Experimental Analysis of Forced Convection Drying Process for Potato

John-Bosco Namwamba, Patrick Mensah

Mechanical Engineering Department
Southern University and A&M College

Abstract

In this work studies were carried out on effect of temperature and air velocity (for low flow rates) on drying kinetics of English potatoes (*batata inglesa*). English potato slices of dimensions 4cm by 4cm by 5mm were put in four trays and air at different conditions and flow rates passed through them for analysis of corresponding drying characteristics. Air flow and source of heat were provided by a suction pump. Though low air flow rates were used, increase in their quantity resulted in increase in the drying rate. Increase in drying air temperature resulted in increase in rate of loss of moisture. A unique method of prediction (interpolation) is also attempted here. Experiments of drying at 1000 l/min and 2000 l/min were carried out. Best curves of fit for resulting data were plotted. The prediction for drying curves at 1500 l/min was done by interpolation between curves of 1000 l/min and 2000 l/min and results compared with experimental data (see Figure 4). The averages of three experimental data at 1500 l/min were, 0.7781, 0.7759 and 0.7741. The percentage error between each of experimental data set and corresponding values from predicted data was less than 1%. Another unique method used here is prediction of drying characteristics by polynomial models. Polynomial models gave the best fit when moisture content was defined in wet basis.

Introduction

Due to failure of natural air to adequately dehydrate agricultural food products to safe storage and processing levels, heated air food dehydrator or dryer use of the heated air dehydrator becomes necessary. Compared to natural air drying, the heated air drying system absorbs more moisture from food products thus, drying the food faster. This paper is limited to mass transfer during drying process. However equations for solving heat transfer have also been outlined here due to their important in modeling heat and mass transfer in drying processes. MacGregor (2005) carried out a series of experiments to characterize the effect of air velocity, air temperature, and packed bed depth on drying wild blueberries (*Vaccinium angustifolium*). The data in this research were used to successfully design, build, and commission a commercial dryer with a tenfold increase in production capacity over previous equipment. Freire et al (2004) studied the drying kinetic behavior of soybean seeds in the fixed bed and the moving bed with crossed flow under thin layer conditions. The analysis of the available data followed the diffusive model approach with re-parameterization. The results showed that the effective diffusivity of the moving bed is 24% to 44% higher than that of the fixed bed. Tironi et al (2004) performed a three-factorial experiment design. The experimental results were fitted through Lewis and Page models. Hassini et al (2004) carried out work on evaluation of the moisture coefficient. Two models, Fick's model and model based on numerical solution of the equation of conservation of mass of both solid and liquid phase. Gaspareto et al (2004) carried out studies on drying papaya by a convective vertical tray dryer. Drying kinetics showed that diffusion in the fruit was the controlling phenomenon. A linear form of the Fick's diffusion model was fit to experimental data (R2 > 0.99), showing that the drying kinetics is satisfactorily described by the model. Diffusion coefficients of banana and papaya were successfully determined. Panduro et al (2004) carried out studies on drying parameters on clams (*Anodontites trapesialis*) and tilapia (*Oreochromisniloticus*). The results indicated that water diffusion coefficients increased when increased the temperature from 40 ºC to 60 ºC. The obtained values are in the suitable range for similar products reported in the literature. Guine´ (2002) investigated the main mass transfer phenomena occurring during drying of pears by carrying out experiments to determine the time evolution of the radial profiles of water and sugar content. The results led to the conclusion that the concentration profiles of water and sugar, both in space and time, follow an expected pattern if the rates of water removal and the diffusion mechanisms are taken into account.

Mathematical Model

Analysis used in this work was based on the following assumptions.

(a) The unsteady terms of the equations are independent of spatial location.
(b) Spaces between potato slices are uniform
(c) Flow energy is low due to low flow rates involved.
(d) Moisture diffusion coefficient remained unchanged throughout an experiment.
(e) Effect of shrinkage is negligible.

