MODELLING OF ROUGH RICE SOLAR DRYING UNDER NATURAL CONVECTION

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Abstract

In this study, the sun drying behaviour of aromatic rough rice was investigated. Drying experiments were conducted at three different seasons in Ivory Coast. The drying data were fitted to ten different mathematical models. Among the models, the Two-term model was found to best explain thin layer open sun drying behaviour of the rice. The performance of these models was investigated by comparing the determination of coefficient (R^2), sum square error (SSE) and root mean square error (RMSE) between the observed and predicted moisture ratios. The effective diffusivity coefficient of moisture transfer during drying, computed on the basis of Fick's law, was within the range of $8.345.10^{-12}$ and $4.517.10^{-11} m^2.s^{-1}$. In addition, the activation energy was estimated to 68.255 $Kj.mol^{-1}$.

Keywords: Thin layer modelling, Open sun drying, Effective diffusivity, Activation energy

Nomenclature

T: air drying temperature (°C)
HR air drying relative humidity (%)
MR dimensionless moisture ratio
M instantaneous moisture content
Vadrying velocity ($m.s^{-1}$)
ms dry matter

t time (min)
pf mass of grains (g)
SSD sum of squared error
RMSE root mean square error
R^2 coefficient of determination
Ta absolute temperature (K)
D_{eff} coefficient of effective diffusivity ($m^2.s^{-1}$)
Ea activation energy of Arrhenius equation ($kj.mol^{-1}$)
R universal gas constant ($kj.mol^{-1}.K$)
L half thickness of grain (m)
a, b drying constant
k, g drying coefficient

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Introduction

Rough rice water content (estimated to 20% when harvested) influences rice quality during stotage. Therefore, it is important to reduce this value to 12-14% using an appropriate drying process.

Drying is one of the processing technologies used in agriculture prior to storage and the ultimate utilisation of agricultural products (Bassey, 1989). Its principle is based on water driving to product surface and from this surface by preliminary heated air (Rozis, 1995).

The development of rice drying techniques was the subject of many studies during these last decades. These studies led to the development of industrial and semi-industrial dryers, unfortunately limited by their costs.

In addition to these industrial or artificial methods, other drying methods, known as traditional or natural ones, use sun as energy source. Then in order to take advantage of this free and renewable energy source, the introduction of solar dryers to natural convection were proposed by many authors (Wieneke, 1977;Exell and Kornsakoo, 1978 ; Exell and Kornsakoo, 1980 ; Boonthunjinda, 1980 ; Phongsupasamit, 1981). Although, these dryers can be built at lower cost with local material, their insertion in rural world is always difficult because farmers still prefer the direct sun drying.

Solar drying must be studied and modelled in order to know the particular requirements of each agricultural product and predict the performance of solar drying systems (Steinfeld and Segal, 1986).

Many thin-layer drying equations for rough rice have been developed, as presented in table 1. These models were studied either in forced convection with air at constant temperature and humidity (Agrawal and Singh, 1977, 1984 ; Wang and Singh, 1978 ; Verma*et al.*, 1985 ;

Noomhorm and Verma, 1986; Basunia and Abe, 1998) or under natural convection with air at variable temperature and humidity (Zaman and Bala, 1989 ; Basuniaand Abe, 2001).

Table 1: Mathematical models given by various authors for the drying curves

Noms	Models	References
Newton	$MR = \exp(-kt)$	O'Callaghan and*al*. (1971)
Page	$MR = \exp(-kt^n)$	Agrawal and Singh(1977)
Henderson et pabis	$MR = a\exp(-kt)$	Chhinnan, (1984)
Logarithmic	$MR = a_0 + a\exp(-kt)$	Chandra and Singh (1995)
Logistic	$MR = \frac{a_0}{1 + a\exp(kt)}$	Chandra and Singh (1995)
Two-term	$MR = a\exp(-k_0t) + b\exp(-gt)$	Henderson (1974)
Geometric	$MR = at^{-n}$	Chandra and Singh (1995)
Thomson	$t = a\ln(MR) + b(\ln(MR))^2$	Paulsen and Thomson (1973)
Wang et singh	$MR = 1 + a_1t + a_2t^2$	Wang and Singh(1978)
Diffusion approach	$MR = a\exp(-kt) + (1 - a)\exp(-kbt)$	Kassem (1998)

All equations were used in many studiesconcerningthin-layer drying modelling. But very few of these studies concern drying of rough rice under natural convection with air at variable temperatures and humidity (Jeon and*al*., 1989).

