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Method for Determining the Appropriate Thin Layer Drying Model for a Feedstock

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Abstract: ***In practice, drying is one of the most common food preservation technique. At microscopic level, drying is not merely a moisture removal process and it involves complex heat and mass transport phenomena and depends on material properties. So mathematical models in drying are important for process design, optimization and energy integration. Therefore, in the present study, first theory of drying is elucidated concisely. Further, general modelling approaches and commonly used thin layer drying equations are presented. Later, method for evaluation of appropriate thin layer drying model for a feedstock is explained. Effective moisture diffusion coefficient (D_{eff}) and activation energy (E_a) calculations methods are also presented.***

Keywords: ***Drying kinetics, Thin-layer drying modelling, Statistical techniques, Effective moisture diffusivity, Activation energy.***

I. INTRODUCTION

Drying is the traditional method employed at one stage or another in almost all industries and is an inevitable in food processing industry as it increases shelf-life of the product and facilitate its handling. Besides, drying also aids in obtaining a desired physical form of the product, reduces its storage cost and its freight transport cost [1]. Drying is merely a moisture removing technique, yet it is an intricate process which requires knowledge of analysis methods from thermodynamics, heat, momentum and mass transfer, porous media, psychometrics and material science [2]. Hence, mathematical modelling of drying techniques, assists dryer design and optimization [3].

Thin layer drying equations give good results and are crucial mathematical modelling tools of drying. But to utilize this thin-layer equations, drying rate curves are to be measured experimentally [4]. Fig.1 shows a typical drying curve which is depicted between moisture ratio and time for a feedstock in the presence of any drying medium. First, feedstock heats up and consequently drying rate steadily increases. Later, water transport through the solid is exceptionally expeditious to keep conditions saturated at its surface and hence constant drying rate is perceived in this stage.

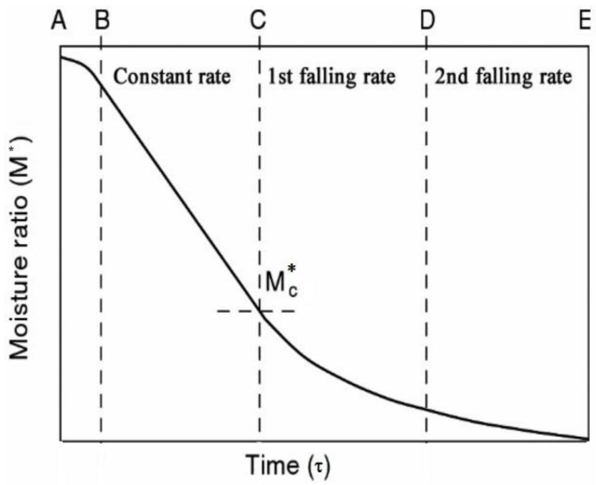

Fig. 1. A typical drying curve for a feedstock [53].

Surface diffusion is the dominant mechanism therefore external factors such as drying air properties plays a major role in this stage [5]. At the last rung of this stage, dry spots are formed over the surface of the feedstock indicating critical moisture content in the product. Later, First falling rate drying period commences with dominating liquid diffusion. Therefore, in this stage internal conditions viz., moisture content, product’s physical properties play an important role [6]. Finally, second falling rate period begins with evaporation of entire liquid from the surface. In this stage, vapor diffusion is the governing drying mechanism [7].

In the present work, thin layer drying fundamentals are explained and generally employed thin-layer drying models are presented. However, the main agenda of the paper is to interpret the method for evaluation of best suited thin layer drying model for a feedstock. In addition, estimation of transport properties viz., D_{eff} and E_a values for a feed stock are presented.

II. MATHEMATICAL MODELING OF DRYING

Drying procedures can be mathematically modelled with distributed and lumped parameter models. Both the models assess parallelly heat and mass transfer during drying. But, precise estimation of drying rate at any position after a certain recess of time can be obtained by using distributed models as shown in Eqs. (1) and (2) [8].

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The main difference between them is, distributed parameter model considers the effect of both internal and external heat and mass transfer resistance, whereas influence of internal resistance is neglected in lumped parameter models as illustrated in Eqs. (3) and (4) [9].

