15], [27] and [33]. Moreover, these values were higher than those obtained by [17], in the case of cocoa beans solar drying. The diffusivity obtained by these authors, ranged between 3.78×10^{-11} $m^2.s^{-1}$and 5.38×10^{-11} $m^2.s^{-1}$. The mass transfer coefficients (k_m), were in the range 9.872×10^{-7} $m.s^{-1}$and 21.333×10^{-7} $m.s^{-1}$. It had the same order size than those obtained by [25], [28] and [30]. These results show the exchanges amplitude between cocoa bean and the surrounding medium.

Table 1: Drying and the mass transfer parameters values during cocoa beans microwave pulse drying

Microwave Power	R^2	J_1	$S\times10^{-4}$	Dincer and Dost model		
				Bi	**$D\times10^{-9}$ ($m^2.s^{-1}$)**	**$k_m\times10^{-7}$ ($m.s^{-1}$)**
700 W	0.929	1.150	4.285	0.624	11.949	21.333
600 W	0.935	1.152	3.610	0.607	10.278	17.847
450 W	0.957	1.156	2.026	0.574	6.010	9.872

3.3. Model application

The figure 3 shows the calculated values of Fick model. It shows a very good adequacy between experimental and simulated values. For each microwave power level (450 W, 600 W, 700 W), R^2 was respectively 0.9989, 0.9993 and 0.9990 (Table 2). They were close to 1.The MRE varied from 4.06 % to 13.64 % (Table 2). These values were close to those reported by [2], in the cocoa's beans hot air drying case. Indeed, these authors obtained a ranging between 3.1 % and 12.1 %. These results showed that the diffusion model explains well the moisture content distribution. It suggests that diffusion phenomena were dominant transport mechanism during cocoa beans microwaved pulse drying. These results can be explained by the heterogeneous cocoa bean structure. This heterogeneity caused mainly by the cocoa bean histology, and cells structural disorganization due to fermentation. Indeed during fermentation, the heat and acetic acid, involves a cells destruction. As a result that, variable soluble constituents, amino acids, purines, flavonoids, and sugars are reorganize [1]. This would support the moisture migration by diffusion. Moreover, these results show that the moisture transfer during cocoa microwave pulse drying, is the same one as that observed in the cases of cocoa hot air drying [2], [34], [35] and [36]. Moreover, this moisture transport way does not differ from the moisture transport mechanism observed during the foodstuffs microwave drying [18], [37].

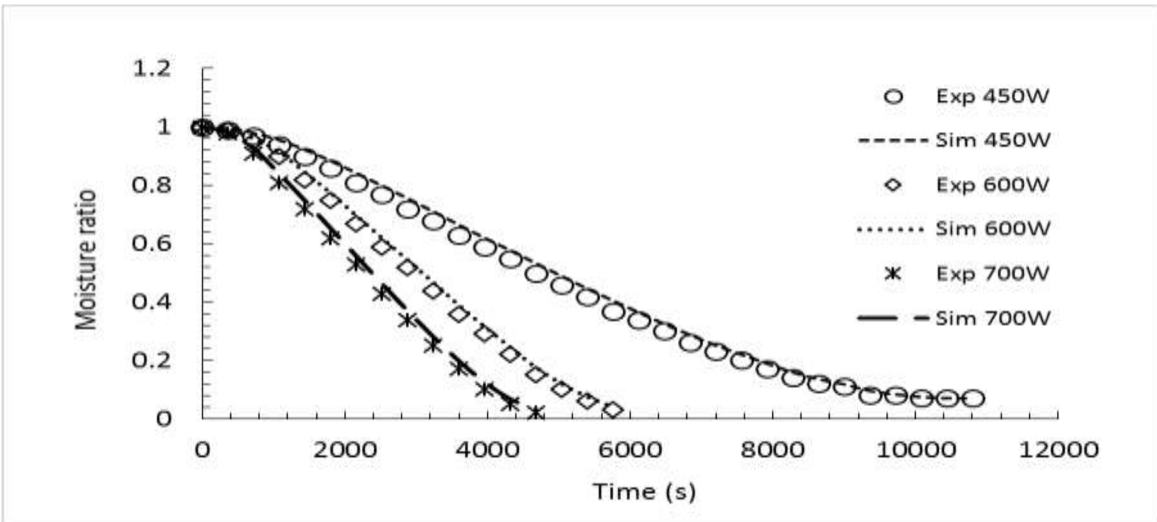

Figure 3: Diffusion model simulation for various microwave powers levels.

Table 2: Statistical parameters of the diffusion model for various microwave powers levels

Statistical parameters	450 W		600 W		700 W	
	R^2	*MRE (%)*	R^2	*MRE (%)*	R^2	*MRE (%)*
Diffusion model	0.9989	4.06	0.9993	0.0991	0.9990	13.64

4. CONCLUSION

This study aimed to characterize and simulate the moisture transfer during cocoa beans microwave pulse drying. To achieve this aim, the drying kinetics for three microwave power levels (450 W, 600 W and 700 W) were initially given. Then, the moisture transfer characterization was carried out from the Biot number (Bi), diffusivity (D) and the mass transfer coefficient (k_m). Lastly, a moisture transfer simulation was carried out by solving the 2nd Fick's law. The results showed, initially that drying rate increased with the microwave powers. Then, the Bi values were all in the range 0.1 to 100 and suggest the presence of internal and external resistance to the moisture diffusion, during cocoa beans microwaved pulse drying. Diffusivity, and the mass transfer coefficient, increased with the microwave power. Finally, moisture transfer simulation using 2nd Fick's law, showed that diffusion explains well the moisture ratio distribution during cocoa beans microwave pulse drying.

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