The purpose of this study is to evaluate a certain number of empirical or semi-empirical models in order to find the best one that could accurately fit rice kinetics drying under natural convection. This enabled us to determine the effective water diffusivity and the activation energy.

I- Material And Methods

1- Mathematical formulation

1-1- Selection criteria of the suitable model

Ten different moisture ratio (MR) equations given in table 1 were taken into account for the purpose of specifying the most suitable model for rice drying under natural convection.

The moisture ratio is defined as follows:

$$MR_{exp} = \frac{M - M_e}{M_o - M_e} \quad (1)$$

with M, M_o, M_e are the instantaneous, initial, and equilibrium moisture content respectively.

The determination coefficient (R^2) was one of the primary criteria for selecting the best equation. In addition to determination coefficient (R^2) (Thompson *etal*., 1979), sum square error (SSE), root mean square error (RMSE) (Hagan *etal*., 1996 ; Principe *etal*., 2000)were used to determine suitability of the fit. These parameters are defined as follows:

$$SSE = \sum_{i=1}^{p}\sum_{j=1}^{n_i} x_{ij}^2 - \frac{\left(\sum_{i=1}^{p}\sum_{j=1}^{n_i} x_{ij}\right)^2}{N} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_e - y_c\right)^2} \quad (3)$$

$$R^2 = \frac{\sum_{i=1}^{N}\left(y_c - \overline{y_e}\right)^2}{\sum_{i=1}^{N}\left(y_e - \overline{y_e}\right)^2} \quad (4)$$

Withyc and ye experimental and calculated values respectively for i = 1,...., N

1-2- Determination of effective diffusivity and activation energy

In the foodstuffs, water transport is generally considered due to liquid water diffusion under the effect of the concentration gradient. The moisture content evolution is expressed according to moisture gradient and total diffusivity that takes account the various transport phenomena, in a law similar to the second law of Fick(Fick, 1855).

$$\frac{\partial MR}{\partial t} = D_{eff}\nabla^2 MR \quad (5)$$

WithD_{eff} , effective diffusivity ($m^2. s^{-1}$) which generally varies with the product temperature and moisture content(Benhamou*et al.*, 2008). The analytical solution of the Fick second law, developed by Crank, 1975 assuming an initial moisture uniform distribution, a simplification of moisture movement by diffusion, a negligible shrinkage, constant diffusion coefficients and temperature, can be expressed as:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (6)$$

When time is sufficiently long, all the terms of the series are negligible and one obtains:

$$MR = \frac{8}{\pi^2}\exp\left[-\frac{\pi^2 D_{eff} t}{4L^2}\right] \quad (7)$$

with L (m) the half thickness of the grain.

In addition, the origin of the auto diffusion is thermal agitation. The diffusion is thus thermically activated and the diffusion coefficient follows an Arrhenius law:

$$D_{eff} = D_0 \exp\left(-\frac{Ea}{RT}\right) \quad (8)$$

with D_0 the pre-exponential factor of the Arrhenius equation ($m^2.s^{-1}$), E_a the activation energy ($kJ.mol^{-1}$), which is the equivalent of a potential barrier which is opposed to reaction evolution, R the universal gas constant ($kJ.mol^{-1}.K^{-1}$) and T the absolute temperature (K) (Doymaz, 2004 ; Doymaz and Pala, 2003).

2- Experimental procedure

Raw paddy, WAB 638-1 variety, freshly harvested, was obtained (approximately 19% moisture content dry-basis) from an agricultural farm of Yamoussoukro city (Ivory Coast, West Africa). The rough rice samples drying using black plastic was operated during three seasons (*i.e.* small dry season S1, harmattan season S2 and great dry season S3) with variable air temperatures and relative humidity.

The paddy initial moisture content was determined using standard oven method (AOAC, 1985). For this purpose about 5 g sample, in triplicate, were drawn in aluminium moisture boxes and kept in an air oven which was maintained at 130°C ± 3°C during 2 hours (Association internationaled'essais de semence, 1999).

