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A numerical model of cocoa beans drying kinetics in an indirect solar and air crossing dryer

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ABSTRACT: Cocoa beans moisture content behavior during drying in natural convection was estimated by integration of differential semi-empiric equation and mass flow formula. The new model was found to give better result (correlation coefficient is 0.97) respectively under experimental condition (55, 70 and 105°C), solar dryer, and sun drying. In addition, knowing that the drying kinetic was inversely dependent on the temperature, we have found the high drying temperatures lead to shortening of drying phases. Finally we conclude that the exponential two-member function is the improved model to describe falling drying rate.

KEYWORDS: cocoa drying; drying kinetics; moisture contents; modeling.

1 INTRODUCTION

The process of cocoa drying takes place in 3 phases. The first phase is very short and is characterized by gradual increase of beans temperature [2]. During this phase heat allows rapid evacuation of beans (pulp and shell) free water, then increase the drying kinetic. In the second phase, the temperature of the beans is stabilized because all supplied drying energy is expended in water evaporation. During this step, drying front moves from the outer surface of the shell to inside beans and the drying rate remains constant. The last and the longest phase is characterized by an increase of the temperature of the product and a decrease in the drying rate [2,3]. The duration of the last step, the high temperature, may cause the degradation of the quality of the product [4]. The free fatty acids (FFA) contained in the cotyledon are generally not modified in the drying process, they constitute cocoa butter [5] and are essential for making chocolate [6]. However, drying reduces water content in beans, evaporates the volatile acidity (acetic acid) and fixes the flavors by stopping chemical changes in the amino acids and polyphénols [7, 8].

The quality of drying process depends respectively on the air velocity, the hygrometry, and the temperature of the drying air [4], [9-13]. Nevertheless, drying air temperature is the most important drying parameter because its increase leads to faster of drying, but also trapping of acidity in the cotyledon. In addition, temperatures above 60 °C can stop bean browning and considerably reduce antioxidants and polyphénols. Therefore, to have good drying processes, the temperature value must be adapted to the behavior of the product.

Considering the problems of optimum drying temperature mentioned above, this study focuses on the development of a new numerical model to predict evolution of beans moisture taking into account time and temperature. Most of studies solved the diffusion model for describing the evolution of beans moisture during drying [7, 12], [14–16].

Alean [7] solved it numerically and obtained different average absolute deviation value for each temperature, namely 21.8 % for 40°C, 29.3 for 50°C and 27.2% for 60°C. Hii [15] obtained a prediction between 98% and 99% by modeling the evolution of the moisture content day to day for sun and different temperatures (60°C, 70°C and 80°C). Hii [12],and Koua [16] used the solution proposed by Crank [17].

However, to solve diffusion model equation, the simplification hypotheses are to consider conservation of initial shape of the product and homogenization of moisture extract [18]. The initial moisture of the product must be also uniform [19]. The high beans moisture content after fermentation (55% moisture basis) induced deformation during drying, taking into account the change of form in diffusion model is very difficult.

The aim of this study is to use a behavior model to predict moisture modification during drying. Thus, this paper presents the use of mass flow equation to predict the drying of cocoa beans in three conditions: artificial drying (AD), direct solar drying (DSD), and indirect solar drying (ISD).

2 Materials And Methods

2.1 Raw Materials

Cocoa bean pods were harvested and stored for5 days. On the 6th day, pods were opened with a piece of wood similar to the method in rural areas. Two kind of cocoa fermenter were manufactured with wooden material: an experimental cylindrical fermenter (FCR)base radius r= 0.28m with 1.44 m of height[20], and classic wood box fermenter whose dimension are0.55×0.55×0.55 m(L*l*h). In each fermenter, 150 kg of healthy fresh beans were fermented .Beans were turned regularly during fermentation. Finally, after 6 days, they were taken out to be dried.

2.2 Study Drying Processes

The drying changes the moisture content of the beans at the end of the fermentation, from 1.22 in dry basis (~55% moisture basis) to 0.08 in dry basis (~7,5% moisture basis) to reach the hygroscopic equilibrium [21]. Three experiments were performed, one in the laboratory for artificial drying and the two others on the test site (Côte d'Ivoire, Mbrimbo).

2.2.1 Artificial Drying (AD)

The sample of fermented beans were dried in desiccators (MB C120, PCE) (Fig. 1)usingthreetemperatures:55°C, 70°C and 105°C, for 25% relative humidity. Heat was generated by two halogen heaters (λ=118 mm), and weight was measured each second with automatic balance of dryer. Mass loss was stopped about7 hoursor13 hours, only after hygroscopic equilibrium is reached with surrounding air.

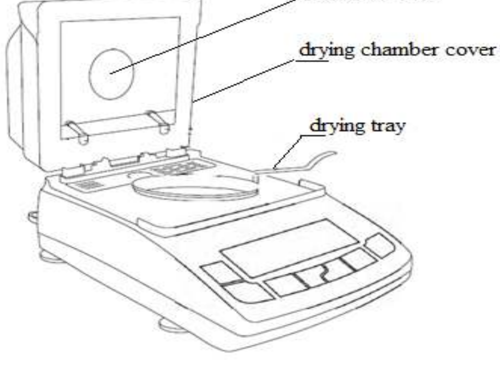


Fig. 1. Schematic diagram of the artificial drying equipment

2.2.2 DIRECT SUN DRYING (DSD)

Beans from each fermenter were spread thinly on a woven rattan tray. The drying surface area, (0.98*0.95) m² (L*l) was raised 1.5 m above ground level. The wind can flow through the beans by natural convection. Mixing of beans took place twice daily during weighing. Drying starts at about 9:00 a.m UTC and finishes at 5:00 p.m UTC, during 7 days. Throughout this period, daily solar radiation ranged between 300W/m² and 800 W/m², ambient air temperature ranges from 25°C to 34°C, ambient air relative humidity ranged 80% to 57%, and wind from 0 to 2 m/s. At night, the beans were covered with black plastic and ambient temperature was 22°C and humidity 97%. Drying parameters (T°C, RH%, wind direction and speed, solar radiation, dew point, barometric pressure, heat index and rain rate) were measured by a weather station (Vantage Pro2Plus, DAVISINSTRUMENTS).

2.2.3 INDIRECT SOLAR DRYING (ISD)

Indirect solar drying uses the same process as direct sun drying and drying was stopped by hygroscopic equilibrium. But for ISD, drying temperature ranged from 35°C to 45°C, relative humidity range from 33% to 65% and air flow between 0.04m/s to 0.06 m/s. At night, air temperature ranged from 27°C to 24°C and humidity between 75% to 90%. Drying parameters were measured during process. Temperatures at each drying tray by thermo-hygrometric data logger (EL-USB-2+, LASCAR) with a resolution of 0.3°C/2%RHand air flow by hotwire anemometer with a resolution of 0.01m/s (hot-wire WIMESURE). This prototype was manufactured by EnIT (Côte d'Ivoire, Abidjan) for experimentation. The collector surface size is 2m (width)×4.62m(length), the drying chambers size is 2m (width)×1.21m (length) ×1m (height). The air enters by natural convection and redirected by fins at the outlet of the collector (Fig. 2).

