Kinetics of potato drying using fluidized bed dryer

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Abstract The effect of air temperature and two different shapes (cuboidal and cylindrical) with 3 aspect ratio of each shape on the drying kinetics of potato (*Solanum tuberosum*) in fluidized bed dryer was investigated. Drying was carried out at 50, 60 and 70°C at 7 m/s air velocity. Drying data were analysed to obtain effective diffusivity of moisture transfer. During drying moisture transfer from potato were described by Fick's diffusion model. Two mathematical models were fitted to experimental data. The Page model gave better fit than simple exponential model. The Arrhenious activation energy value expresses the effect of temperature on diffusivity.

Keywords Potato · Fluidised bed drying · Cuboidal and cylindrical shape · Aspect ratio · Diffusivity · Activation energy

The popular potato products are potato chips, potato powder, potato flakes and potato granule. Potato granules are used for preparation of different variety of crispy food products like *namkeen*, *bhujia*, soup curry and snack foods. It can be used for making sweetened food. Few organized and several private sectors produce potato granules with other processed food products. It is necessary to dry the product with minimum cost, energy and time. In

fluidized bed drying, drying time is shortened due to intensive heat and mass transfer between drying air and particles being dried and overheating is prevented (Giner and Calvelo 1987). The drying of vegetables in a fluidized bed dryer produces dry vegetable pieces of excellent quality in a much shorter time than in continuous belt dryers (Bobic and Bauman 2002).

During drying, shapes and sizes of food particulates constantly change as a result of water removal and moisture diffusion from particulates. The knowledge of changes in shape and size during fluidized bed drying is very much required for designing of processing, drying, handling and packaging equipments for food industry. Even though, considerable work is done on drying of various fruits and vegetables, the information on drying kinetics of vegetables is scanty, particularly for potato shapes. Drying is affected by nature of product, type of dryer, parameters of drying kinetics such as moisture ratio, temperature, air velocity, drying rate, drying constant as moisture diffusivity. The moisture migration during this period is controlled by diffusion. The rate of moisture movement is described by an effective diffusivity. So it is necessary to study the effect of shapes and effect of temperature on drying kinetics.

Therefore the present investigation was undertaken to study the effect of product shape on drying kinetics of potato particulates drying behaviour with the help of models and to estimate the Arrhenious activation energy during potato drying.

Modeling

The empirical model and Page's model were used to investigate the effect of shapes and their aspect ratio on drying characteristic of food. The basic model is known

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as the simple (exponential) model and is as follows (Noomborn and Verma 1986; Pathak et al. 1991).

$$MR = e^{(-k_s t)} \quad (1)$$

where, MR = Moisture ratio, K_s = drying constant and t = time

Page model is applied to overcome the shortcomings of a simple exponential model with an empirical modification to the time term by introducing a exponent 'n'; (Madamba et al. 1996).

$$MR = e^{(-k_p t^n)} \quad (2)$$

where, K_p = Drying constant in Page model.

The moisture and/or vapour migration during this period is controlled by diffusion. The rate of moisture movement is described by an effective diffusivity a lumped value. Fick's second law of diffusion is used to describe a moisture diffusion process.

The diffusion equation of potato particulates for cuboidal shape (Senadeera et al. 2005) is:

$$MR = \frac{M - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} \frac{4}{\beta_n^2} \exp \left[-\frac{\beta_n^2 D_{eff}}{r_c^2} \right] = \frac{8}{\Pi^2} \exp \left[-\frac{\Pi^2 D_{eff} t}{L^2} \right] \quad (3)$$

Table 1 Drying conditions and drying time for potatoes of different shapes

Aspect ratio	Air temp oC	Drying time, h
Cuboidal shape		
1:1	50	1.66
	60	1.63
	70	1.5
1:2	50	1.7
	60	1.65
	70	1.5
1:3	50	1.75
	60	1.68
	70	1.51
Cylindrical shape		
1:1	50	1.66
	60	1.65
	70	1.51
1:2	50	1.71
	60	1.65
	70	1.53
1:3	50	1.75
	60	1.7
	70	1.5

The diffusion equation of potato particulates for cylindrical shape (Senadeera et al. 2005) is:

$$MR = \frac{M - M_e}{M - M_0} = \frac{8}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp \left[-(2n-1)^2 \frac{\Pi^2 D_{eff} t}{L^2} \right] = \frac{4}{\beta_1^2} \exp \left[-\frac{\Pi^2 D_{eff} t}{r_c^2} \right] \quad (4)$$

where, MR = Moisture ratio,

M Final moisture content (% db), M_0 = Initial moisture content (%db)

M_e Equilibrium coefficient (m^2/s), β = Roots of Bessel moisture content (%)

D_{eff} Diffusion function, L = Slab thickness (mm), n = Positive integer, r_c = Cylindrical ratio, t = Time (h)

A general form of equation can be written in logarithmic form as

$$\ln MR = A - Bt \quad (5)$$

where, A = constant and B = constant is $\Pi^2 D_{eff}/L^2$ for cuboidal and $\beta_1^2 D_{eff}/r_c^2$ for cylindrical shape.

