Revue des Energies Renouvelables Vol. 13 N°2 (2010) 295 – 309
DOI: https://doi.org/10.54966/jreen.v13i2.198

Determination of the drying speed in thin layer of shrimp

Lahinirina Fridolin Gervais Andriazafimahazo[1,*], Ignace Abel José Razafiarison[1],
Belkacem Zeghmati[2], Bertin Olivier Andriantiana Ramamonjisoa[1],
Fanomezantsoa Marie Roland Rabary[1] and Andrianelison Rakotomahevitra[3]

[1] Laboratoire de Physique Appliquée de l'Université de Fianarantsoa,
B.P 1264, 301 Fianarantsoa, Madagascar
[2] Laboratoire de Mathématiques et Physique des Systèmes – Groupe de Mécanique Energétique,
Université de Perpignan Via Domita, 52 Avenue Paul Alduy, 66860 Perpignan, France
[3] Department des Sciences Exactes de l'Université de Mahajanga,
B.P. 652 Ambondrona, 401 Mahajanga, Madagascar

(reçu le 20 Mars 2010 – accepté le 25 Juin 2010)

Abstract - *This survey consists in determining the drying speed in thin layer of non shelled shrimp with the help of a climatic chamber. The experiences made permitted to elaborate a universal model. The considered parameters are the drying air temperature, the product absolute humidity as well as the drying air relative humidity and its speed. The adsorption curve of the product is also established. The model is validated through confrontation between experimental and theoretical results.*

Résumé - *Cette étude consiste à la détermination de la vitesse de séchage en couche mince de crevettes non décortiquées à l'aide d'une enceinte climatique. Les expérimentations effectuées ont permis d'élaborer un modèle universel. Les paramètres considérés sont la température de séchage, l'humidité absolue du produit, l'humidité relative de l'air asséchant et la vitesse de l'air asséchant. Nous avons pu établir également la courbe de l'isotherme de désorption du produit. Nous avons pu valider ce modèle par confrontation entre les résultats expérimentaux et théoriques.*

Keywords: Universal mode - Drying speed - Shrimp - Hygroscopic product -Numerical simulation.

1. INTRODUCTION

Drying operation, transformation common to many industrial sectors, is energizingly expensive. Besides, most thermal drying processes have a low energizing efficiency. The improvement of drying efficiency requires the control of heat and mass transfers that governs the behaviour of the product during drying.

Modelling and simulating the functioning of an industrial drier is necessary to know the drying speed in thin layer of the considered product [1]. In general, this last is determined experimentally and is subject to many works. Let's mention the one elaborated by Troeger *et al.* for the corn drying in thin layer [2] and the other by Kachru *et al.* for the paddy drying in thick layer [3, 4].

For the drying of fruit cut in small discs or in slices, the El-Salman model [5] is more appropriated. Several works adopt the Combes model of transfer [6]. But these models have some limits since they are based on polynomial expressions, mainly function of the equilibrium content in water of the product and the relative humidity of drying air.

[*] fridolinlahinirina@yahoo.fr (L.F.G. Andriazafimahazo)

To palliate these inconveniences, this survey concentrates on the experimental determination of the drying speed in forced convection of a thin layer of shrimp and the adsorption isotherm of this product while adopting the universal model which was used with success for the drying of small discs of pineapple [7].

After the experimental device description is analyzed the influence of the drying air relative humidity, that of the product temperature and drying air speed influence on the product behaviour during drying.

2. EXPERIMENTAL DEVICE

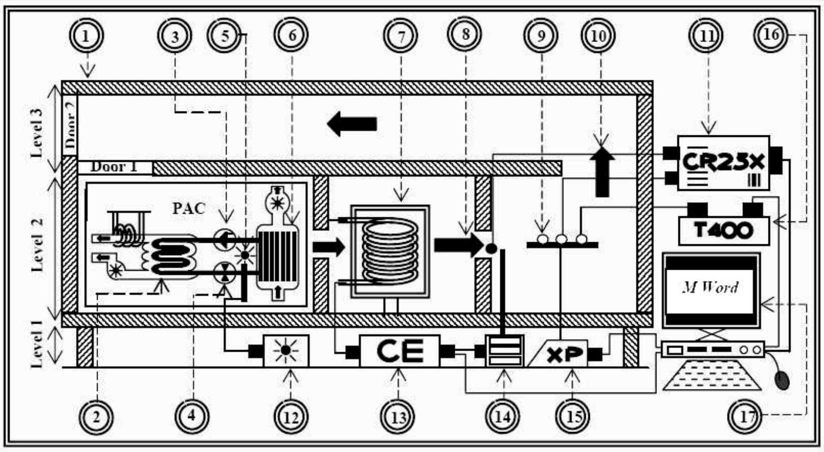
The device used is a climatic chamber (Fig. 1) provided with auxiliary contribution systems in energy and in humidity. It is aimed to experimental determination of the drying speed in forced convection for various products.