Paddy samples (100 g) are exposed to open air and the evolution drying process was followed by weighting at regular intervals of 10 minutes with digital balance (±0.01). Concomitantly, dry and wet bulb temperatures, relative humidity, insulation and pluviometrywere determined. Approximately 12% moisture content (dry-basis) represents the end of drying and is defined as follows:

$$M = \frac{pf - ms}{pf} \times 100 \quad (9)$$

M = moisture content calculated at instant t

pf= sample weight

ms= dry matter

II- Results And Discussion

1- Weather characteristics

During experiments, the different data of insulation, pluviometry, air temperature and relative humidity were recorded and presented in figures 1 to 3.

1.1- Season 1

The first experiments period was from August to October. It corresponded to the small dry season with a wet wind called monsoon.It is characterized by high variation ofpluviometry and insulation due to rain and sun alternation (Figure 1a). It is also observed low temperatures and high relative moistures ranging respectively between 28 and 32°C and 65 and 80% (Figure 1b). The mean temperature for this season is 30.70°C and 69.26% for its relative humidity.

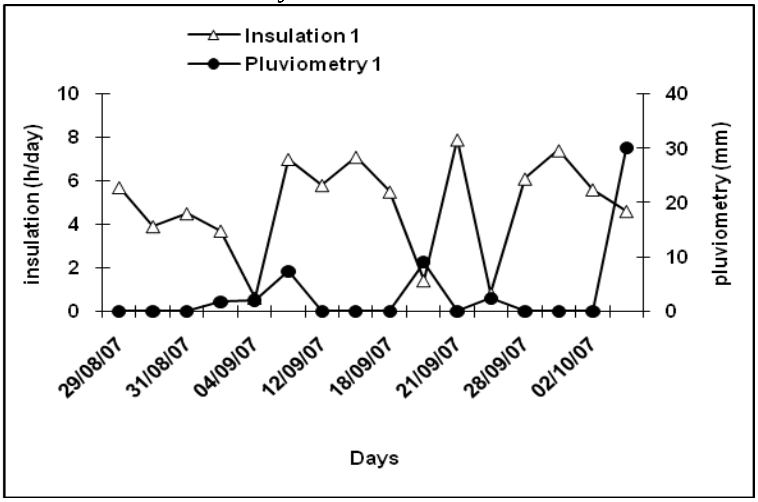

Fig 1a: Variation of insulation and pluviometry

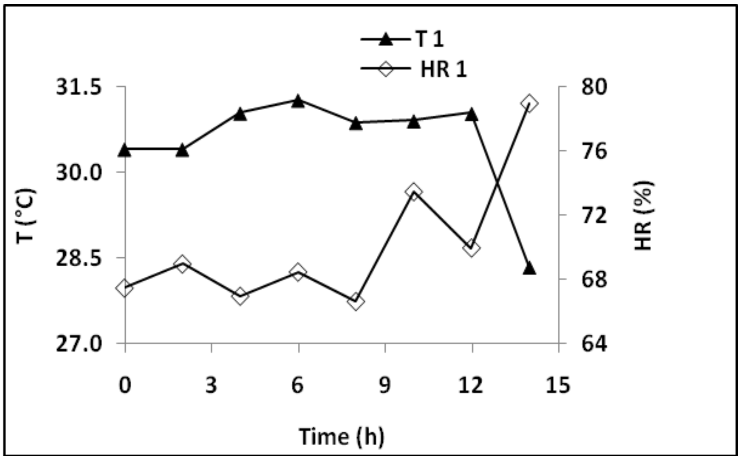

Fig 1b: Variation of air temperature and relative humidity

1.2- Season 2

The second experiment set was from December to January. It corresponds to the great dry season with the presence of a dry wind called harmattan. During this season, whereas insulation and temperature range from 6 to 10h and 30 to 33°C respectively, the relative humidity varies from 30 to 60% (Figure 2 (a, b)). It is also noticeable the absence of rainfall. The mean temperature for this season is 31.52°C and its relative humidity is 45.86%.