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T \quad (1)$$

$$\frac{\partial T}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T \quad (2)$$

$$\frac{\partial M}{\partial t} = K_{11} \nabla^2 M \quad (3)$$

$$\frac{\partial T}{\partial t} = K_{22} \nabla^2 T \quad (4)$$

Equations (3) and (4), can be rearranged into Eqs. (5) and (6)

$$\frac{\partial M}{\partial t} = D_{eff} \left[\frac{\partial^2 M}{\partial x^2} + \frac{\lambda}{x} \frac{\partial M}{\partial x} \right] \quad (5)$$

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{\partial^2 T}{\partial x^2} + \frac{\lambda}{x} \frac{\partial T}{\partial x} \right] \quad (6)$$

where, for planar shapes $\lambda = 0$; for polar geometries $\lambda = 1$ and for spherical configuration $\lambda = 2$ [10].

Akpinar [11], dried the product samples as single thin layer to maintain thermal equilibrium between the product samples and its prevailing ambient. Therefore, the influence of temperature variation can be neglected throughout the drying process. Unlike distributed models, these thin layer drying models are widely applied because it requires less data and simple in usage. These equations can be categorized into following three models.

A. Theoretical Models

These can be applied to drying process under all circumstances. But these models can cause significant errors, as they are based on many assumptions such as homogeneous and isotropic material, infinitesimal external resistance, insignificant temperature gradients and shrinkages. They are attained from Fick's II law of diffusion. It considers only the influence of internal resistance to moisture transfer [12]. Then Eq. (5) which describes the mass transfer can be solved using following conditions:

$$\begin{aligned} &M(x,0) = M_i, \text{ at } \tau = 0 \\ &M(0,\tau) = M_e, \text{ at } x = L \\ &M(0,\tau) = \text{finite}, \text{ at } x = 0 \end{aligned} \quad (7)$$

The solution of Eq. (5) for slab and sphere is presented in Eq. (8) and for infinite cylinder in Eq. (9) [13].

$$M^* = \theta_1 \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{\left[-\frac{(2n+1)^2 \pi^2 D_{eff} \tau}{\theta_2} \right]} \quad (8)$$

$$M^* = \theta_1 \sum_{n=0}^{\infty} \frac{1}{J_0^2} e^{\left[-\frac{J_0^2 D_{eff} \tau}{\theta_2} \right]} \quad (9)$$

θ_1, θ_2 are geometric constants as indicated in Table 1.

Table- I: Values of θ_1, θ_2

Geometry/ Shape	θ_1	θ_2
Infinite slab	$\frac{8}{\pi^2}$	$4L^2$
Sphere	$\frac{6}{\pi^2}$	$4r^2$
3D finite slab	$\left(\frac{8}{\pi^2}\right)^3$	$\frac{1}{\left(L_1^2 + L_2^2 + L_3^2\right)}$

M^* can also be determined based on the external conditions as in Eqs. (9) and (10) [14].

For constant RH,

$$M^* = \frac{M_\tau - M_e}{M_i - M_e} \quad (10)$$

For varying RH,

$$M^* = \frac{M_\tau}{M_i} \quad (11)$$

B. Semi-theoretical Models

These models consider only the external resistance to moisture transport at the interface of feedstock and air [15]. They are obtained either from modified Fick's II law of diffusion or from Newton's law of cooling. They are simple and need only fewer assumptions [16]. Table 2, represents semi-theoretical drying models developed by various researchers for different conditions.

Table- II: Semi-theoretical models

Model Name	Drying Equation	Reference
Models analogues with Newton's law of cooling		
Lewis (Newton) model	$M^* = e^{(-k\tau)}$	[17]
Page model	$M^* = e^{\left(-k\tau^n\right)}$	[18]
Modified Page – I model	$M^* = e^{(-k\tau)^n}$	[19]
Modified Page – II model	$M^* = e^{-(k\tau)^n}$	[20]
Modified Page – III model	$M^* = e^{-k\left(\tau/l^2\right)^n}$	[21]
Models analogues to Fick's II law of diffusion		