In this case, shrimps are arranged in thin layers on racks and submitted to an air flow preheated by a heating pump. The experimental device is constituted by a CR23X measure central, a computer for the management of the CR23X central, K type thermocouples, a thermo hygrometer (Probe Testo 400), an electronic scale (Denver Instrument IR30), a humidifier, a heating pump and a balance resistor. This device is divided in three levels.

The first level includes the anemometer, the electronic central, the humidifier and the balance resistor.

The second is divided in three cells. The first cell is occupied by the heating pump. The second cell contains the balance resistor and the humidifier hose.

The third cell includes the system of hurdle to expose product samples to dry. The third is the higher level of the device. It is used only for the circulation of the drying air.



Legend: PAC: Heating pump - 1: Climatic chamber - 2: PAC condenser - 3: PAC compressor - 4: PAC regulator - 5: Ventilator - 6: PAC Evaporator - 7: Electric resistor - 8: Drying air - 9: Hurdle and product - 10: Drying air sense - 11: Central of measure CR23X - 12: Anemometer - 13: Electronic power station - 14: Humidifier - 15: Electronic scale - 16: Probes TESTO 400 - 17: Post computer.

Fig. 1: The experimental device

3. MATHEMATICAL MODEL

The adopted model is based on the research of linear transfer functions for every output parameter. This model exploits the similarity between drying kinetic and chemical kinetic. Knowing that the product is hygroscopic and, by hypothesis, the water transfer within the product is of capillary origin [8], the product drying speed can be formulated by the following relation:

$$\frac{dN_s}{dt} = -m \times (N_s - N_{se}) \quad (1)$$

Relation (1) is constituted by a non linear equation (first order differential equation) that can be solved using the mathematical method of separated variable. The solution is formulated in relation (2). It is the instantaneous absolute humidity of the product.

$$N_s = N_{se} + (N_s - N_{se}) \times \exp(-m.t) \quad (2)$$

The constant of drying is designated by m. This time, it is function of the product temperature T_p (T_p is assimilated to the drying temperature), of the drying air relative humidity hr and of the drying air speed. Thus, the speed of drying can be expressed by the following way:

$$\frac{dN_s}{dt} = -m \times F.(N_s) \quad (3)$$

$$F.(N_s) = N_s - N_{se} \quad (4)$$

$$m = \alpha.E(T_p).H(h_r).G.(V_a) \quad (5)$$

$E(T_p)$ represent the influence of the product temperature on the constant of drying in maintaining constant the other parameters (relative humidity and speed of drying air). It results from the Arrhenius law [9] and is expressed by the following way:

$$E(T_p) = \exp\left(-\frac{a}{T_p} - b \right) \quad (6)$$

Thus, relations (7, 8) represent the influences of respectively the relative humidity and the drying air speed on the constant of drying. Indeed, the constant of drying m can be expressed by the relation (9).

$$H(h_r) = \exp(c \times h_r + d) \quad (7)$$

$$G(V_a) = \exp(e \times V_a + f) \quad (8)$$

$$m = \exp\left(-\frac{a}{T_p} + c \times h_r + e \times V_a + Q \right) \quad (9)$$

$$Q = d + f + \ln\alpha \quad (10)$$

The coefficients a, b, c, d, e and f f are gotten while using the linear regression method [10]. Henderson model [11] is adopted to determine the adsorption isotherm curve of shrimp {relation (11)}. The equilibrium absolute humidity N_{se} is gotten from this model:

$$h_{re} = 100 \times \left[1 - \exp\left(-\frac{9\,K \times T_p \times N_{se}^{n}}{5} \right) \right] \tag{11}$$

Besides, the product absolute humidity is defined like being the quotient of the mass of water and the mass of the dry matter contained in the product. Relation (12) is used for the calculation of the initial absolute humidity of the product.

$$N_{si} = \frac{M_i - M_s}{M_s} \tag{12}$$

4. RESULTS AND DISCUSSIONS

4.1 Experimental results

We chose samples of whole and cool no shelled shrimp. Before experimenting, the product is soaked in boiling water to 100 °C during two minutes then cooled to free air during five minutes. The shrimps are arranged in a single homogeneous layer on racks and are exposed in forced convection to an air flow previously conditioned by the heating pump.

The sense of the outflow drying air is parallel to the products to dry. The drying is supposed finished when the temperature of the surface of shrimps is nearly equal to the drying air temperature.

4.1.1 Determination of the initial absolute humidity of the product

The initial absolute humidity N_{si} of the product is calculated from the determination of the dry matter mass contained in the product. The mass of dry matter is the mass of the product after a drying process during one day under a drying air temperature of 80 °C.

Knowing the sample initial mass and the dry matter mass, the relation (12) is applied to determine the product initial absolute humidity. The result is shown in **Table 1**.