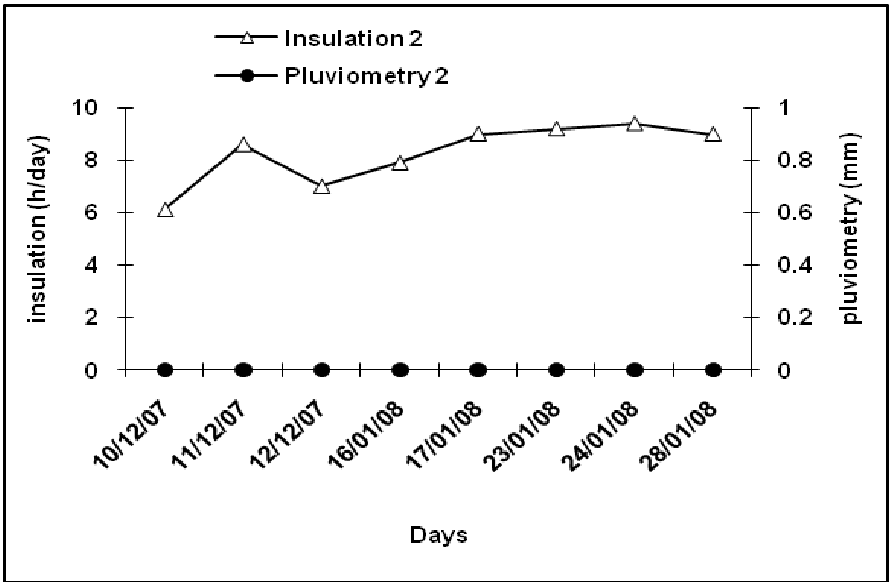

Fig 2a: Variation of insulation and pluviometry

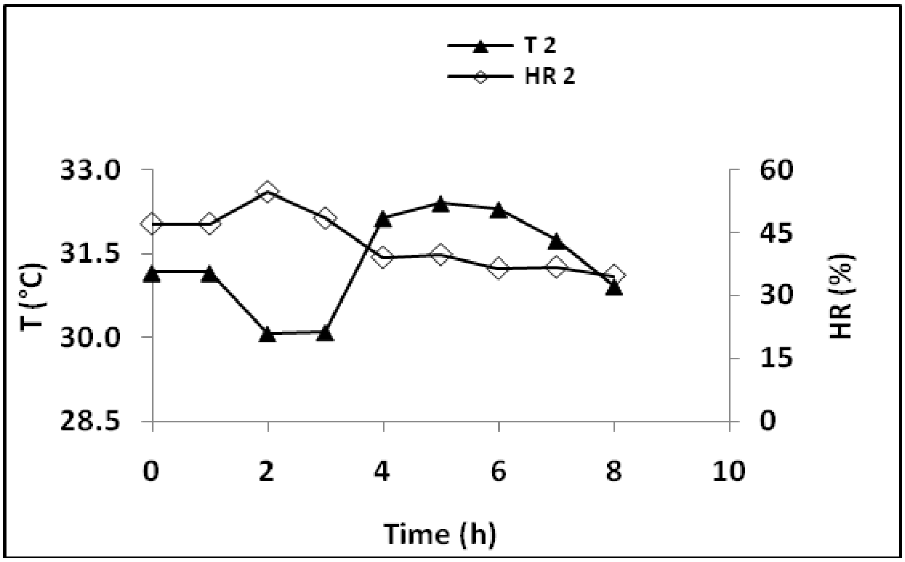

Fig 2b: Variation of air temperature and relative humidity

1.3- Season 3

The third experiments period ranges from the end of February to mid-March. This period is characterized by the end of the great dry season and harmattan. Some rains appear, with air humidity increase as drawback (Figure 3a). As expected, the temperatures and relative humidity increased ranging respectively from 30 to 35°C and from50 to 80% (Figure 3b). The mean temperature for this season is 32.42°C and 60.66% for the relative humidity.