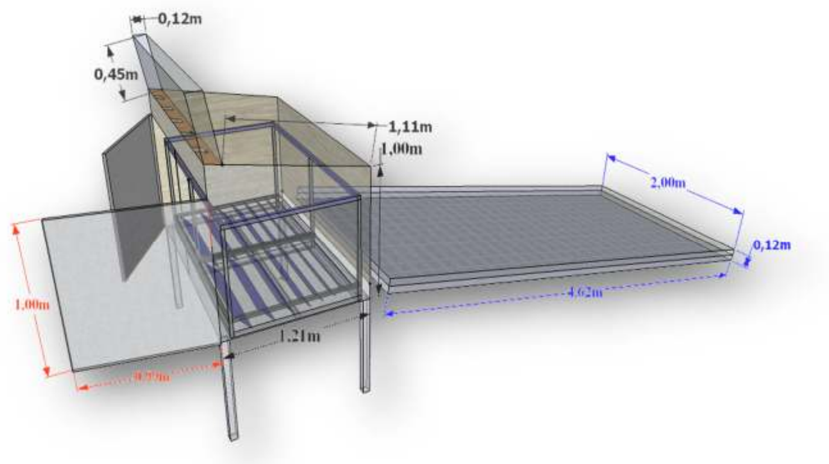


Fig. 2. Schematic of the experimental drying equipment [22]

2.3 DRYING MODELING FORMULA

Each sample was taken at the end of the drying and each dry mass was determined after 24 hours at 105°C in the moisture analyzer**.** The drying rate at each moment during experimentation was calculated by the following formula(see Eq. 1)[19], [23],

$$F_m = -\rho_s * e_s \frac{dW}{dt} \tag{1}$$

where $W$is beans moisture in dry basis,ρ_s is the dry product density, and e_s is the thickness of the product layer.

2.4 OPTIMIZATION AND DATA FITTING TOOLS

A software QtiPlot 0.9.8.9 was used to analyze experimental data and perform comparison between values obtained experimentally ($Fm_{exp.i}$) and prediction model value ($Fm_{mod.i}$). The highest values of R²(see Eq. 2) and the lowest value of RMSE (Root Mean Square Error)(see Eq. 3), RSS (Residual Sum of Squares)(see Eq. 4) and χ² (chi-square)(see Eq. 5) were used to select the best model for describing moisture course,

$$R^2 = 1 - \frac{\sum_1^n (Fm_{exp.i} - Fm_{mod.i})^2}{\sum_1^n (Fm_{exp.i} - \overline{Fm}_{exp})^2} \tag{2}$$

$$RMSE = \sqrt{\frac{1}{n}\left[\sum_{i=1}^{n}\left(Fm_{exp.i} - Fm_{mod.i}\right)^2\right]} \quad (3)$$

$$RSS = \sum_{i=1}^{n}\left(Fm_{exp.i} - Fm_{mod.i}\right)^2 \quad (4)$$

$$\chi^2 = \frac{\sum_{1}^{n}(Fm_{exp.i} - Fm_{mod.i})}{n-N} \quad (5)$$

where $\overline{Fm}_{exp}$ is the average of experimental values,n is the number of measurement points during one experience and N is the number of constants of the model expression.

3 Results And Discussion

3.1 DSD And ISD Drying Kinetics

The moisture contents rate curves versus time for DSD and ISD drying are shown in Fig 3.Moisture decreases continuously with drying time. The first day, kinetic is more important, this shows free water quantity is considerable on the test a of bean [24]. For the second and third days kinetic is less important. From fourth day, drying kinetic becomes constant. This modification may be explained by equilibrium of moisture between the beans and the surrounding drying air[10]. Globally in both dryer, changes are the same, and showed no recovery of water during the night.

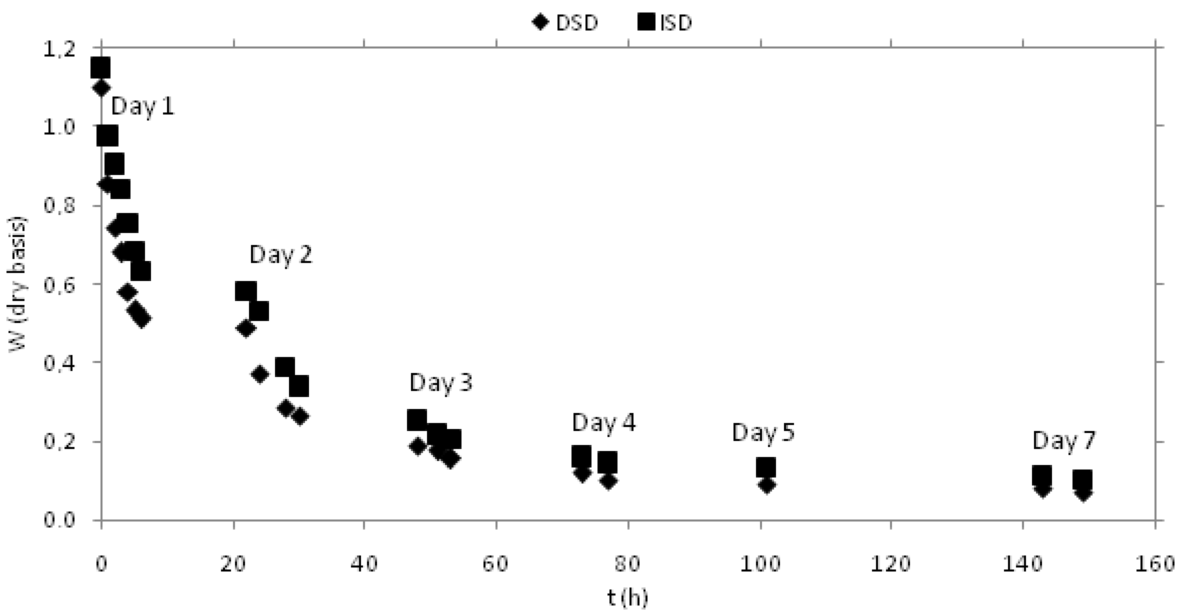


Fig. 3. Cocoa beans Moisture contents rate curves for DSD and ISD different temperatures

3.2 Drying Kinetic Model Building

3.2.1 Moisture Kinetic

The initial moisture is 1.041±0.015 dry basis (51±1.4% moisture basis). InFig.4at the beginning of experiment(first 3h)it is observed a decrease of the moisture content inartificial dryer at constant temperature. This observation is also reported by Alean Hii [7], and [15]. After 3h, a progressively reduction of moisture appears to obtain the equilibrium moisture (Wbs=0.08[25]). This experiment was repeated three times at different temperatures. For each experiment (at different temperature) the dry times are:

10 hours for T=55°C,5 hours for T= 70°C, 3 hours for T=105°C.