Table 1: Initial absolute humidity of the product

Symbols	Numeric values	Units
M_i	$10.000\ 10^{-3}$	kg
M_s	$03.047\ 10^{-3}$	kg
M_e	$06.953\ 10^{-3}$	kg
$N_{s.m}$	2.300	kg water. kg^{-1} DM
ΔM_s	10^{-6}	kg
ΔM_e	10^{-6}	kg
ΔN_s	10^{-3}	kg water. kg^{-1} DM
N_s	2.300 ± 0.001	kg water. kg^{-1} DM

4.1.2. Operative conditions of drying

The operative drying conditions are conforms to the different essays that will be made. In principle, these conditions represent the different concerned parameters, their variations and their values. The operative drying conditions kept in this survey are given in **Table 2**.

Table 2: Operative conditions of drying

Essays	T_{ae} **(°C)**	T_p **(°C)**	H_{re} / h_r	V_a **(m.$^{-1}$)**	M_i **(g)**
C1	61.06	59.35	40.00/39.50	03.000	26.500
C2	55.40	53.83	40.00/39.00	03.000	26.500
C3	42.51	41.62	40.00/39.00	03.000	26.500
C4	60.85	59.55	50.00/47.00	03.000	26.500
C5	61.09	59.07	60.00/52.00	03.000	26.500
C6	61.09	59.07	40.00/39.00	02.750	26.500
C7	61.09	59.07	40.00/39.00	02.500	26.500
E.A	0.60	0.60	5.00	0.001	0.001

4.1.3 Experimental results

Essays C1, C2 and C3 are achieved at different drying air temperatures, the other parameters are maintained constant. These three tests permit to study the influence of the drying air temperature on the product drying, therefore to verify Arrhenius law [9] for the drying kinetic [12, 13].

Figure 2 presents the temporal variations of the product absolute humidity and the influence of the product temperature. During the drying, with the conditions reported in the **Table 2**, the product absolute humidity decreases and tends toward an asymptotic value. Product drying is so fast that drying air temperature is high.

The evolution of the shrimp absolute humidity during the time is typical of that of a hygroscopic product. The shrimp drying speed (the evolution in relation to the time of the shrimp absolute humidity) is a decreasing function of the air temperature. It tends asymptotically toward a quasi-constant value close to the drying air temperature value.

Essays C1, C4 and C5 are about the analysis of the relative drying air humidity influence on the drying kinetic.

Figure 3 shows that product drying is so fast that drying air relative humidity is low. Indeed, the speed of drying, proportional to the difference between the steam concentration at the shrimp surface and that of the drying air, decreases with the increase of the air relative humidity. It follows a reduction of the drying speed when the air relative humidity increases.

Essays C7, C6 and C1, are about the analysis of the air speed drying influence on the drying kinetics.

Figure 4 shows that product drying is so fast that drying air speed is strong. Indeed, the drying speed, proportional to the difference between the steam concentration at the shrimp surface and that of air drying decreases with the reduction of the drying air speed.

It follows an increase of the drying speed when the air speed increases. In general, for all essays, drying time increases according to the increase of drying air relative humidity and, contrarily, it decreases when the temperature and speed of the drying air increase.

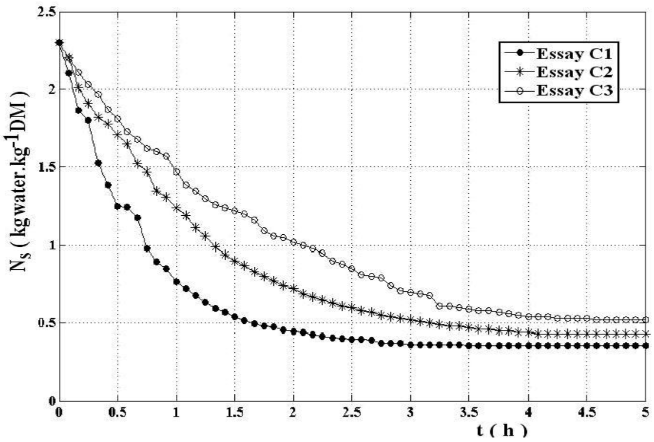


Fig. 2: Influence of the product temperature on the evolution of the product absolute humidity according to the drying time

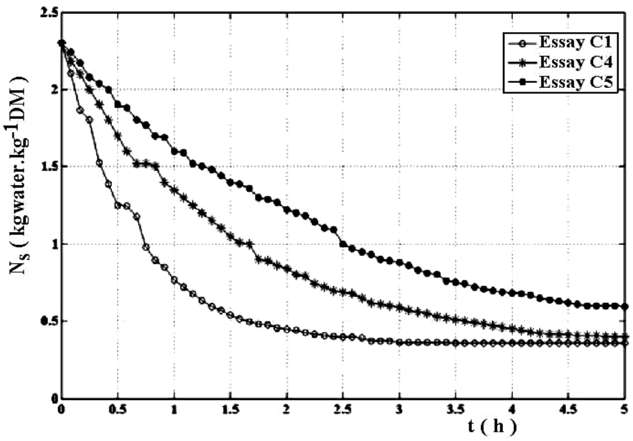


Fig. 3: Influence of the drying air relative humidity on the evolution of the product absolute humidity according to the drying time