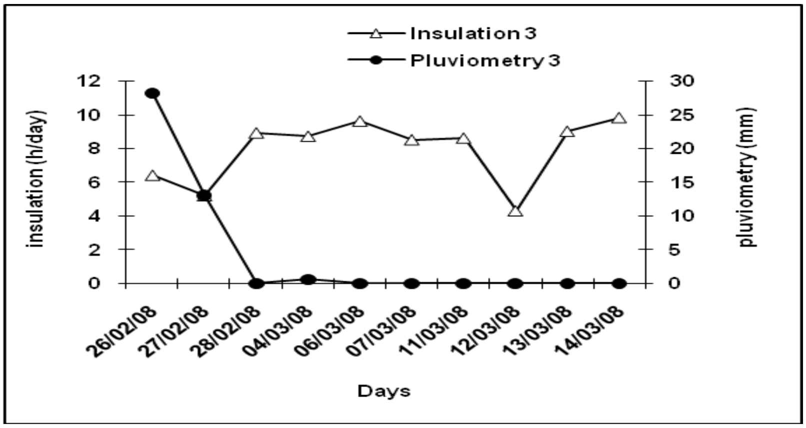

Fig 3a: Variation of insulation and pluviometry

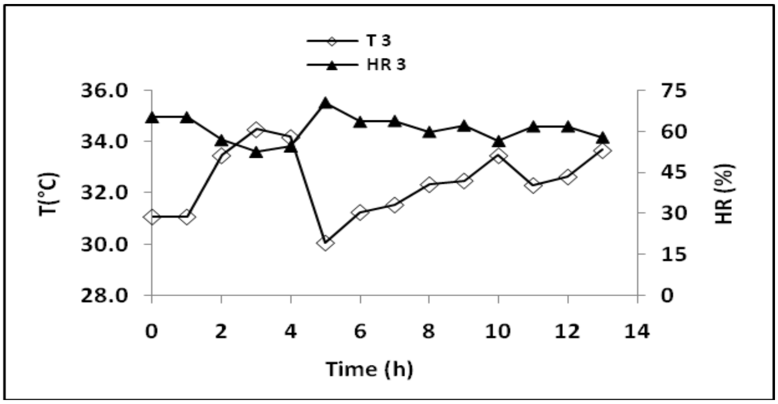

Fig 3b: Variation of air temperature and relative humidity

Analyzing the figures (1 to 3), it appears that weather characteristics of the three study periods differ from one period to the other. This result is due to the fact that Yamoussoukro city, where experiments were run, is situated in Baoulean type weather. Indeed, as Kassi and Toure (2002) have pointed out in their book, this weather zone is divided in four seasons grouped in dry and wet ones.

2- Rough rice drying curve modeling

Rice samples mean initial moisture, air temperature and relative humidity are given for each season in table 2. The different equilibrium moistures according different seasons characteristics were also determined from desorption isotherm curve and presented also in table 2.

Table 2: samples initial and equilibrium moisture content for each season

saisons	T (°C)	HR (%)	M_0(%)	M_e (%)
S1	30.7	69.26	18.53	9.78
S2	31.52	45.86	17.99	7.03
S3	32.42	60.66	19.19	8.58

The analyse of this table shows that, as expected, equilibrium moisture rate is related to relative humidity characterizing each season. Therefore, the lower equilibrium moisture is obtained during season <2. Indeed, when relative humidity is lower, higher is the air drying power (Rozis, 1995)

The experimental data were fitted to the models presented in table 1. Only five models seem to give exploitable results that are plotted in tables 3, 4 and 5.

Table 3: Modelling parameters for season 1

Model	Value	SSE	RMSE	R^2
Wang and Singh	$a = -0.0041$	0.0233	0.0289	0.9791
	$b = 6.17.10^{-6}$			
Henderson and Pabis	$a = 0.9552$	0.0115	0.0203	0.9897
	$k = 0.0038$			
Logarithmic	$a = 0.8453$	0.0098	0.0190	0.9913
	$c = 0.1262$			
	$k = 0.0049$			
Two-terms	$a = 0.9005$	0.0054	0.0144	0.9951
	$b = 0.1058$			
	$g = 0.9366$			
	$k = 0.0035$			
Page	$k = -0.0090$	0.0067	0.0155	0.9940
	$n = 0.8480$			

Table 4: Modelling parameters for season 2

Model	Value	SSE	RMSE	R^2
Wang and Singh	$a = -0.0036$	0.0026	0.0109	0.9972
	$b = 3.58.10^{-6}$			
Henderson and Pabis	$a = 1.0085$	0.0066	0.0174	0.9929
	$k = 0.0043$			
Logarithmic	$a = 1.8080$	0.0012	0.0076	0.9987
	$c = -0.8265$			
	$k = 0.0019$			
Two-terms	$a = 3.9156$	0.0041	0.0143	0.9956
	$b = -2.9129$			
	$g = 0.0067$			
	$k = 0.0060$			
Page	$k = -0.0028$	0.0045	0.0109	0.9951
	$n = 1.0854$			