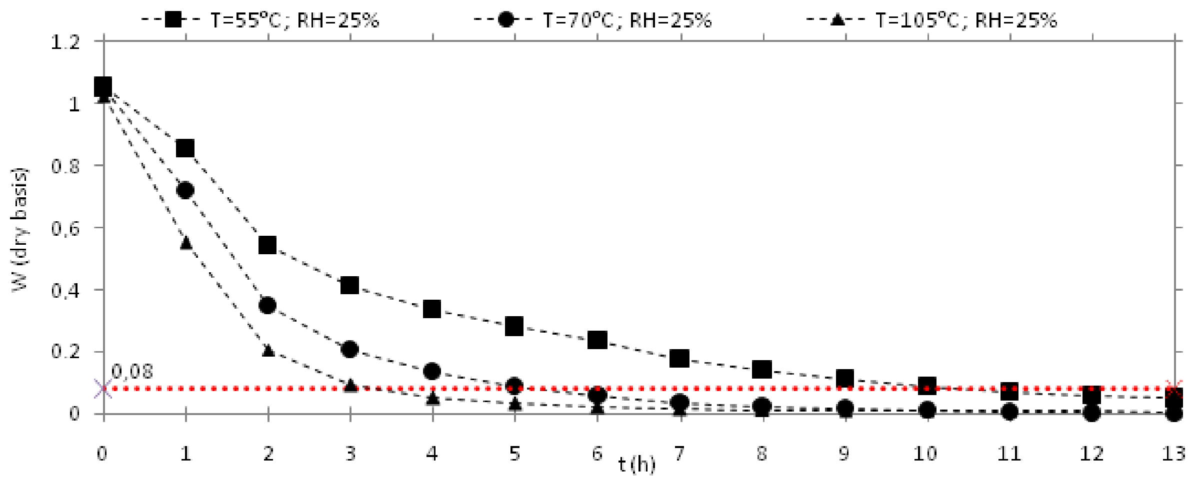


Fig. 4. Cocoa beans Moisture contents rate curves for 3different temperatures.

3.2.2 Drying Kinetic By Using Mass Flow Formula

Fig.5 shows experimental drying rate at different temperatures. It is observed three phases for each temperature and a shortening of each phase duration when the temperature increases. Each point of measurement corresponds to 5 mn. The drying rates increment beginning up initial moisture (1.041) to 0.895 (d.b.) within 25 mn, to 0.887 (d.b.) within15 mn and to 0.761 (d.b.) within 10mn, respectively for 55°C, 70°C and 105°C. Beyond drying remains constant for a very short time (about 7 mn) for three temperatures. During the last phases, drying rate decreases and values are very close at the end of process. These results are in agreement with previous observation of foods drying [2], [11], [15], [26]. For each drying phases, higher of drying temperature induce shorter and stronger in evolution mass flow course. This is probably caused by dependence of moisture diffusion to temperature[4], [27].

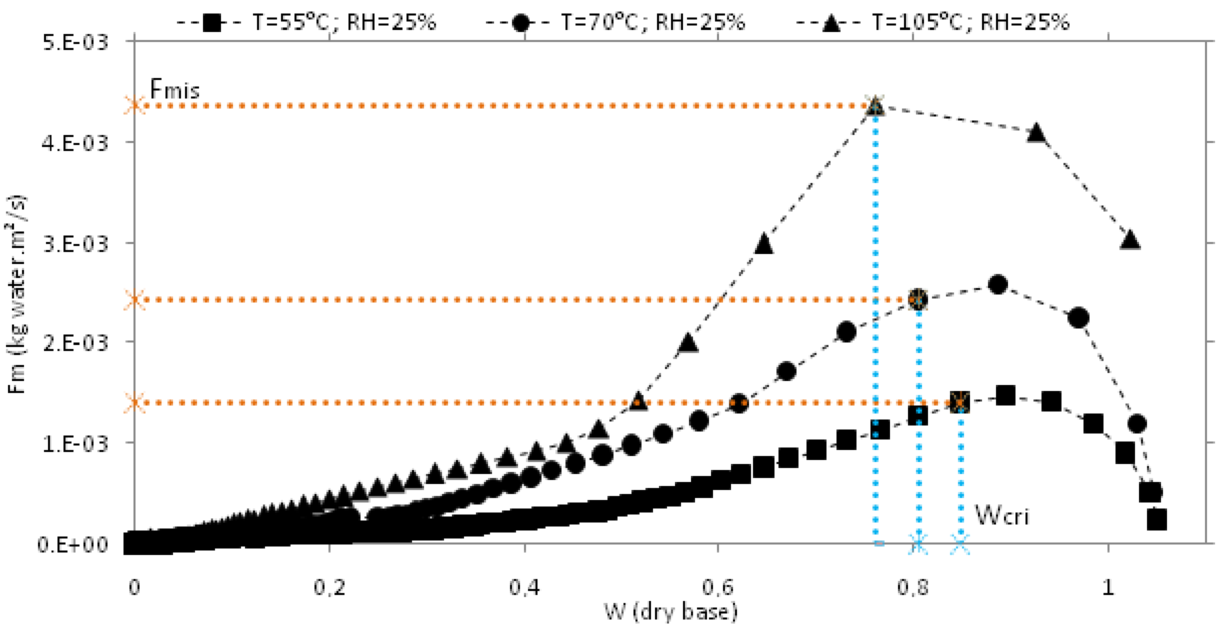


Fig. 5. Drying rate curves for 3 treatments in artificial dryer

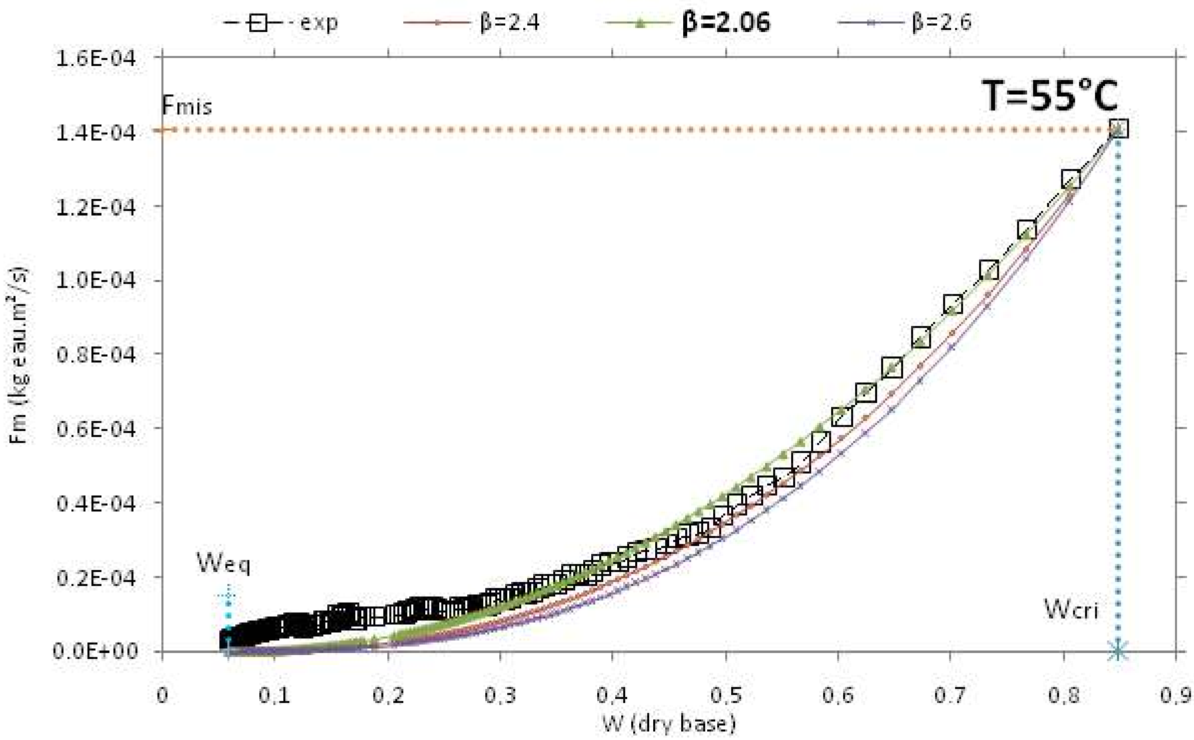
Identification of drying constant phase (isenthalpic phase) makes it possible to write drying rate as the following equation (see Eq. 6) and make graphic identification of formula parameters with Fig.5.