The dependence of drying constants k_s and k_p of two models was evaluated using Arrhenius type equation as given below

$$k = k_0 \exp \left[\frac{-E_a}{R(T + 273.15)} \right] \quad (6)$$

where, K = Drying constant (h^{-1}), k_0 = Reference value of drying constant (h^{-1}),

E_a Energy activation (kJ/mol), R = Universal gas constant (Joule/mol.K) and

T Absolute temperature (K),

Parameters k_0 and E_a were estimated using $\ln k$ and $1/K$.

Material and methods

The drying fluidized bed drying of potato (*Solanum tuberosum*) particulates were investigated in fluidized bed dryer (FBD) installed in the Department of Processing and Food Engineering, College of Technology and Engineering, MPUAT, Udaipur. The table top FBD (Model HE-75 Sherwood Scientific Ltd, Cambridge, England) was used for the study. The FBD used was simple, compact, portable and easy to operate. The cabinet contained the air distribution system and electrical controls. Air was drawn

Fig. 1 Drying curves of moisture content with drying time at different temperature (Aspect ratio 1:1)

in through a mesh filter provided at the base of the cabinet and blown by the centrifugal fan over a 2 kW electrical heater. The tube unit consisted of a container with a fine mesh distributor and stainless steel support. A filter bag, which fitted over the top of the tube, retained any particles expelled from the fluidized bed. The FBD had PID controller of the range of 0–200 °C; which regulated the operation of the heater to maintain desired preset temperature of drying air. The batch size of potato particulates used for drying was 430–500 g/h.

Air flow rate of 7 m/s was measured using anemometer. The samples were dried in the perforated cylindrical chamber with variable diameter. The air was circulated by variable speed blower and heated by electricity. Potatoes procured from local market were washed under tap water, peeled and cut into different dimensions and shapes i.e. cuboidal as well as cylindrical. The cuboidal shape potatoes were cut into dimensions of (5×5×5 mm), (5×5×10 mm) and (5×5×15 mm) i.e. having aspect ratio of 1:1, 1:2 and 1:3, respectively. The cylindrical shaped pieces had dimensions of 5×5 mm, 5×10 mm and 5×15 mm to have

diameter to length ratio of 1:1, 1:2, 1:3, respectively. Three batches of potatoes were prepared for each shape (cuboidal and cylindrical) and each ratio (1:1, 1:2, 1:3). The drying temperatures used were 50, 60 and 70 °C at 7 m/s air velocity.

Immediately after cutting, potatoes were immersed in a sodium meta-bi-sulphite solution (0.1% w/w) for 15 min to prevent browning during drying. After that, cut potatoes were drained on a mesh tray and kept in a cold room at 4 °C for 24 h to equilibrate the moisture content. The initial moisture content of potatoes was determined by using vacuum oven (70 °C, 13.3 kPa) according to AOAC (2002) method. The drying of potato particulates were finalized when the moisture content decreased to 6% from an initial 80.7%. The dried cooled product was kept in air tight glass jars.

Statistical analysis The values of drying parameters for three replications were taken for statistical analysis. Analysis of variance (ANOVA) was carried on to study the effect of temperature and shape on moisture diffusivity (Madamba et al. 1996).

