NUMERICAL INTERPRETATION OF DRYING CURVE OF FOOD PRODUCTS

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Introduction

In this work the possibility of modelling convective drying kinetics for food products was studied. The experimental runs were conducted in two ways; drying in fluidized bed with vibrating screen and drying in deep fixed bed. Because of indispensable computer use in chemical engineering processes for analysing, simulating and controlling adequately, it is necessary to find an appropriate mathematical model. The modelling of convective drying of porous material is based on heat and mass accumulation, as well as the heat and mass flux through accumulation, as well as the heat and mass flux throu solid phase. In this work kinetic modelling was based on heat and mass accumulation of air, as drying media, as well as of drying material. For a complete process description according to elemental layer theory four general equations were used (Techasena *et al*, 1991; Bakker-Arkema *et al*, 1974; Bakker-Arkema, 1985; Cobbinah *et al*, 1984; Sokhansanj and Wood, 1991; Beke, 1992):

- **heat and mass balance for air:**

$$\frac{\partial(\rho_{da}c_{p,da}T_g + \rho_{wv}c_{p,wv}T_g)}{\partial t} = -\operatorname{div}\left(\vec{\phi}_{q,a}\right) \quad (1)$$

$$\frac{\partial(\rho_{ha}H)}{\partial t} = -\operatorname{div}\left(\vec{\phi}_{m,a}\right) \quad (2)$$

- **heat and mass balance for drying matter:**

$$\frac{\partial(\rho_{sm}c_{p,sm}T_s + \rho_w c_{p,w}T_s)}{\partial t} = -\operatorname{div}\left(\vec{\phi}_{q,s}\right) \quad (3)$$

$$\frac{\partial(\rho_s \zeta)}{\partial t} = -\operatorname{div}\left(\vec{\phi}_{m,s}\right) \quad (4)$$

These equations can be solved using a series of more or less real assumptions.

Complexity of the appropriate model depends on purpose of its use. More detailed models have to be used for dynamic simulation and process control, while for the design and technical estimation some more simple models can be used. More detailed models are, in general, very complex and a lot of time has to be used for their solution, although their practical importance, useally, don't justify required time. Simple drying models are used mostly for determination of drying kinetics which describe mechanisms and influence of process variables on drying process. Some of the typical kinetic models used in the industry are empirical or semi-theoretical equations which consist of phenomenological parameters. Although, these parameters do not always have a physical meaning, but with an adequate driving force enable a prediction of drying

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Fig. 1 The scheme pilot vibrating dryer

Table 1. The results of the drying kinetics approximation with model (5)

PARAMETERS	DRYING IN FLUIDIZED BED				DRYING OF PLUM IN DEEP FIXED BED
	BARLEY MALT	CARROT	PEA		
a	0.3069	0.818	14.614	3.528	3.098
$k \cdot 10^3$	4.019	14.78	89.30	27.43	2.074
n	1.305	1.001	1.011	1.191	1.013
ϱ	0.99731	0.9926	0.9990	0.9936	0.9993
σ	0.00451	0.0300	0.2024	0.1237	0.0339
$t_{k,1}/\text{min}$	22.50	0.08	0.13	4.41	6.10
$\zeta_{k,1}/\text{kg} \cdot \text{kg}_{\text{sm}}^{-1}$	0.243	0.817	14.456	3.005	3.058
$(-d\zeta/dt)_{\text{max}}/\text{kg} \cdot \text{kg}_{\text{sm}}^{-1} \cdot \text{h}^{-1}$	0.198	0.723	76.532	7.819	0.395
$t_{k,2}/\text{min}$	80.51	67.40	11.03	23.20	450.73
$\zeta_{k,2}/\text{kg} \cdot \text{kg}_{\text{sm}}^{-1}$	0.089	0.301	5.318	1.106	1.125

kinetics. In that case such models can replace more complex mathematical models. Based on this approach a series of models (Techasen et al, 1991; Tomas et al, 1993; Tomas et al, 1994; Skansi et al, 1992; Tomas et al, 1992; Kiranoudis et al, 1992; Beke, 1992; Zhang and Litchfield, 1991; Courtois et al, 1991; Sokhansanj and Wood, 1991; Lebert et al, 1989; Bimbenet and Lebert, 1989; Laguerre et al, 1989; Rattanapant, 1989; Brennan, 1989; Brennan, 1978) have been developed which experimental results leave a lot of space for further investigation of kinetics in convective drying process.

In this work the possibility of the application (instead of equation 4) of chosen function was investigated:

$$\zeta(t) = a \cdot \text{EXP}(-kt^n), \quad (-d\zeta(t)/dt) = nkt^{(n-1)}\zeta(t) \quad (5)$$

where $t \geq 0$, $a > 0 = \zeta(0)$, $k > 0$ and $n > 1$.