$$F_m = F_{mis}(\frac{W-W_{eq}}{W_{cri}-W_{eq}})^{\beta} \quad (6)$$

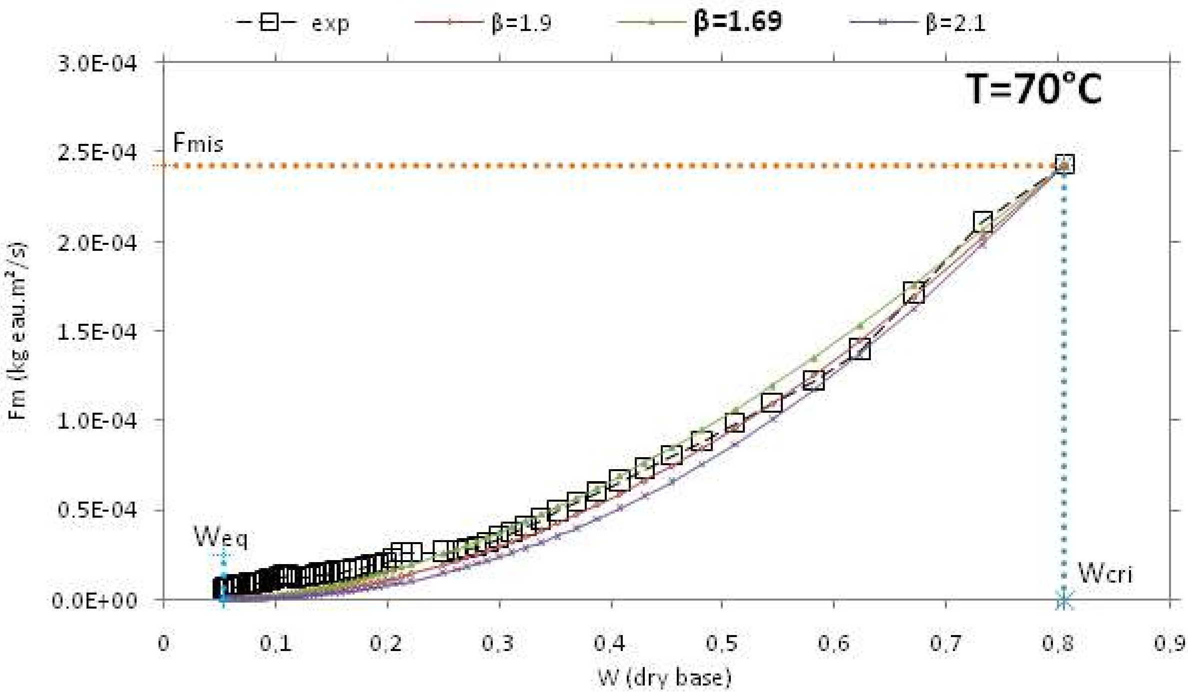
In this formula F_{mis} is the isenthalpic mass flow and its value corresponds to end value of second drying phase.W_{cri} its moisture at the end of isenthalpic phase. Both values are determined visually by the point where curves of drying rate jump from substantially constant to continuous decrease. The orthogonal projection of this point on F_m axis give F_{mis} and the orthogonal projection on W axis giveW_{cri}. W_{eq} is equilibrium beans moisture, it also determinate visually by the orthogonal projection of F_m on W axis when value drops below$1.10^{-5} kgwater.m^2/s$. The last parameter (β)corresponding to beans resistance under the drying condition and value is adjusted to have very close mass flow values between theoretical (Eq. 12, with previous parameters values) and experimental data (Fig.6). Values of the mass flow formula parameters are shows in Table 2.The new formula of drying rate can be writing like following (see Eq. 7).

$$\left.\begin{array}{l} F_m = F_{mis} for w > w_{cri} \\ F_m = F_{mis}(\frac{W-W_{eq}}{W_{cri}-W_{eq}})^{\beta} for w < w_{cri} \end{array}\right\} \quad (7)$$

The best value of β for each temperature is determinate inFig.6.It can observed for 55°C and 70°C modification of β value lead to reach a best agreement between each experimental point and model prediction. But for 105°C prediction were not upgrade by β values.



(a)