4.2 Treatment of the experimental results

This part consists to use mathematical tools to determine the different constants (a , b , c , d , e , f) and (K , n) used respectively in the drying constant m expression and the equilibrium absolute humidity N_{se} of the product.

4.2.1 Determination of the coefficients a and b

Drying speed models analysis is based on the product temperature and content in water, the drying air relative humidity and temperature.

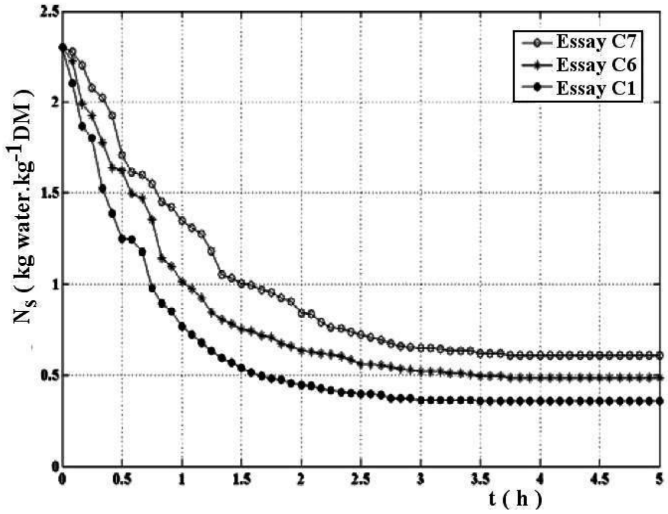


Fig. 4: Influence of the drying air speed on the evolution on the product absolute humidity according to the drying time

Essays C2 and C3 are considered to this effect. As the product parietal temperature T_p is very closer of the drying air temperature, they are soon considered as equal and the experience is finished.

Graphical representations of $-\ln(d\,N_s \times d\,t^{-1})$ according to the inverse of the absolute temperature T for different values of the product absolute humidity is appreciably parallel straight lines (Fig. 5).

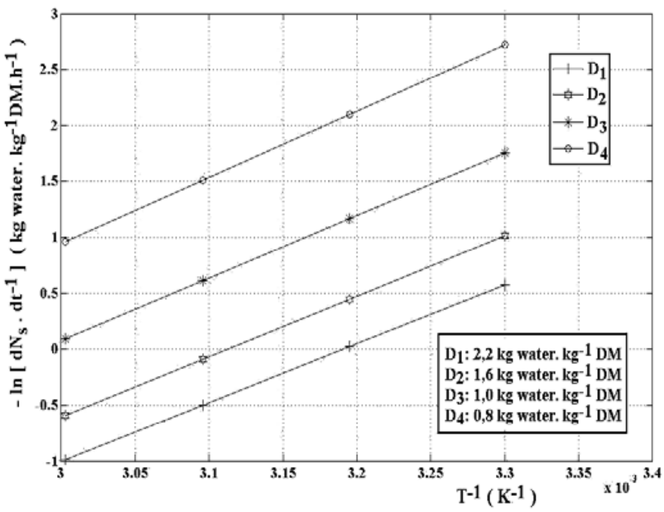


Fig. 5: Evolution of the drying constant according to the inverse of the product temperature for different values of the product absolute humidity

The product drying follows Arrhenius law. The coefficients a and b are determined by the linear regression method [9] according to **Table 3**.

The calculation of absolute measure uncertainty by the quadratic mistake method permits to write the numeric value of a that:

$a = (5.542 \pm 0.146).10^3$ K.

Table 3: Numeric values of the coefficients a and b

N_S (kg water . kg^{-1} DM)	a (K)	b
2.2000	5263.3600	-16.7947
1.6000	5392.0900	-16.7830
1.0000	5576.1200	-16.6511
0.8000	5936.0100	-17.2485
Mean	**5541.8900**	**-16.8694**