Table 5: Modelling parameters for season 3

Model	Value	SSE	RMSE	R^2
Wang and Singh	$a = -0.0056$ $b = 9.94.10^{-6}$	0.0111	0.2251	0.9925
Henderson and Pabis	$a = 1.0446$ $k = 0.0067$	0.0140	0.0253	0.9906
Logarithmic	$a = 1.0585$ $c = -0.0165$ $k = 0.0065$	0.0140	0.0258	0.9906
Two-term	$a = 1.1014$ $b = -0.1060$ $g = 0.0587$ $k = 0.0071$	0.0093	0.0215	0.9938
Page	$k = -0.0033$ $n = 1.1343$	0.0121	0.0235	0.9919

The suitability check of each model was based on R^2, Sum of Square Error (SSE) and Root Mean Square Error (RMSE) values. A model is suitable when the R^2 value is closer to 1, and the SSE and RMSE values are closer to 0. It appears, from the three tables, that the most appropriate model in bulk drying of rough rice is the two-term model with R^2 =0.9956, RMSE = 0.0143 and SSE = 0.0041. In addition to this model, logarithmic, Page, Henderson and Pabis, and Wang and Singh models are other adequate models in describing the experimental data.

In order to determine the overall mathematical model, as the different coefficients of the two-terms models vary according to the different weather characteristics, linear regression of the model coefficients (*i.e.* a, k, b and g) were expressed according to air temperature and relative humidity of each season (Table 6).

Table 6: model coefficient for each season

Seasons	Model coefficients	R^2
1	$a = -64.8869 + 0.6382\,T + 0.6714\,HR$	0.9337
	$b = 66.4963 - 0.496\,T - 0.6752\,HR$	0.9340
	$g = 4.36502 - 0.04450\,T - 0.04282\,HR$	0.9523
	$K = -0.0781 + 0.0046\,T - 0.0008\,HR$	0.9957
2	$a = 334.2749 - 11.9842\,T + 1.0388\,HR$	0.8299
	$b = -332.726 + 119648\,T - 1.0374\,HR$	0.8299
	$g = -0.0482 + 0.0054\,T - 0.0021\,HR$	0.9999
	$k = 0.0143 - 0.0006\,T + 0.0002\,HR$	0.9833
3	$a = 1702.2081 + 41.1861\,T + 6.0861\,HR$	1.0000
	$b = 1702.0262 - 41.1571\,T - 6.0821\,HR$	1.0000
	$g = 12.264 - 0.297800\,T - 0.0425\,HR$	1.0000
	$k = -51.6627 + 1.2491\,T + 0.184\,HR$	1.0000

The data were calculated using the above two-terms models and plotted against experimental one (Figures 4, 5, 6). It appears that in all cases, the predicted data is banded around the straight line. The different R^2 values range from 0.9938 to 0.9957; values that are close to 1 indicating therefore that the proposed model is suitable to predict the drying behaviour of rough rice in natural convection.

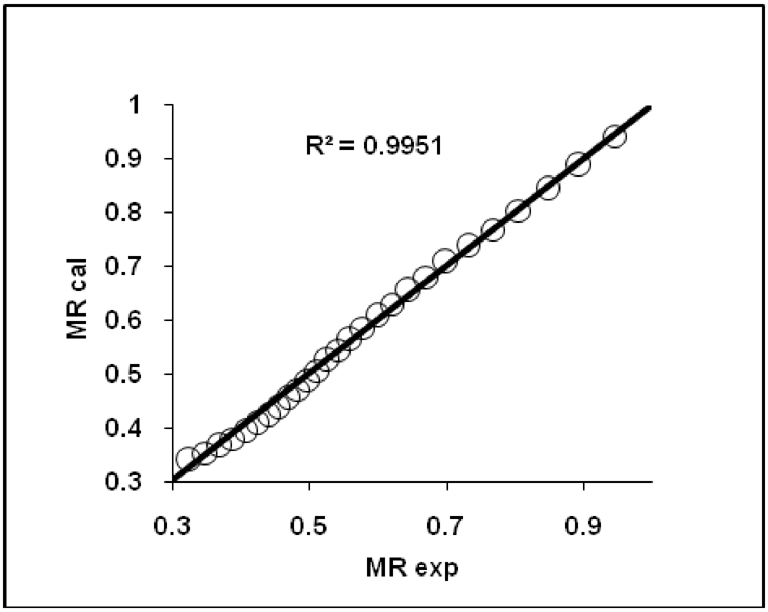

Fig4: Experimental and predicted moisture ratio values for rough rice at season 1