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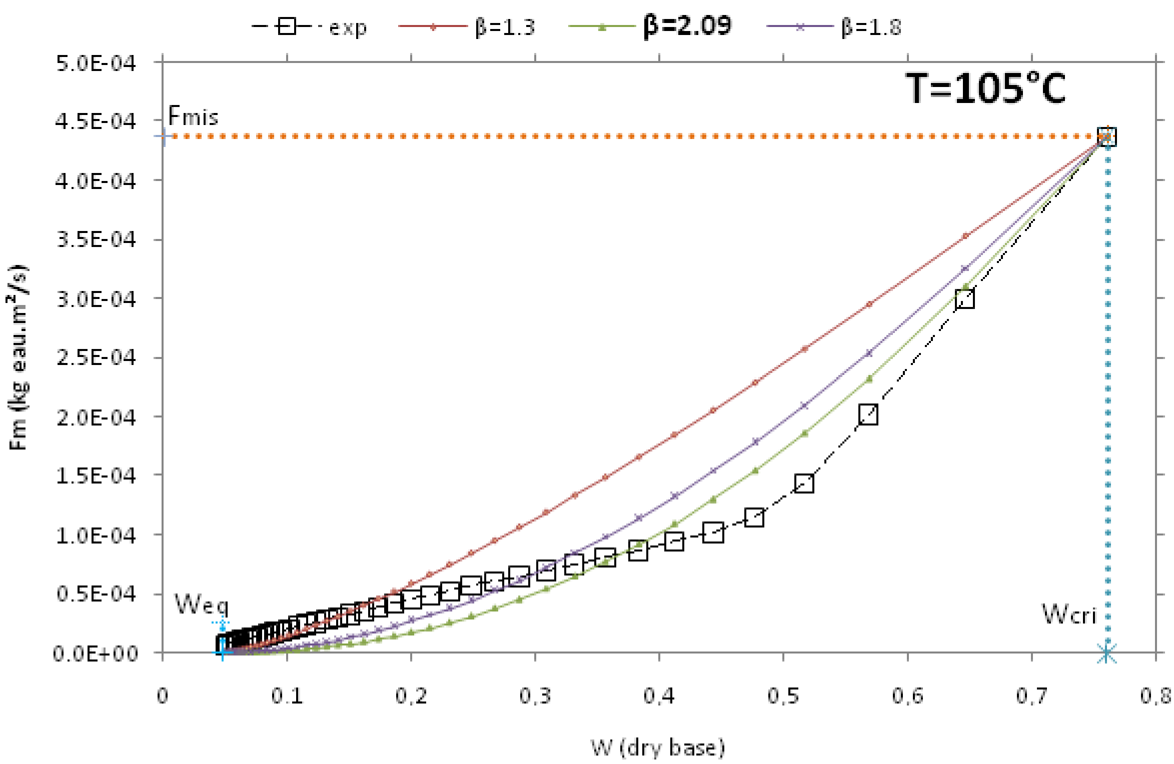
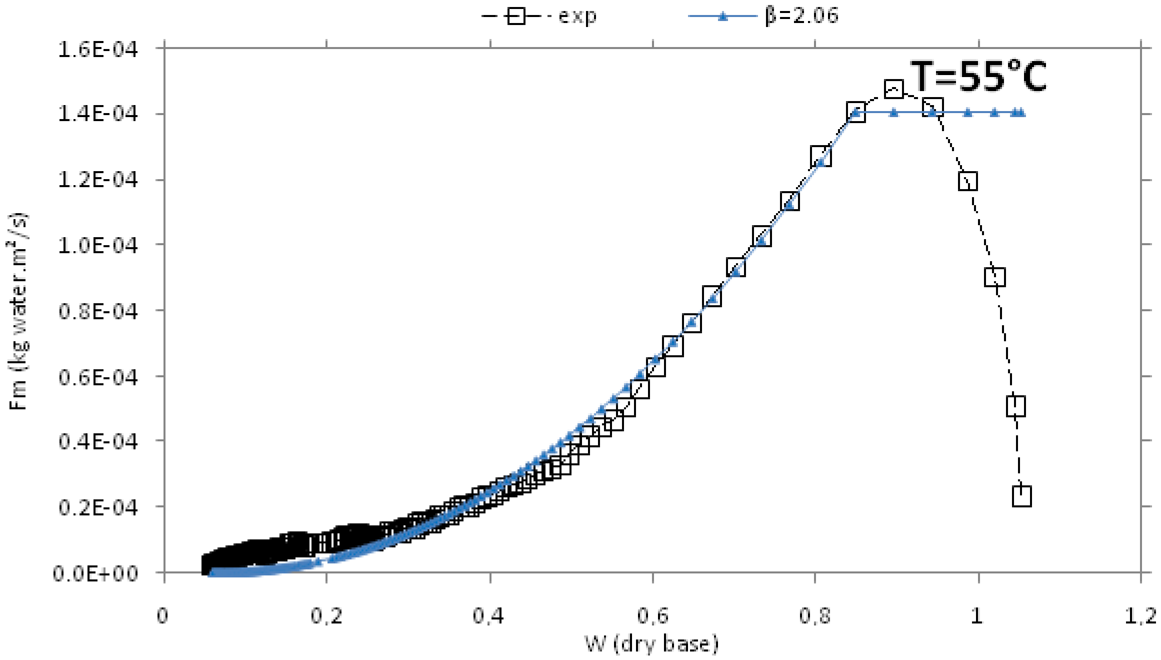


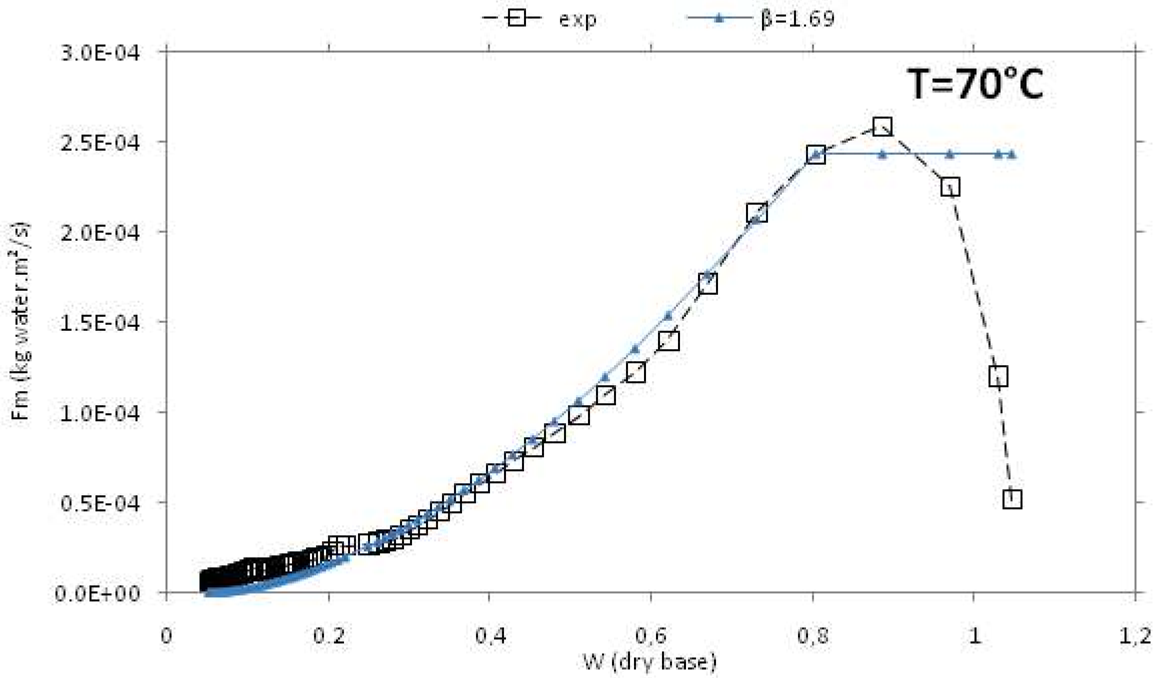
(c)

***Fig. 6.** Determination process of β of mass flow model for each temperature: □ experimental data, *predict data according βvalue: (a) 55°C, (b) 70°C, (c) 105°C*

Mass flow model (see Eq. 7) give close value between experimental and calculate result in each temperature in the drying phase 3, except for 105°C (Fig.7 and Table 2). Mass flow formula was not appropriate to predict drying kinetic for temperature above 70°C.