In this analysis, experimental data was used to partially supplement theoretical formulation. To model moisture transfer, considering a constant diffusion coefficient and infinite slab geometry, Fick's second law may be applied as illustrated by the following equations Guerman (2002)

$$\frac{\partial^2 M}{\partial t} = D\frac{\partial^2 M}{\partial x^2} \qquad (1)$$

The boundary conditions are:

At $t = 0 \quad M = M_0$

At $x = 0 \quad \frac{\partial M}{\partial x} = 0$

At $x = d_\tau / 2 \quad D\rho_l \frac{\partial M}{\partial x} = N$ (2)

Conduction heat transfer takes place according to the following equations based on the Fourier's law:

$$\rho_l Cp \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} \tag{3}$$

At $t = 0 \quad T = T_0$

At $x = 0 \quad \frac{\partial T}{\partial x} = 0$

At $x = d_\tau / 2 \quad \left(D\rho l \frac{\partial M}{\partial x} \right) \Delta H - K \frac{\partial T}{\partial x} = h(T_g - T_s)$ (4)

The parameters such as moisture content, moisture diffusivity, the dry, wet bulb and sample surface temperatures, the drying time, and the sample thickness, that are required to solve the above system of equations were determined experimentally (Kalbasi,2003). The other parameters such as the heat transfer coefficient and the thermal conductivity were evaluated theoretically.

To determine the moisture distribution in potato slice, the thickness of the slice may be divided into two parts, the middle and the surface points (Kalbasi, 2003)

The above equations of moisture and heat transfer can be solved by use of such as the moisture content, the dry, wet bulb and sample surface temperatures, the drying time, and the sample thickness. These parameters were determined experimentally. Other parameters such as the heat transfer coefficient, the thermal conductivity, and the moisture diffusivity were evaluated theoretically.

Equation (2) as follows can be written as:

At $x = d_\tau / 2 \quad N = D\rho_l \frac{\Delta M}{\Delta x}$ (5)

from which the moisture content difference between the sample surface points and middle point may be determined through calculation for each time step.

Assuming uniform moisture profile throughout the onion slice, the moisture content at the surface points and middle point may be defined as:

$$M_s = M - \frac{\Delta M}{3} \tag{6}$$

$$M_m = M + \frac{\Delta M}{3} 2 \tag{7}$$

For the half sample thickness, one may write the Equation (11) as follows:

$d_\tau / 2 \quad N\Delta H - K \frac{\Delta T}{\Delta x} = h(T_g - T_s)$ (8)

From Equation (15), the temperature difference between the sample surface points and middle point can be calculated for each time step.
The sample middle point temperature may be defined as:

$$T_m = T_s - \Delta T \quad (9)$$

$$D\rho l \frac{\Delta M}{\Delta x} \Delta H - K \frac{\partial T}{\partial x} = h(T_g - T_s) \quad (10)$$

In order to determine the effective diffusion coefficients of water in the potatoes a mathematical model from Fick's second law was used with the solution supplied by J. Crank (Gaspareto et al, 2004), for very long periods shown in Equation 4.

$$\frac{M - M_e}{M_i - M_e} = \frac{8}{\pi^2} \exp\left(- \frac{\pi^2 Dt}{L^2} - \right)$$

(11) The linear form of equation (11) is:

$$\ln M^* = B - At$$

(12)

Where $M^* = \dfrac{M - M_e}{M_i - M_e}$

(13)

A = angular coefficient = $D\pi^2 / L^2$ (14)

B=linear coefficient = $\ln(8/\pi^2)$ (15)

Equation (11) can also be written in the Lewis and Page model forms represented by the following equations, (16) and (17) respectively:

$$\frac{M - M_e}{M_i - M_e} = C \exp(-Kt) \quad (16)$$

$$\frac{M - M_e}{M_i - M_e} = C \exp(-Kt^n)$$

(17)

If the final moisture content is very low, M_e can be neglected and the following models could be used to describe the drying process.

$$\frac{M}{M_i} = C \exp(-Kt) \quad (18)$$

$$\frac{M}{M_i} = C \exp(-Kt^n) \quad (19)$$

Where C, K and n represent the corresponding model parameters (Tanko et al, 2005)
Equations (12) equivalent to the expression obtained when the natural logarithms of the left and right hand sides of equation (16) are taken.
Hence, B in equation (12) is approximately equal to natural logarithms of C in equation (16). B and K in equations (12) and (16) are equivalent.