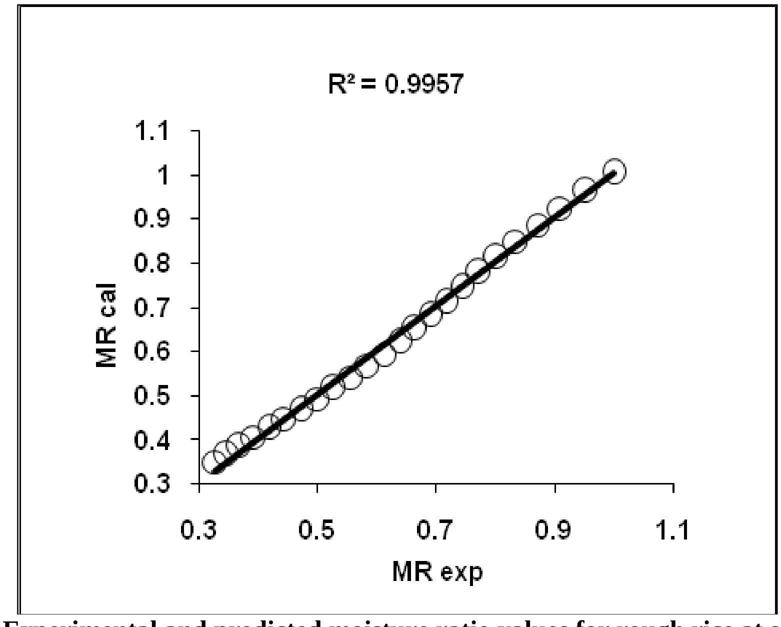

Fig 5: Experimental and predicted moisture ratio values for rough rice at season 2

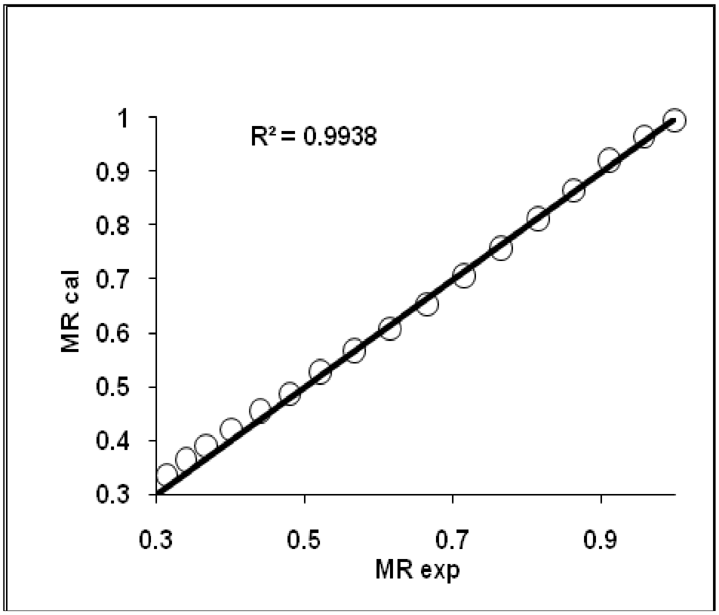

Fig 6: Experimental and predicted moisture ratio values for rough rice at season

3- Diffusion coefficient and activation energy

According Benhamou*et al*. (2008) the effective diffusivity (Deff) gathers the various transport phenomena and is typically calculated using graphic method by representing the experimental data of drying in term of the natural logarithm of moisture content MR according to the drying time. The result is in principle a line whose slope $\left(-\frac{\pi^2 D_{eff}}{4L^2}\right)$ can enable the determination of effective diffusion coefficient for various operation conditions as summarised in Table 7.