(a)



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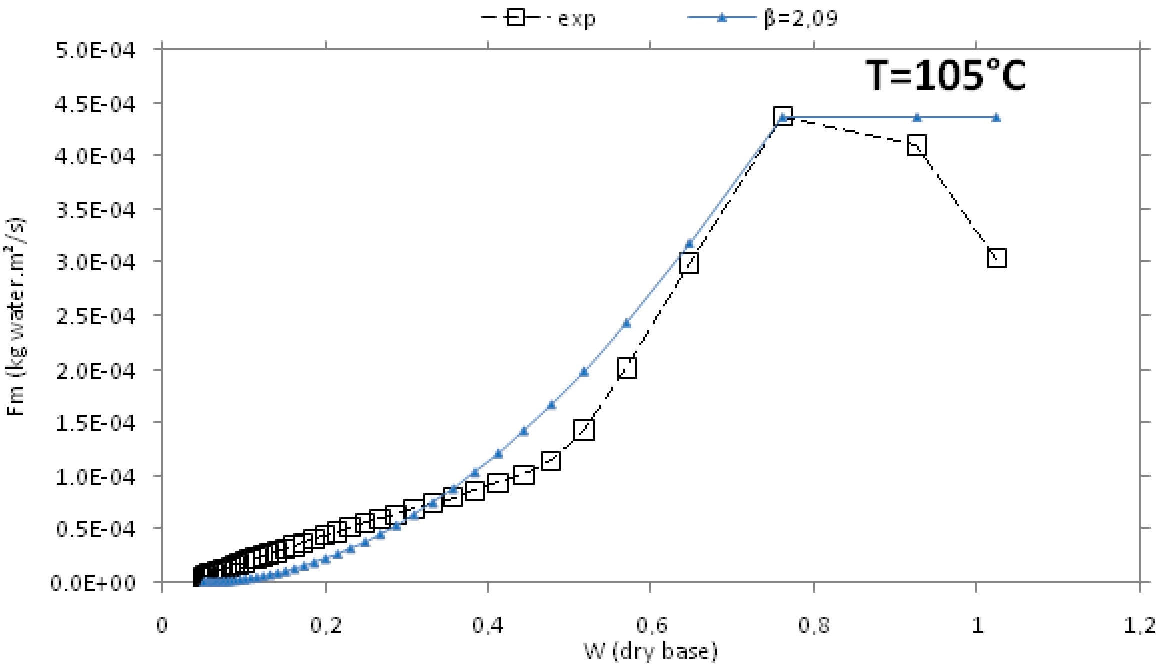

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Fig. 7. Experimental and analytic drying rate curves for each temperature: (a) 55°C, (b) 70°C, (c) 105°C

3.2.3 Drying Kinetic By Using Semi Empiric Model

The falling drying kinetics curve (where $F_m < F_{mis}$)is modeling by ten semi empirical model formula (Table 1) based on the moisture content (W)and time (t) and used classically on thin layer drying. These models are used to fit only experimental data and $f$is mass flow and $x$is moisture.

Table 1. Semi empirical models most used in drying kinetics [10], [12]

Name and references model	Expression	Eqs. number
Logarithmique **[28]**	$f(x)=a\exp(-kx)+b$	(8)
Newton **[29]**	$f(x)=\exp(-kx)$	(9)
Page **[30]**	$f(x)=\exp(-kx^n)$	(10)
Henderson and Pabis **[31]**	$f(x)=a\exp(-kx)$	(11)
Two-term**[32]**	$f(x)=a\exp(-kx)+b\exp(-hx)$	(12)
Two term exponential **[33]**	$f(x)=a\exp(-kx)+(1-a)\exp(-kax)$	(13)
Diffusion approch**[34]**	$f(x)=a\exp(-kx)+(1-a)\exp(-kbx)$	(14)
Wang and Sing **[35]**	$f(x)=1+ax+bx^2$	(15)
Verma *et al*.**[36]**	$f(x)=a\exp(-kx)+(1-a)\exp(-gx)$	(16)
Midilli *et al*. **[37]**	$f(x)=\exp(-kx^n)+bx$	(17)

Results (parameters and statistical analysis) of drying rate modeling after using formulas of Table 1 on part of curve for each temperature (55°C. 70°C and 105°C) are shown in Table2. It presents highest R^2 values (0.988 to 0.995), the lowest χ^2 ($4.32*10^{-10}$ to $2.39*10^{-9}$), the lowest RMSE ($1.63*10^{-5}$ to $4.89*10^{-5}$), and the lowest RSS ($2.59*10^{-8}$ to $8.36*10^{-8}$) for Two-term model.

Table 2. Result of fitting analyzes of last drying rate phases for each temperature with constant relative humidity at 25%

Model	T°C	Parameters					Statistical analysis			
		Fmis $*10^{-3}$	β	Wcri	Weq		R^2	RMSE $*10^{-5}$	RSS $*10^{-7}$	ki² $*10^{-9}$
Mass flow	T=55	1,41	2,06	0,848	0,059		0,957	4,55	2,71	2,07
	T=70	2,43	1,69	0,805	0,053		0,972	6,90	3,00	4,77
	T=105	4,37	2,09	0,760	0,048		0,941	20,1	15,8	40.5
Semi-empiric models										
		a	b	h	k	n	R^2	RMSE $*10^{-5}$	RSS $*10^{-7}$	ki² $*10^{-9}$
2 Termes	T=55	9,05E-04	-8,79E-04	-2,88	-3,02	-	**0,995**	1,63	34.0	0.26
	T=70	6,81E-02	-6,81E-02	-2,05	-2,06	-	**0,998**	2,08	25.9	0.43
	T=105	1,96E-04	-4,42E-04	17,30	-3,95	-	**0,988**	4,89	83.6	2,39
Hederson and Pabis	T=55	4,13E-05	-	-	-4,37	-	0,992	2,04	0.54	0.41
	T=70	9,75E-05	-	-	-4,29	-	0,983	5,46	1,85	2,98
	T=105	1,47E-04	-	-	-4,55	-	0,963	8,31	2,55	6,90
Logarithme	T=55	5,75E-05	-3,39E-05	-	-3,95	-	0,994	1,71	0.38	0.29
	T=70	2,36E-04	-2,21E-04	-	-3,14	-	0,997	2,18	0.29	0.48
	T=105	4,70E-04	-4,24E-04	-	-2,74	-	0,978	6,55	1,54	4,29
Page	T=55	-	-	-	6,34	-0,29	0,953	4,74	2,93	2,25
	T=70	-	-	-	5,80	-0,25	0,974	6,76	2,84	4,57
	T=105	-	-	-	5,83	-0,18	0,953	9,38	3,26	8,80