Experimental Method

During experiments to analyze dehydration of Irish potatoes, heated air was made to flow through layers potato by a suction pump.
Drying air was heated by electric element. The air heating unit was made up 2mm synthetic material insulated with 2.5cm of insulator material. The heating chamber had a square base of sides 34cm by 34cm and 2.3 mm. Pealed potatoes in the shape of squares of approximate side lengths 37mm were laid on four galvanized mesh trays. An adjustable suction pump capable of moving at least 1000 liters per minute of air was mounted to the top back of the chamber. The air velocity was varied by adjusting the pump's discharge. The temperature was varied by heater knob. The chamber was positioned immediately below the bottom tray. The drying apparatus was placed on a concrete surface. The ambient temperature and temperatures of at least 60 points within drying chamber were recorded during each experiment by use of LABVIEW software. Dehydration was carried out for at different temperatures and air speeds. Batch drying dehydration experiments were also carried out. Fluent, Microsoft Excel and Matlab soft wares were used in modeling the dehydration process
The objectives of this research were the analysis and prediction of the following:

(i) The effect of drying air flow rates on drying characteristics of potatoes.
(ii) The effect of temperature on drying characteristics of potatoes.
(iii) Formulate an interpolation function to predict drying curve for unknown air flow rate.
(iv) Develop functions representing thin layer potato drying other than the Lewis and Page models.
(v) Determine the diffusion coefficient of potatoes.
(vi) Analyze the effect of drying air diffusion coefficient of moisture in the potato.

The modeling involved setting up and solving the following equations

(a) Energy equations, for the air and the product
(b) Mass equations, for the air and the product

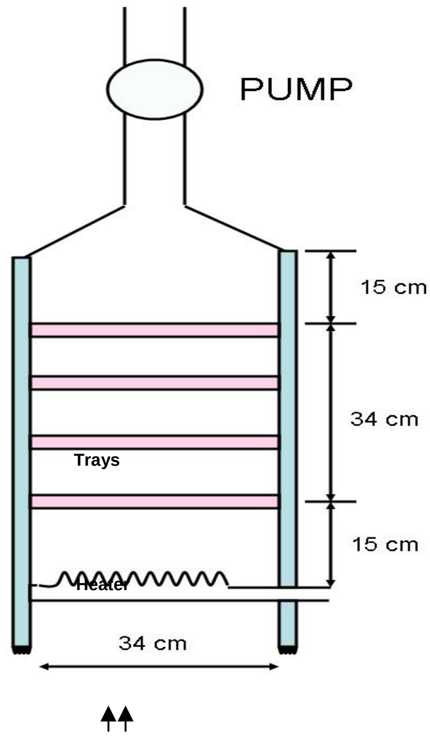

Fig1. Schematic view of Forced Convection Drying Apparatus for Potatoes

Results and Discussions and Conclusion

The effect of drying air flow rate on drying is illustrated by figure 3. For MR (wet basis), linear fitting of lnMR versus time gave 0.9705 and 0.9485 as values of R^2 for air flow of 3000 l/min at temperatures of $70^0 C$ and $80^0 C$ respectively. As temperature is increased, the lnMR (wet basis) versus time deviates further from linearity. Polynomial fitting of second order gave fits of $R^2>0.99$. Table1 compares polynomial expressions for analysis of MR (wet basis). Better linear expressions were fitted by splitting the data into two. The data for the first 50 minutes and the last 50 minutes was analyzed. The splitting of the curves resulted in higher R^2. Moisture content (wet basis) of potatoes during drying process can be predicted accurately by second order polynomial expressions as shown in table 1. Prediction of drying progression at 1500 l/min was done by interpolation between the prediction curves of 1000 l/min and 2000 l/min. Figure 2 illustrates comparison between actual data at 1500 l/min and the corresponding predicted curve. Two experiments at 1500 l/min had average moisture contents (wet basis) given as 0.7759 and 0.7741 while the predicted results had an average of 0.7781. The percentage error between predicted results and experimental results was 1%. Figure 7 illustrates the effect of drying potatoes under different temperatures.