Equation (5) has been taken for description of drying kinetics of experimental data because its suitable physical and phenomenological meaning, and, in the sense of mathematical analysis, equation (5) have the following characteristics:

- 1) $\zeta(0) > 0$, which fits the beginning substance moisture content,
- 2) $\zeta(t) > 0$, $t \in (0, t_k)$,

Fig. 2 The approximation of drying kinetics of barley in fluidized bed with model (5)

Fig. 3 The approximation of drying kinetics of malt in fluidized bed with model (5)

- 3) $\zeta(t)$ at the interval $t \in [0, t_k)$ is the monotonous decreasing function (no local extremes),
- 4) $\zeta(t)$ for $t \rightarrow t_k$ asymptotically approaches to $\zeta(t) = 0$.
- 5) $\zeta(t)$ has one point of inflection for $t = t_{k,1}$
- 6) $(-d\zeta(0)/dt) = 0$,
- 7) $(-d\zeta(t)/dt) > 0$, $t \in (0, t_k)$,
- 8) $(-d\zeta(t)/dt)$ has one maximum for $t = t_{k,1}$ (this coincides with the inflection point of the function $\zeta(t)$) and besides it there are no local extremes,
- 9) $(-d\zeta(t)/dt) \rightarrow 0$ as $t \rightarrow t_k$.

Model parameters have either physical or phenomenological meaning. Parameter a represents initial moisture of drying matter $\zeta(0)$, while parameters k and n present drying coefficients. So, model (5) can be written:

$$\zeta(t) = \zeta(0) \cdot \text{EXP}(-kt^n) \quad (6)$$

and enables determination of a first critical point as a function maximum $(-d\zeta/dt)$:

$$t_{k,1} = ((n-1)/(kn))^{(1/n)} \\ \zeta_{k,1} = \zeta(0) \cdot \text{EXP}((1-n)/n) \\ (-d\zeta/dt)_{\text{max}} = knt_{k,1}^{(n-1)}\zeta_{k,1},$$

and a second critical point in the point inflexion of the function $(-d\zeta/dt)$:

$$t_{k,2} = ((2n-1)/(kn))^{(1/n)} \\ \zeta_{k,2} = \zeta(0) \cdot \text{EXP}((1-2n)/n)$$

From this can be deducible that the critical time depends only on drying coefficients k and n , and that moisture content of porous material in each critical point depends on initial moisture content and drying coefficient n .

This model is used for mathematical description of microwave drying kinetics of clay plate (Tomas, 1993; Tomas and Skansi, 1994; Skansi and Tomas, 1995).

Fig. 4 The approximation of drying kinetics of carrot in fluidized bed with model (5)

Fig. 5 The approximation of drying kinetics of pea in fluidized bed with model (5)

1. Experimental

The chosen model was used for describing kinetics of barley, malt, carrot and pea in fluidized bed with vibrating screen (Figure 1) and drying of plum in deep fixed bed. The experimental data for barley, malt, carrot and pea which were dried in fluidized bed with vibrating screen were taken from reference (Mesaroš, 1997) and the experimental data for plum dried in deep fixed bed were taken from reference (Techasena *et al.*, 1991).

The function parameters a , k and n were determined using least square method. The correlation index (ρ) and the mean square deviation (σ) were used as a criteria which show how good the experimental data fit on with chosen mathematical model.

2. Results

The results obtained using numerical regression method for approximation experimental data with eq. (5) are shown in Table 1 and in Figures 2-6.

The results show good agreement between experimental data and chosen mathematical model. This can be seen from very high values of correlation index, which are between 0.9926 and 0.9993, and from very low values of mean square deviation with regard to moisture content of drying matter.

Another good side of chosen model is that it gives good results regardless of in which period of drying (only period of decreasing drying rate (Figs. 2, 3 and 5) or in both drying periods (Figs. 1 and 4)) process is rolling on.

Fig. 6 The approximation of drying kinetics of plum in deep fixed bed with model (5)

Conclusion

From all these results follow that the mathematical model

$$\zeta(t) = \zeta(0) \cdot \text{EXP}(-kt^n)$$

$$(-d\zeta/dt) = kn t^{(n-1)} \cdot \zeta(t),$$

can be used for a description of kinetics of whole convective drying process of barley, malt, carrot and pea in fluidized bed with vibrating screen and drying of plum in deep fixed bed. The simple mathematical description of kinetics of whole process which is contained in a single equation, as well as physical and phenomenological meaning of its parameters are a good basis for optimal process control.

Furthermore, the application of this mathematical model for description and analysis of drying kinetics could be recommended.

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Notation

A	= amplitude of the vibrating screen, mm
a, k, n	= parameters in model (5)
c_p	= specific heat at constant pressure, $\text{J kg}^{-1} \text{K}^{-1}$
f	= frequency, Hz
h_0	= height of the fixed bed, mm
H	= absolute humidity of air, $\text{kg}_w \text{kg}_{da}^{-1}$
K_1, K_2	= first and second critical point
t	= time, min, h
T_g	= air temperature, °C
T_s	= temperature of drying matter, °C
v	= speed of air flow, $\text{m} \cdot \text{s}^{-1}$
ζ	= moisture content in drying matter, $\text{kg}_w \text{kg}_{sm}^{-1}$
$(-d\zeta/dt)$	= drying rate, $\text{kg}_w \text{kg}_{sm}^{-1} \text{h}^{-1}$
ρ	= correlation index
σ	= density, kg m^{-3}
σ	= mean square deviation
ϕ	= relative humidity, %
$\dot{q}$	= heat flux, W m^{-2}
$\dot{m}$	= mass flux, $\text{kg m}^{-2} \text{s}^{-1}$

Subscripts

a	= air
da	= dry air
ha	= humid air
k	= final
$K, 1$	= first critical point
$K, 2$	= second critical point

max	=	maximum
s	=	solid
sm	=	solid matter
w	=	water
wv	=	water vapour

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