Table 7: Effective diffusion coefficient for various weather conditions

Experiments	Va ($m.s^{-1}$)	HR (%)	T (°C)	$D_{eff}x10^{-11}$ ($m^2.s^{-1}$)	R^2
1	0.80	69.23	30.46	1.791	0.8747
2	0.80	68.40	31.44	4.351	0.9975
3	0.80	68.00	31.60	4.517	0.9905
4	1.15	55.67	32.12	2.073	0.9951
5	1.15	47.00	31.87	2.099	0.9633
6	1.15	25.11	29.99	0.834	0.9899
7	1.21	53.09	31.76	2.872	0.9910
8	1.21	63.29	32.01	2.995	0.9927
9	1.21	65.62	33.52	3.376	0.9955

The paddy grain diffusion coefficient obtained varies from $8.340x10^{-12}$to $4.517x10^{-11}m^2.s^{-1}$. These values are comparable with some others reported in literature. Indeed, diffusion coefficient in parboiled paddy was found ranging from 0.608 to $3.44 \times 10^{-10} m^2.s^{-1}$ (temperature between 70 and 150°C) (Rao*et al.*, 2007), and that in wheat was in order to $10^{-11} m^2.s^{-1}$ between 35 and 70 °C (Gaston *et al.*, 2002).

The diffusion coefficient can be related to temperature by the Arrhenius expression (Lopez *et al.*, 2000)as follows:

$$Ln(D_{eff}) = Ln(D_0) - \frac{Ea}{R}\frac{1}{Ta} \quad (10)$$

WithD_0constant in Arrhenius equation ($m^2.s^{-1}$), E_a activation energy ($Kj.mol^{-1}$), T_a absolute temperature (K) and R the universal gas constant ($Kj.mol^{-1}.K$).

From the equation (10), activation energy can be calculated by representing the natural logarithm of experimental effective diffusivity D_{eff} values according to the reverse temperature(Aghfir*etal.*, 2008) as presented in figure 10.

$$D_{eff} = 14.137064 \exp\left(-\frac{8206.05692}{T_a}\right) \quad (11)$$

From this slope, energy activation is obtained as E_a = 68.255 $Kj.mol^{-1}$ (R^2= 0.9858).

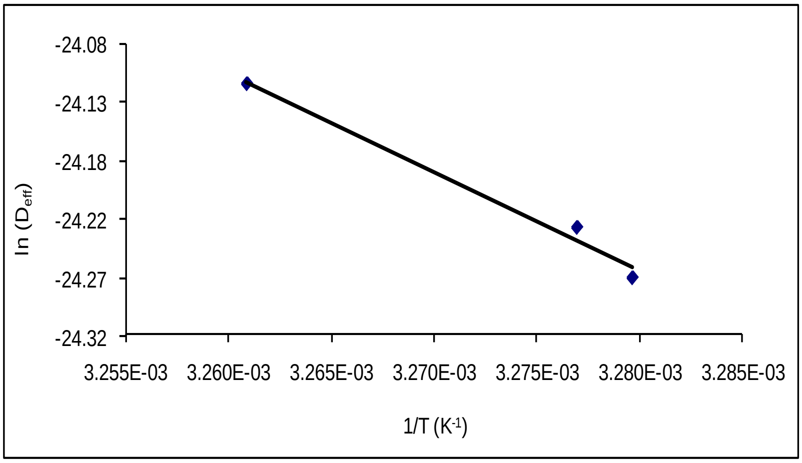

Fig 7: Effect of air temperature on the effective diffusivity of water in rough rice

Conclusion

Ten models have been analyzed for their suitability for bulk drying rough rice under open sun with natural convection mode. The results showed that the Two-term model was found to be the most suitable for describing drying curve of rough rice, in all study season, with R² SSE RMSE ranging respectively from 0.9931 to 0.9957, from 0.0041 to 0.0093 and from 0.0143 to 0.0215,.

The Two-term parameters (*i.e.* a, b, g and k) were expressed as a linear function of air temperature and relative humidity to find out an overall model, each season.

In this study, it was noticed that value of diffusion coefficients for the examined samples changed between $8.34.10^{-12}$ and $4.52.10^{-11} m^2.s^{-1}$, and the activation energy was estimated to 68.255 $Kj.mol^{-1}$.

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