The results indicate that the behavior of the experimental data can be satisfactorily described by theoretical diffusion model based on Fick's 2nd law. The curves used to determine the value of D had R^2 values greater than 0.99. The values of D, obtained from experimental data were within acceptable range. Table 3 and 4 contains air flows, temperatures and corresponding diffusion coefficients. Predicted variation of moisture content along tray 1 horizontally at 47 minutes, is represented curve shown in Fig 6. Also plotted on the same graph, are points for corresponding data from three experiments. Moisture content at 47 minutes can be predicted by the following expression:

$$M = 0.0002\frac{\tau}{\min^3}^{3} - 0.0059\frac{\tau}{\min^2}^{2} + 0.0585\frac{\tau}{\min} + 0.6158$$

The mean of the square of deviations of experimental data from predicted results was found to have the value 0.001237. It should be noted that the drying time used here did not exceed two hours.

Longer drying times could result in different overall results since the drying behavior of biological material changes as moisture is lost over long periods. Previous researches have not considered polynomial modeling in potato drying. The diffusion coefficient values obtained here are within the range given by Saravacos et al. (2001). This work successfully predicted drying curve for drying process by interpolation.

Further work is suggested here to attempt to predict drying curves by interpolation between temperatures. Since the experimental data in this research showed exponential variation with time, it is suggested here that an attempt be made to theoretically model moisture transfer in potato drying here by exponential variation.

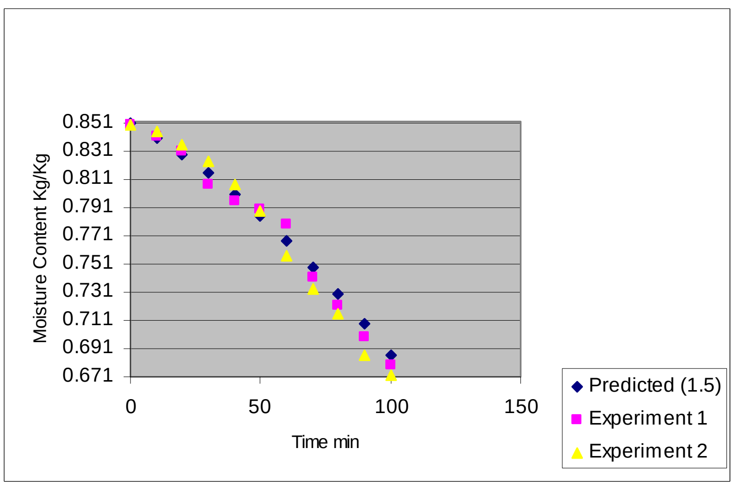

Figure 2. Comparison of Experimental Data and Predicted Data 1500 l/min 70^{0}C

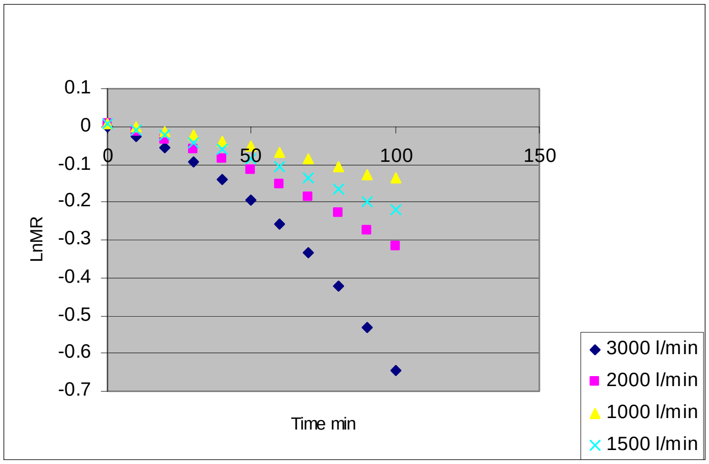

Fig 3- Comparison LnMR Variation with Time for Different Air Flow Rates Moisture Content Wet basis