4.2.2 Determination of the coefficient α

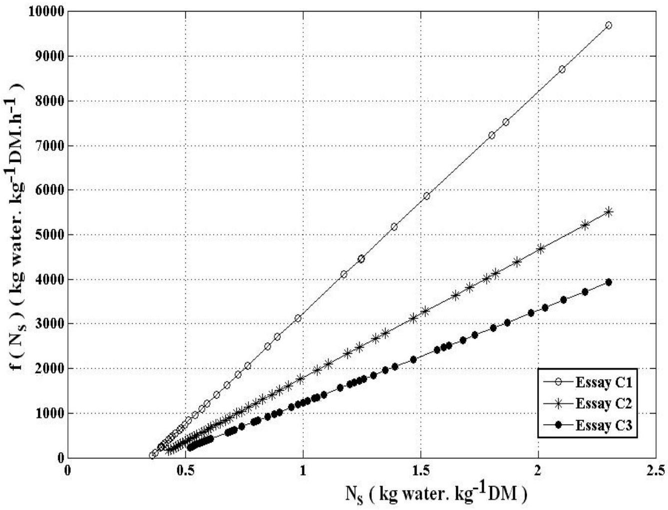


Fig. 6: Evolution of the drying speed according to the product absolute humidity

Figure 6 shows that the evolution of the drying speed according to the product absolute humidity, for the three drying temperatures retained in this survey, obeys a middle curve called drying characteristic curve.

These curves can be assimilated to straight lines. While using the mathematical method of the Lagrange polynomial interpolation [14], numerical value kept is:

$\alpha = (3.30 \pm 0.28) \times 10^3 h^{-1}$.

4.2.3 Determination of the coefficients c and d

Figure 7 represents the product drying constant evolution according to the drying air relative humidity for different values of the product content in water. It is observed that the influence of this last is not negligible.

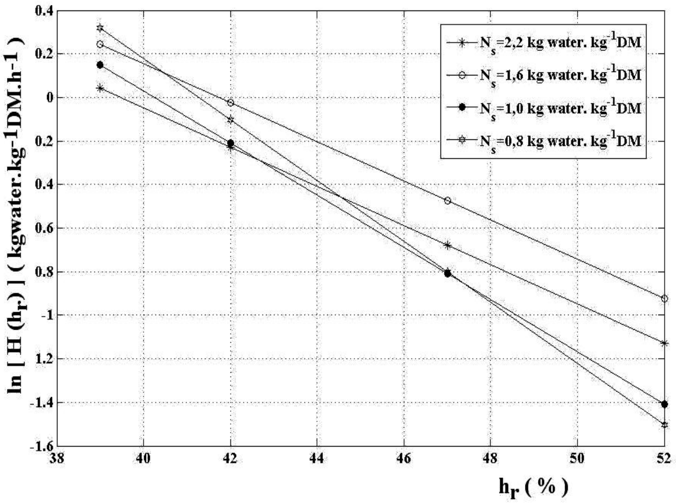


Fig. 7: Evolution of the drying constant according to the air drying humidity

Essays considered are C1, C4 and C5. The values of $\ln[H(h_r)]$ are calculated for different values of the product absolute humidity N_s (kg water . kg^{-1} Dry Matter). The reference value taken for the air relative humidity is h_{ref} = 40.72 %. The curves on Figure 6 can be assimilated to parallel straight lines. The calculations drive to the following numeric values of the parameters c and d, shown on **Table 4**.

Table 4: Numeric values of the coefficients c and d

N_s (kg water . kg^{-1} DM)	c (%$^{-1}$)	d
2.2000	-0.0900	3.5525
1.6000	-0.0900	3.7554
1.0000	-0.1200	4.8303
0.8000	-0.1400	5.7783
Mean	**-0.1100**	**4.4791**

The absolute uncertainty calculations allow to write:

$c = (-0.11 \pm 0.01)\ \%^{-1}$ and $d = (4.4791 \pm 0.5157)$.

4.2.4 Determination of the coefficients e and f

Figure 8 represents the evolution of the drying constant m according to the drying air speed for different values of product content in water. It is observed that the influence of the drying air speed on the drying constant is very important.

Considered essays are C1, C6 and C7. The values of $\ln[G(V_a)]$ are calculated for different values of the product absolute humidity N_s (kg water . kg^{-1} DM). So the curves on Figure 8 can be assimilated to parallel straight lines.

Numeric values calculated for the parameters e and f are shown on **Table 5**. Numerically, these parameters are:

$e = (1.76 \pm 0.17)\ (m.s^{-1})^{-1}$ and $f = (3.5361 \pm 0.3469)$.