Henderson and Pabis (single term) model	$M^* = a\,e^{(-k\tau)}$	[22]
Logarithmic (Asymptotic) model	$M^* = a\,e^{(-k\tau)} + c$	[23]
Midilli model	$M^* = a\,e^{(-k\tau)} + b^*\tau$	[24]
Modified Midilli model	$M^* = e^{(-k\tau)} + b^*\tau$	[25]
Demir et al. model	$M^* = ae^{(-k\tau)^n} + b$	[26]
Two-term model	$M^* = a\,e^{(-k_1\tau)} + b\,e^{(-k_2\tau)}$	[27]
Two- term exponential model	$M^* = a\,e^{(-k\tau)} + (1-a)\,e^{(-ka\tau)}$	[28]
Verma model	$M^* = a\,e^{(-k\tau)} + (1-a)\,e^{(-g\tau)}$	[29]
Diffusion approach model	$M^* = a\,e^{(-k\tau)} + (1-a)\,e^{(-kb\tau)}$	[30]
Three term exponential model	$M^* = a\,e^{(-k\tau)} + b\,e^{(-g\tau)} + c\,e^{(-h\tau)}$	[31]
Hii et al. model	$M^* = a\,e^{(-k\tau^n)} + b\,e^{(-g\tau^n)}$	[32]

C. Empirical Models

These models also take only the external resistance to moisture transfer into account. They don't have any physical interpretation and mainly dependent on the experimental conditions [33]. Table 3 indicate various empirical drying models.

Table- III: Empirical drying models

Model Name	Drying Equation	Reference
Thompson model	$\tau = a\ln\left(M^*\right) + b\left[\ln\left(M^*\right)\right]^2$	[34]
Wang and Singh model	$M^* = 1 + b^*\tau + a^*\tau^2$	[35]
Kaleemullah model	$M^* = e^{-c^*T} + b^*\tau^{(pT+n)}$	[36]
Peleg model	$M^* = 1 - \tau/(a+b\tau)$	[37]
Silva et al. model	$M^* = e^{\left(-a\tau - b\sqrt{\tau}\right)}$	[38]
Weibull model	$M^* = e^{\left(-\left[\frac{\tau}{\alpha}\right]^{\beta}\right)}$	[39]
Diamante et al. model	$\ln\left(-\ln M^*\right) = a + b\left(\ln\tau\right) + c\left(\ln\tau\right)^2$	[40]
Aghbashlo model	$M^* = e^{\left(-k_1\tau/(1+k_2\tau)\right)}$	[41]

III. METHOD FOR DETERMINATION OF APPROPRIATE THIN LAYER DRYING MODEL

Appropriate thin-layer drying model for any feed stock can be determined using statistical techniques. To find the connection between the variables linear and non-linear regression analyses are very important. Thin layer drying equations require M^* *vs* τ curves. Generally, M^* data is plotted against τ and regression analysis is conducted with the selected models to estimate the constant values of the drying model. Different statistical techniques are employed to check the validation of these models [42-46].

The basis for choosing the suitable model that define the drying of a feedstock is the correlation coefficient (r). Besides r, χ^2 and *RMSE* are also applied to determine the appropriate model. The maximum r and minimum χ^2 and *RMSE* values are required to analyse the goodness of fit [47-48]. Eqs. (12) to (17) are used to calculate r, χ^2, *RMSE*, *P*, and *MAPE*.

$$r = \frac{N\sum_{i=1}^{N} M^*_{pre,i}M^*_{\exp,i} - \sum_{i=1}^{N} M^*_{pre,i}\sum_{i=1}^{N} M^*_{\exp,i}}{\sqrt{\left(N\sum_{i=1}^{N}\left(M^*_{pre,i}\right)^2 - \left(\sum_{i=1}^{N} M^*_{pre,i}\right)^2\right)} \times \sqrt{\left(N\sum_{i=1}^{N}\left(M^*_{\exp,i}\right)^2 - \left(\sum_{i=1}^{N} M^*_{\exp,i}\right)^2\right)}} \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(M^*_{\exp,i} - M^*_{pre,i}\right)^2}{N-n} \quad (13)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(M^*_{pre,i} - M^*_{\exp,i}\right)^2} \quad (14)$$

$$P = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{M^*_{\exp,i} - M^*_{pre,i}}{M^*_{\exp,i}}\right| \quad (15)$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(M^*_{\exp,i} - M^*_{\exp,avg,i}\right)} \quad (16)$$