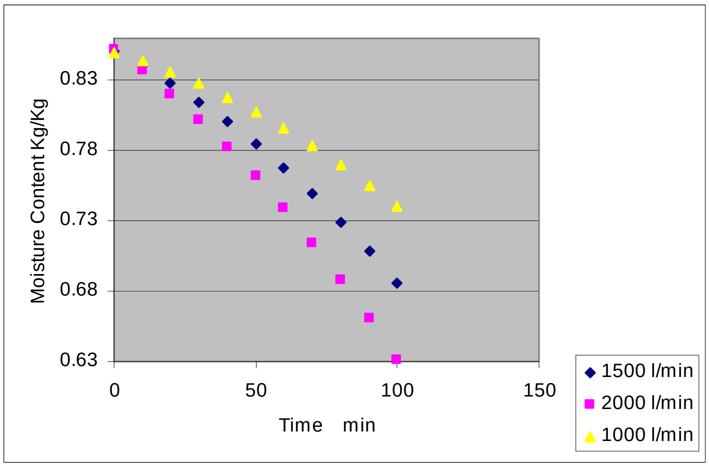

Fig 4- Predicting Moisture Content Variation by Interpolation

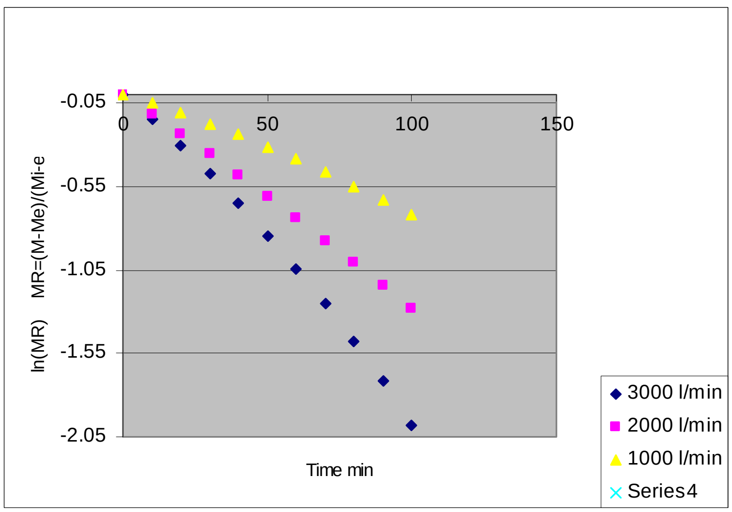

Fig 5- of Air Flow Rate on ln(MR) for Moisture Content Dry Basis T=70^{0}C

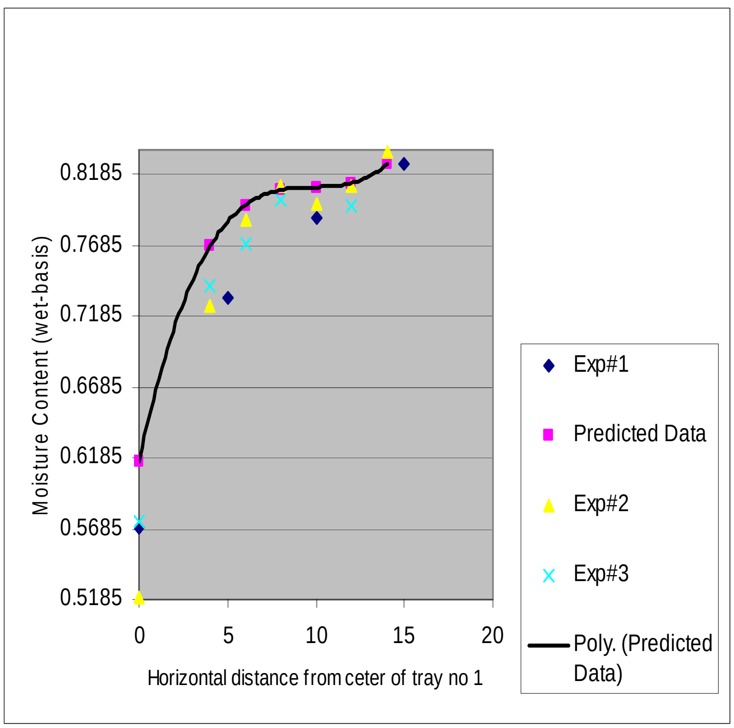

Fig 6- Comparison of Predicted and Experimental data on Moisture Content of drying material along tray no 1 $M = 0.0002x^3 - 0.0059x^2 + 0.0585x + 0.6158$ 0.001237