According Table 2, the best model was chosen (see Eq. 12) and moisture changes was determined through equation (see Eq. 19) by using Euler numeric method for each temperature (55°C, 70°C and 105°C)

$$F_m = a * \exp[-k * w(t)] + b * \exp[-h * w(t)] \quad (18)$$

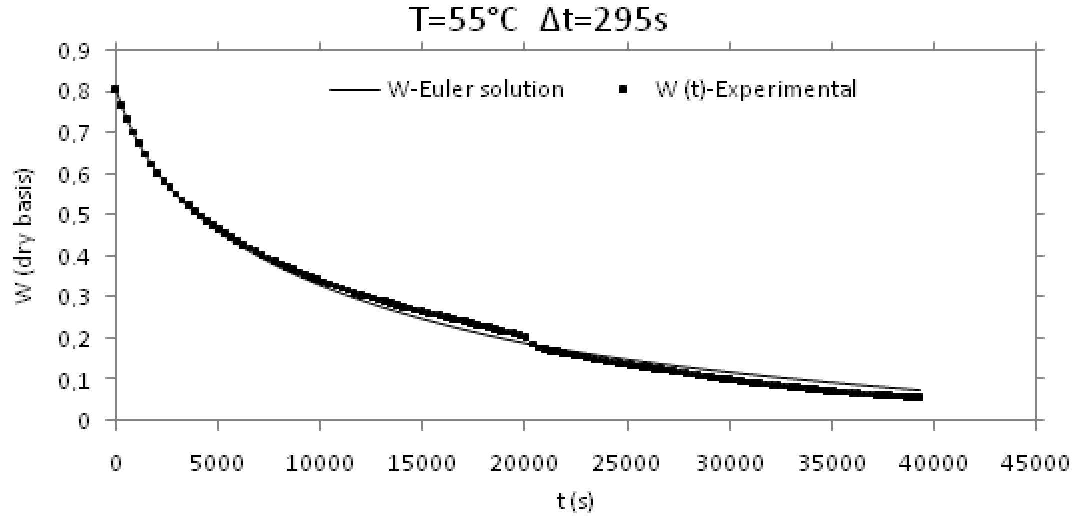
(see Eq. 1) and (see Eq. 18) ➔ $\frac{dW}{dt} = -\frac{1}{\rho_s * e_s}[a * \exp[-k * w(t)] + b * \exp[-h * w(t)]]$ (19)

For the numerical solution of Eq. 19, and in order to express moisture content in beans, we use Euler method. Experimental moisture and Euler solution values are very close (Fig. 8). Numerical solution was fitted with logarithm (see Eq. 20), and all parameters (a, b) were analyzed to create a relation with temperature. This approach leads to a single formula for all temperatures.

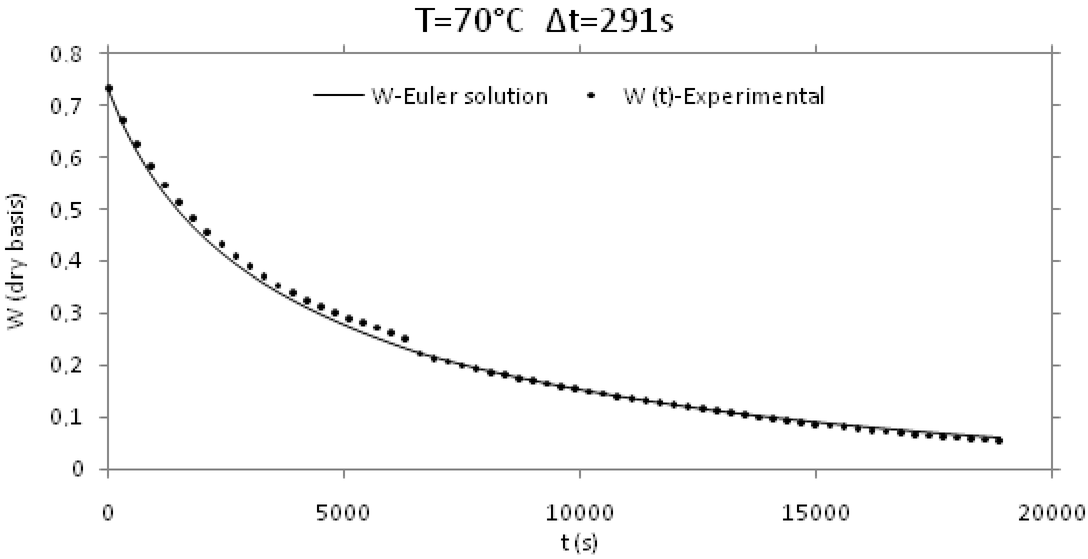
$$w(t) = a * \ln(t + cst) + b \quad (20)$$

The final expression of moisture (new semi empirical model) which takes into account drying time and temperature has been found (see Eq.21).

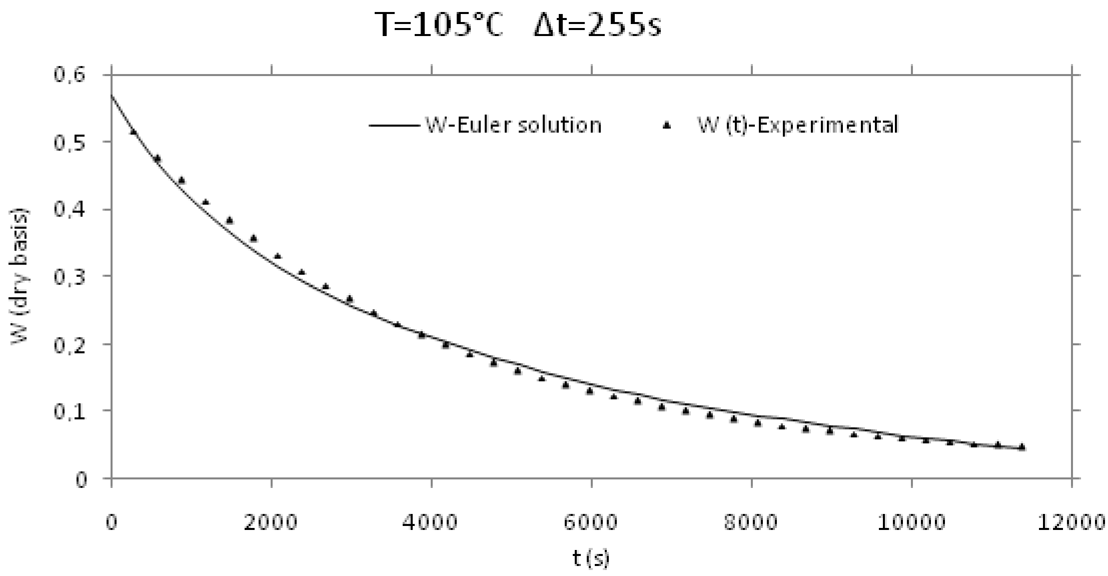
$$w(t, T_\infty) = (\frac{5.729}{T_\infty + 273.15} - 0.224) * \ln(t + 1025.62) + \frac{2.18 * 10^6}{(T_\infty + 273.15)^2} - \frac{1.18 * 10^4}{T_\infty + 273.15} + 17.963 \quad (21)$$