Table 5: Numeric values of the coefficients e and f

N_S (kg water . kg^{-1} DM)	e $(m.s^{-1})^{-1}$	f
2.2000	1.28	4.3782
1.6000	2.03	2.6790
1.0000	1.83	3.5283
0.8000	1.91	3.5588
Mean	**1.76**	**3.5361**

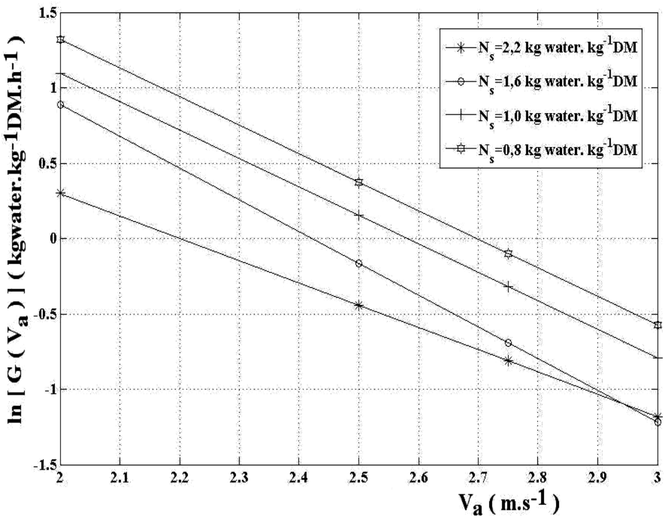


Fig. 8: Evolution of the drying constant according to the drying air speed

4.2.5 Determination of the constants of Henderson K and n

The model adopted is the Henderson model [9], the drying air equilibrium relative humidity can be expressed according to the product temperature, the product equilibrium absolute humidity and Henderson constants.

While applying the mathematical method of polynomial interpolation [14], the constants are determined for the different couples of tests according to **Table 6**.

Table 6: Numeric values of the constants K and n

N_S (kg water . kg^{-1} DM)	K	n
C1/C3	0.195534	5.308070
C1/C5	0.190706	5.279884
C3/C5	0.194487	5.301511
Mean	**0.193575**	**5.296488**

The kept values are:

$K = (0.193575 \pm 0.001466)$ and $n = (5.296488 \pm 0.008515)$.

Shrimp isotherm adsorption curve is traced from the expression (10). It is shown on Figure 9.

This curve shows that the shrimp equilibrium absolute humidity is an increasing function of the drying air equilibrium relative humidity.

4.3 Result summing-up

The shrimp drying speed in thin layer is defined by the relation (1). This relation is expressed according to the drying constant m, the product instantaneous absolute humidity N_s and the product equilibrium absolute humidity N_{se}. According to the treatment method applied to different essays, numerically the constant of drying m is:

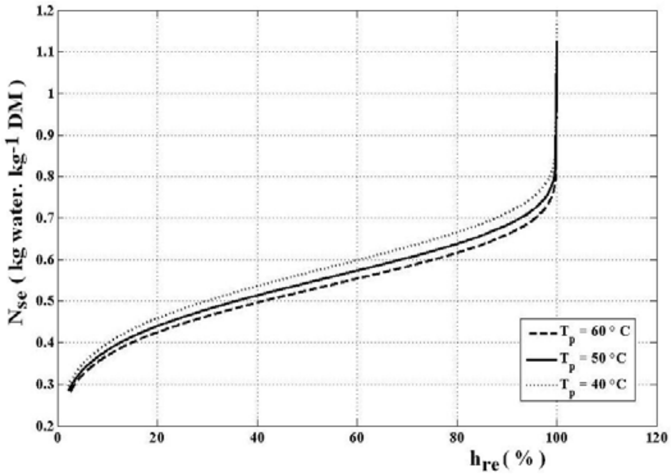


Fig. 9: The shrimp adsorption isotherm curve

$$m = \exp\left(-\frac{5542}{T_p} - 0.11.h_r + 1.76.V_a + 16.1174 \right) \tag{13}$$

The temporal evolution of the product absolute humidity is assimilated to its initial and final value. Initial value is: $N_{si} = 2.300 \pm 0.001$ kg water.kg^{-1} dry matter and final value is represented by the equilibrium absolute humidity N_{se}. It is determined from Henderson relation.

The calculations drive that numerically, Henderson constants are:

$K = (0.193575 \pm 0.001466)$ and $n = (5.296488 \pm 0.008515)$.

4.4 Discussion

Figures 10-12 represent the validations of the universal model respectively on the influence of the product temperature, the influence of the drying air relative humidity and the influence of the drying air speed.

This model has been successfully used in drying pineapple small discs, pouzzolane [7] and ripe banana [15]. There is a concordance between experimentally and theoretical results. Maximal gap between experimentally and theoretical results is lower than 5 %.

The model takes also drying air speed impact to account because it has a very important role during drying. However, the present survey doesn't introduce the product thickness influence in the shrimp drying speed model in thin layer because of all shrimp samples are considered having the same thickness.