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$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{M^*_{exp,i} - M^*_{pre,i}}{M^*_{exp,i}}\right| \quad (17)$$

IV. TRANSPORT PHENOMENA OF DIFFUSION

A. Effective Moisture Diffusivity

Diffusion in solids is an intricate phenomenon during drying as it involves molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow and surface diffusion. Eqs. (3) and (4) combines all these phenomena with a lumped parameter model concept and termed as effective moisture diffusivity. Henderson and Pabis model are derived for longer drying times and the constant values of D_{eff}. Eq. (18) is obtained from a simple arrangement.

$$\ln\left(M^*\right) = \ln(a) - k\tau \quad (18)$$

where k is attained from Eq. (19)

$$k = -\frac{\pi^2 D_{eff}}{\theta_2} \quad (19)$$

where θ_2 is shown in Table I.

The D_{eff} usually gets influenced by internal factors like feedstock temperature and its moisture content. The same is in accordance with the thin layer concept assumptions [49]. It is important to estimate D_{eff} for describing the drying characteristics.

B. Activation Energy

The influence of temperature on D_{eff} is usually defined by an Arrhenius equation [50].

$$D_{eff} = D_o\, e^{\left(-10^3 \frac{E_a}{R(T+273.15)}\right)} \quad (20)$$

The sensibility of diffusivity against temperature is obtained E_a value. The large value of E_a indicates more sensibility of D_{eff} to temperature [51].

For microwave drying [52],

$$D_{eff} = D_o\, e^{\left(\frac{-E_a m}{P_m}\right)} \quad (21)$$

V. CONCLUSIONS

In the present work, general approach for mathematical modelling of drying is explained. Also, the most commonly used thin layers drying equations are presented. Method for assessment of appropriate thin layer drying model for a feedstock is elucidated. The effective moisture diffusion coefficient and activation energy calculation methods are interpreted.

The following conclusions can be drawn from this study:

1. A technique to propose a novel mathematical model that describe the drying kinetics of a feedstock is explained.
2. The analytical solutions for fractional moisture ratio of infinite slab, infinite cylinder and sphere geometries of feedstock are determined.
3. The maximum r and the minimum χ^2 and $RMSE$ values are essential to assess the best suited model to define the drying phenomenon of a feedstock.
4. Temperature strongly influences the effective moisture diffusivity of a product.

NOMENCLATURE

D_{eff}	:	Effective moisture diffusivity, m^2/s
D_o	:	Arrhenius factor, m^2/s
E_a	:	Activation energy, kJ/mol
g, h	:	Drying constant obtained from experiments, s^{-1}
J_0	:	Bessel function roots
K	:	Drying constant, s^{-1}
K_{11}, K_{22}	:	Phenomenological coefficients
K_{12}, K_{21}	:	Coupling coefficients
L	:	Sample thickness, *mm*
L_1, L_2, L_3	:	Dimensions of finite slab, *m*
m	:	Sample amount, *g*
M	:	Local moisture content, *kgw/kgds* or (% dry basis)
M_e	:	Equilibrium moisture content (% dry basis)
M_i	:	Primary moisture content (% dry basis)
M_τ	:	Moisture content at time τ (% dry basis)
M^*	:	Moisture ratio fraction
$M^*_{exp,i}$	:	i[th] experimental M^* value
$M^*_{pre,i}$	:	i[th] predicted M^* value
n	:	Empirical model constant
P	:	Pressure, *kPa*
P_m	:	Microwave output power, *W*
r	:	Correlation constant
R	:	Universal gas constant, *kJ/mol*
RH	:	Relative humidity
RMSE	:	Root mean square error
T	:	Temperature, ° C
τ	:	Drying time, *s*
x	:	Diffusion path, *m*
χ^2	:	Reduced chi-square
α	:	Thermal diffusivity m^2/s
λ	:	Shape parameter

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θ_1, θ_2	:	Geometric constants

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