T=55°C Δt=295s
W-Euler solution
W (t)-Experimental
W (dry basis)
t (s)
0,9
0,8
0,7
0,6
0,5
0.4
0,3
0,2
0,1
0
0
5000
10000
15000
20000
25000
30000
35000
40000
45000

(a)


T=70°C Δt=291s
W-Euler solution
W (t)-Experimental
W (dry basis)
t (s)
0.8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
5000
10000
15000
20000

(b)

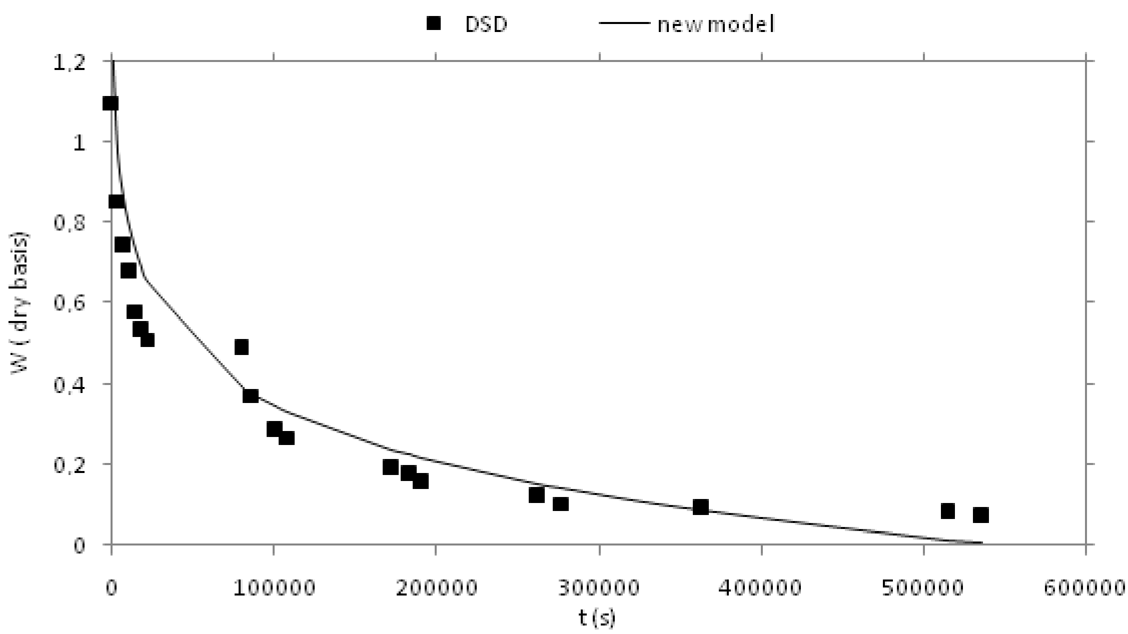


(c)

Fig. 8. Moisture numerical solution: (a) 55°C, (b) 70°C, (c) 105°C

3.3 COMPARISON OF EXPERIMENTAL AND MODEL RESULTS

Moisture model values are as indicated by the solid lines in Fig. 9, experimental values for direct sun drying (DSD) and indirect solar drying (ISD)are as shown by squares. Model profiles fit well the experimental data. The new model was able to predict cocoa moistures variation for indirect and direct drying with good precision (R^2), 97.40%for DSD and 97.13%for ISD. The same prediction has been reported by Clement[10] with logarithmic drying model on beans under only ambient conditions(DSD). A capacity of prediction of98% has been found with a modification of drying model 2terms by Hii [12] but its model doesn't take into account the temperature above 80°C. The new semi empiric model gives an excellent result in natural convection for artificial, direct and indirect drying.



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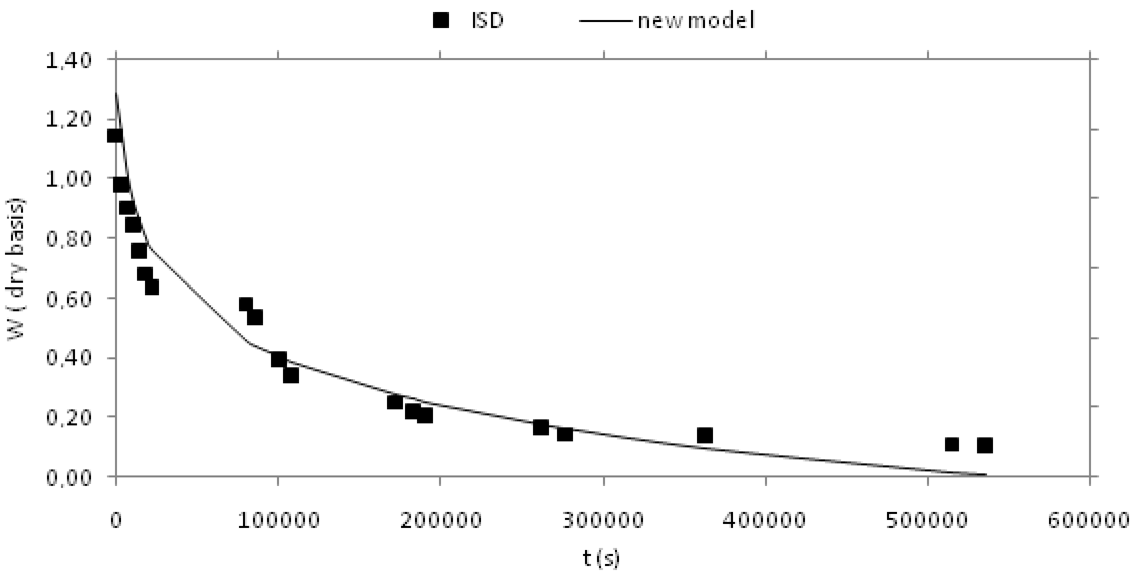

(b)

Fig. 9. ***Comparison of experimental moisture and new model prediction in DSD (a) and ISD (b)***

4 CONCLUSION

The present study shows the use of the mass flow curve for modeling moisture content. Our drying model can reproduce the experimental evolution of moisture, in artificial dryer at constant temperature, and in real condition of drying (sun drying or indirect solar dryer) with an accuracy of 97%. It can be applied to assess one parameter (moisture of beans, time of drying and drying temperature) by knowing two others and it can be used in automatic cocoa dryers. Beans drying temperature increase induces shorting of drying phases. Future studies shall explore artificial neural network to improve model design in forced air convection.

NOMENCLATURE

F_m	Masse flow (kg/m^2s)
F_{mis}	Isentalp masse flow (kg/m^2s)
m	Masse of sample (kg)
S	exchange surface (m^2)
T	Temperature ($°C; K$)
V	Volume of product (m^3)
W	Moisture content ($kgwater/kgdryproduct$)
t	Time (h ; s)
Symbols	
α	Compactness (m^{-1})
β	Expansion or volumetric shrinkage
ρ	Density (kg/m^3)
Subscripts	
cri	Critical value
ds	Dry solid basis
eq	Equilibrium value
exp	Experimental value
i	Data at any moment
mod	Model value
s	Dry product
∞	Drying air

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