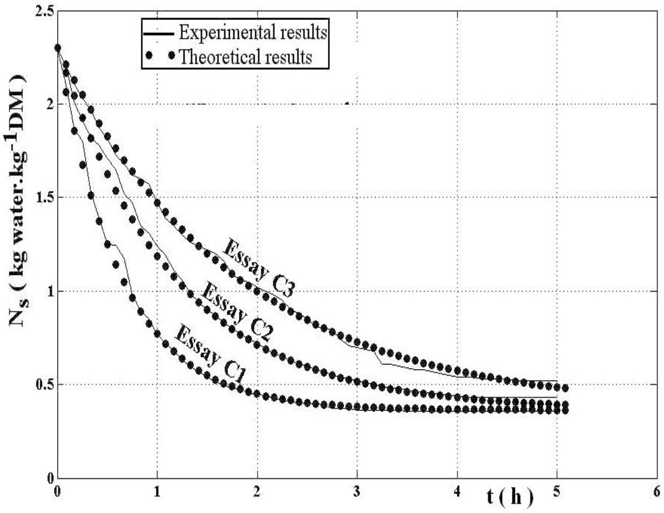


Fig. 10: Confrontation of theoretical and convenient results for the influence of the product temperature

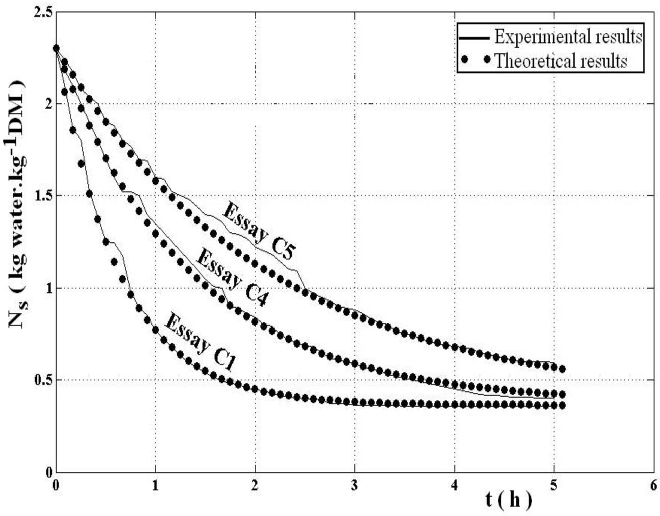


Fig. 11: Confrontation of theoretical and convenient results for the influence of the air drying relative humidity

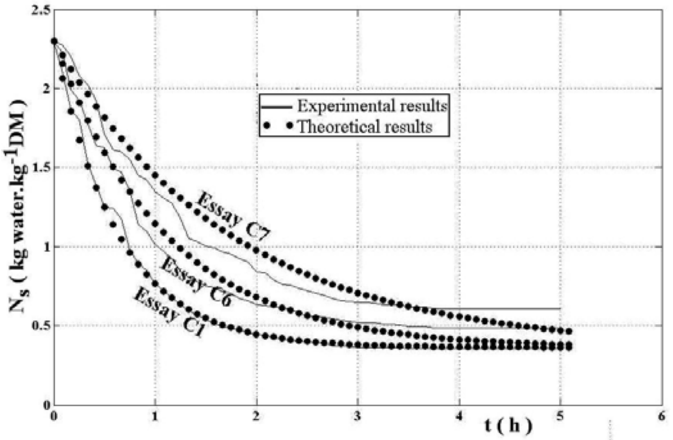


Fig. 12: Confrontation of theoretical and convenient results for the influence of the drying air speed

5. CONCLUSION

In this survey was established a universal model of drying speed in forced convection of shrimp in a single layer according to main drying parameters such as drying temperature, product absolute humidity, drying air relative humidity, drying air speed, and according to product features such as instantaneous and equilibrium absolute humidity.

Product equilibrium absolute humidity has been calculated using Henderson model. It is concluded that shrimp is a hygroscopic product and that water transfer within shrimp is of capillary origin.

The next stage consists to experiment and simulate a new configuration for an industrial shrimp drier already constructed at the University of Mahajanga, Madagascar, intended to shrimp drying in forced convection in thin layer, and to propose a dimension calculation method for driers of the same type [16-19].

NOMENCLATURE

DM	Dry matter, (kg)
$d N_s / d t$	Product drying speed, (kgwater.kg^{-1}DM.h^{-1})
h_r	Instantaneous relative humidity of air drying, (%)
H_{re}	Relative humidity of order, (%)
h_{re}	Equilibrium relative humidity of drying air (%)
m	Constant of drying, (h^{-1})
M	Product initial mass, (kg)
M_s	Dry matter mass in the product, (kg)
N_s	Product instantaneous absolute humidity, (kgwater.kg^{-1}DM)
N_{sc}	Product critical absolute humidity, (kgwater.kg^{-1}DM)
N_{si}	Product initial absolute humidity, (kgwater.kg^{-1}DM)

N_{se}	Product equilibrium absolute humidity, (kgwater.kg^{-1}DM)
t	Time, (h)
t_s	Drying time, (h)
T_{ae}	Drying temperature (raising average), (K)
T_p	Product temperature (raising average), (K)
η	Reduced humidity rate
V_a	Drying air speed, (m/s)

REFERENCES

[1] B. Coulibaly, M. Fournier and M. Amouroux, '*Optimisation de la Commande d'un Séchoir Solaire à Bois*', Journal de Physique III France, Vol. 2, N°4, pp. 701 – 714, 1992.