Table 1-Comparison of linear and quadratic model fitting for MR (wet basis) at 70^{0}C

Volume l/min	Linear Model	Polynomial Model
850	y = -0.0015t + 0.0155 R^2 = 0.9855	$MR = -6\times10^{-6}\dfrac{t^2}{\min^2} - 0.0009\dfrac{t}{\min} + 0.0067$ R^2 = 0.9975
2000	MR = -0.0033t+ 0.0302 R^2 = 0.983	$MR = -2\times10^{-5}\dfrac{t^2}{\min^2} - 0.0017\dfrac{t}{\min} + 0.0073$ R^2 = 0.9997
3000	y = -0.0063t + 0.0703 R^2 = 0.9489	$MR = -5\times10^{-5}\dfrac{t}{\min^2}^2 - 0.0011\dfrac{t}{\min} + 0.0078$ R^2 = 0.9993

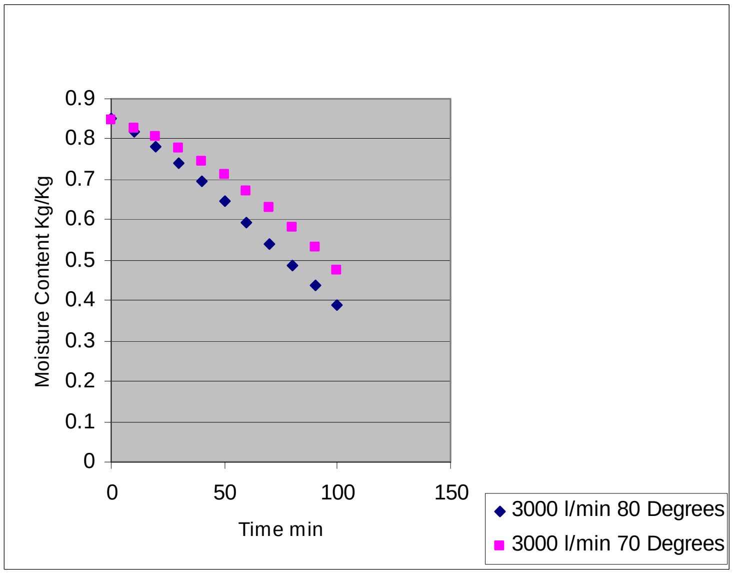

Figure 7 Effect of Temperature on Moisture Content Variation

Table 2-The variation of moisture content along tray 1 at 47 minutes.

Location from center of tray cm	Moisture content at 25 min	Moisture content at 87 min	Moisture content at 47 min	Predicted moisture content (wet basis) at 47 min from interpolation method
0	0.649038	0.495953	0.612002	0.568678
5	0.824955	0.766167	0.810732	0.731799
10	0.777927	0.545933	0.721799	0.778
14	0.81532	0.729272	0.794502	0.794

Table 3- Results obtained from the analysis of experimental data for drying of the potatoes (MR= $(M-M_e)/(M_i-M_e)$)

Volume Flow Rate	Temperature ^{0}C	C	K	$D\times10^{-8}$ M^2/s	R^2
1000	70	1.032311	0.0073	0.390957	0.9944
2000	70	1.019284	0.0128	0.685514	0.9993
3000	70	1.089153	0.0197	1.05505	0.9931
3000	80	1.04029	0.0248	1.32818	0.9998

Table 4- Results obtained from the analysis of experimental data for drying of the potatoes MR=M/Mi

Volume Flow Rate	Temperature ^{0}C	C	K	$D\times10^{-8}$ M^2/s	R^2
1000	70	1.029425	0.0069	0.369535	0.995
2000	70	1.012174	0.0121	0.648025	0.9997
3000	70	1.063005	0.018	0.964004	0.9964
3000	80	1.0004	0.022	1.17823	0.9994