[2] M.J. Troeger and W.V. Hukill, '*Mathematical Description of the Drying Rate of Fully Exposed Corn*', ASAE Paper. N°70, pp. 324 – 335, 1970.

[3] S. Janjai, A. Esper and W. Muhlbauer, '*A Procedure for Determining the Optimum Collector Area for a Solar Paddy Drying System*', Renewable Energy, Vol. 4, N°4, pp. 409 – 416, 1994.

[4] R.P. Kachru and A.A. Zomorrodian, '*Determination of Thick-Layer Drying Coefficients for Rough Rice*', Journal of Food Science and Technology, Vol. 22, N°2, pp. 93 – 97, 1985.

[5] H. El-Salman, '*Mesure de la Vitesse de Quelques Produits et Contribution à l'Etablissement d'un Fichier Précisant les Modalités de Séchage de Divers Produits*', Diplôme Universitaire de Recherche, Université de Perpignan, France, 1989.

[6] S. Youcef-Ali and S.Y. Desmons, '*Influence of the Aerothermic Parameters and Product Quantity of the Production Capacity of an Indirect Solar Dryer*', Renewable Energy, Vol. 32, N°3, pp. 496 – 511, 2007.

[7] A. Ramamonjisoa and J.C. Gatina, '*Contribution au Développement de Séchoirs à Chauffage Partiellement Solaire à la Réunion: Mise au Point d'un Dispositif de Mesure de Vitesse de Séchage en Couche Mince et d'un Code de Calcul d'abaques de Dimensionnement*'. Travaux Universitaires, Thèse Nouveau Doctorat, Université de La Réunion, 204 p., 1993.

[8] J. Confais et M. Le Guen, '*Premiers Pas en Régression Linéaire avec SAS*', Revue Modulad, N°35, 2006.

[9] J.L. Bailleul, D. Delaunay et Y. Jarny, '*Identification des Propriétés Thermiques de Composites Fibres de Verre/ Résine Thermodurcissables. Application à l'Optimisation de Procédés de Moulage'*, Revue Générale de Thermique, Vol. 35, pp. 65 - 77, 1996.

[10] S. El Hajji, '*Interpolation Polynomiale*', Université Mohammed V, Agdal, Faculté des Sciences, Rabat, Maroc, 2007.

[11] M. Kouhila, A. Belghith et M. Daguenet, '*Approche Expérimentale des Courbes de la Menthe en vue d'un Séchage par Energie Solaire*', Revue des Energies Renouvelables, Vol. 2, pp. 61 – 68, 1999..

[12] Y. Jannot, J.C. Batsale, C. Ahouannou, A. Kanmogne and A Talla, '*Measurement Errors Processing by Covariance Analysis for an Improved Estimation of Drying Curve Characteristic Parameters*', Drying Technology, Vol. 20, N°9, pp. 1919 – 1939, 2002.

13] M. Kouhila, N. Kechaou, M. Oiman, M. Fliyou, S. Lahsasni, '*Experimental Study of Sorption Isotherms in Drying Kinetics Maroccan Eucalyptus Globules*', Drying Technology. Vol. 20, N°10, pp. 2027 – 2039, 2002.

[14] H. Faudet, '*Principes Fondamentaux du Génie des Procédés et de la Technologie Chimique*', Editeur, Lavoisier, Technique & Documentation, 1997.

[15] A.B.O. Ramamonjisoa, '*Élaboration d'un Logiciel Interactif pour le Dimensionnement et le Diagnostic Energétique de Séchoirs à Chauffage Partiellement Solaire*'. Thèse de Doctorat, Université d'Antananarivo, Madagascar, 1997.

[16] M. Daguenet, '*Les Séchoirs Solaires: Théorie et Pratique*', Unesco, 1985.

[17] M. Kouhila, '*Etude Expérimentale et Théorique des Cinétiques de Séchage Convectif Partiellement Solaire des Plantes Médicinales et Aromatiques dans la Région de Marrakech*', Thèse de Doctorat d'Etat, Université de Cadi Ayyadi, Marrakech, Maroc, 2001.

[18] N. Kechaou, '*Etude Théorique et Expérimentale du Processus de Séchage de Produits Agro-Alimentaires*', Thèse de Doctorat d'Etat, Faculté des Sciences, Université de Tunis, 2000.

[19] S. Lahsasni, M. Kouhila, M. Mahrouz and J.T. Jaouhari, '*Drying Kinetics of Prickly Pear Fruit* (*Opuntia ficus indica*)', Journal of Food Engineering, Vol. 6, N°2, pp. 173 – 179, 2003.