NOTATION

C	Water vapor concentration (G: bulk air, S: saturated air) (kg/m^3)
Cp	Specific heat (kJ/kgK)
D	Moisture diffusion coefficient (m^2/s)
d	Sample thickness (o: initial, τ : at time τ) (m)
E	Mean relative deviation modulus (%)
h	Convective heat transfer coefficient (W/m^2K)
ΔH	Heat of vaporization (kJ/kg)
K	Thermal conductivity (W/mK)
k	Mass transfer coefficient (m/s)
L	Thickness of drying food slab (m)
M	Moisture content (o: initial, m: middle point, s: surface point) (kg/kg)
ΔM	Moisture content difference (kg/kg)
m	Values (e: experimental, p: practical)
N	Drying rate (g/m^2s)
n	Number of experimental (data)
Pr	Prandtl number (dimensionless)
Re	Reynolds number (dimensionless)
S	Dry solid content (o: initial) (fraction)
T	Temperature (G: bulk air, S: saturated air, m: sample middle point, s: sample surface point) (K)
t	Drying time (min)
u	Velocity (m/s)

x Sample thickness dimension (m)

Δx Half the sample thickness (m)

ρ Density (l: moisture, s: sample) (kg/m^3)

τ At time t (min)

REFERENCES

Freire, F.B, Marcos A. S. B, Dermeval, J.M S and Freire T. 2004, Study of the Drying Kinetics in Thin Layer Fixed and Moving Bed. *Drying 2004* – Proceedings of the 14th International Drying Symposium (IDS 2004) São Paulo, Brazil, 22-25 August 2004, vol. C, pp. 1684-1691

Gaspareto, O.C.P, Getrudes E, Silver D.J, Honorato G.C, Magalhaes M.M And Oliveira E.L, 2004, Application of Model Diffusional of Plain plate in the Drying of Tropical Fruits. Oliveira *Drying 2004* – Proceedings of the 14th International Drying Symposium São Paulo, Brazil, 22-25 August 2004, vol. C, pp. 2113-2119

Guerman I.F, 2002 Drying Kinetics Derived from Diffusion equation with Flux-Type Boundary Conditions. Drying Technology, 20(1), 55–66 . 2003 Marcel Dekker Inc.

Guine, R.P.F, and Castro J.A.A.M, 2002, Drying Rates and Evolution of Water and Sugar Concentrations in Space and Time, Drying Technology, 20(7), 1515-1526 (2002)

Kalbasi M, 2003. Heat and Moisture Transfer Model for Onion Drying. Drying Technology 21 (8), 1575–1584, Marcel Dekker Inc.

MacGregor, W. 2005, Effects of Air Velocity, Air Temperature, and Berry Diameter on Wild Blueberry **Drying,** Drying Technology, Volume 23, Number 1-2 / 2005, pages 387 - 396

Panduro B.T, Garcia-Vasquez Y, Medina-Vivanco M And Mendieta T O, Air Drying Of Clams (*Anodontites Trapesialis*) And Tilapia (*Oreochromis Niloticus*) Fillet.
Drying 2004 – Proceedings of the 14th International Drying Symposium (IDS 2004)
São Paulo, Brazil, 22-25 August 2004, vol. C, pp. 1977-1983

Saravacos G.D and Maroulis Z.B, 2001, Transport Properties of Food, p193, Marcel Dekker Inc, New York, NY.

Tanko H.M, Carrier D.J Sokhasanj S, And Growe T.G, 2005, Drying of Feverfew (*Tanacetum parthenium).* Le Génie Des Biosystèmes Au Canada. P. 3.57-3.61.

Tironi, A., Crozza, D.E. and Pagano A.M. 2004. Drying Kinetics of Carthamus Tinctorius L. Seeds
Drying 2004 : Proceedings of the 14th International Drying Symposium (IDS 2004)
São Paulo, Brazil, 22-25 August 2004, vol. C, pp. 1612-1619