Fig. 2 Drying curves of moisture ratio (MR) with drying time at different temperature (Aspect ratio 1:1)

Table 2 Effective diffusivity and regression coefficient values

Shape	Drying temp, °C	Drying time, h	Regression equation	Moisture diffusivity, m ² /s	R ²
Cuboidal					
1:1	50	1.66	$y = -0.0036x + 0.014$	2.277×10^{-09}	0.98
	60	1.63	$y = -0.0043x + 0.013$	2.721×10^{-09}	0.99
	70	1.5	$y = -0.005x + 0.020$	3.165×10^{-09}	0.99
1:2	50	1.7	$y = -0.0034x + 0.016$	5.612×10^{-09}	0.97
	60	1.65	$y = -0.0040x + 0.027$	1.013×10^{-08}	0.99
	70	1.5	$y = -0.0052x + 0.028$	1.317×10^{-08}	0.99
1:3	50	1.75	$y = -0.0032x + 0.01$	1.824×10^{-08}	0.99
	60	1.68	$y = -0.0041x + 0.019$	2.337×10^{-08}	0.98
	70	1.51	$y = -0.0055x + 0.035$	3.314×10^{-08}	0.98
Cylindrical					
1:1	50	1.66	$y = -0.0036x + 0.71$	2.277×10^{-09}	0.99
	60	1.65	$y = -0.0047x + 0.070$	2.295×10^{-09}	0.99
	70	1.51	$y = -0.005x + 0.042$	3.418×10^{-09}	0.97
1:2	50	1.71	$y = -0.0033x + 0.016$	5.358×10^{-09}	0.98
	60	1.65	$y = -0.0044x + 0.014$	1.114×10^{-08}	0.99
	70	1.53	$y = -0.0050x + 0.013$	1.266×10^{-08}	0.97
1:3	50	1.75	$y = -0.0033x + 0.016$	1.880×10^{-08}	0.99
	60	1.7	$y = -0.0041x + 0.015$	2.336×10^{-08}	0.99
	70	1.5	$y = -0.0044x + 0.036$	2.507×10^{-08}	0.99

$y = \ln MR$, dimensionless; $x = \text{drying air temperature, } ^\circ\text{C}$, Shapes: As in text

Results and discussion

Drying curves The drying times according to the experimental conditions selected are presented in Table 1. The drying curves of moisture content versus drying time for drying of potato cuboidal and cylindrical particulates for aspect 1:1 ratio at 50, 60 and 70 °C are presented in Fig. 1. Similar trend was found for other aspect ratio of cuboidal as well as cylindrical shape of potato particulates. In general, time required to reduce moisture content to any given level was dependant on drying conditions, being highest at 50 °C and lowest at 70 °C irrespective of product shape and its aspect ratio. As ratio increased from 1:1 to 1:3 at given air

temperature the drying time also increased for both cuboidal and cylindrical shaped potatoes. The effect of shape on drying time was not significant.

Moisture diffusivity and activation energy The variation in moisture diffusivity with moisture content is a complex and system specific function. The effective moisture diffusivity (D_{eff}) of a food material characterizes its intrinsic mass transport property of moisture which includes molecular diffusion, liquid diffusion, vapour diffusion, hydrodynamic flow and other possible transport mechanisms (Crank 1975). The moisture loss data during fluidized bed drying were analysed and moisture ratios at every 15 min interval

Table 3 Activation energy E_a (kJ/mol) for different shapes of potato particulates drying using experimental data and values from model

Aspect ratio	Experimental value		Exponential model		Page's model	
	$D_0 \times 10^{-09}$	E_a	K_0	E_a	K_0	E_a
Cuboidal						
1:1	2.30	24.17	401	16.19	580	18.12
1:2	2.32	19.95	440	19.20	610	20.86
1:3	2.36	18.96	490	21.28	640	22.69
Cylindrical						
1:1	2.25	22.36	405	12.80	490	11.97
1:2	2.23	20.60	443	19.20	555	21.86
1:3	2.28	16.04	460	19.78	590	21.28

Table 4 Regression analysis for constants and coefficients for Exponential and Page model

Aspect ratio	Exponential model				Page model			
	Temp, °C	k_s , h^{-1}	R^2	MAE, %	n	k_p , h^{-1}	R^2	MAE, (%)
Cuboidal								
1:1	50	0.818	0.99	14.9	1.51	2.092	0.99	14.7
	60	2.331	0.99	13.8	1.47	2.482	0.97	13.5
	70	2.631	0.98	14.7	1.44	2.923	0.99	14.6
1:2	50	1.702	0.97	14.8	1.49	1.946	0.99	9.4
	60	2.139	0.99	13.7	1.43	2.465	0.99	11.9
	70	2.612	0.98	14.9	1.42	2.881	0.98	9.8
1:3	50	1.640	0.99	15.1	1.47	1.838	0.97	10.3
	60	2.083	0.97	14.9	1.41	2.360	0.99	18.7
	70	2.611	0.99	13.8	1.38	2.839	0.98	23.2
Cylindrical								
1:1	50	2.035	0.97	14.7	1.4	2.293	0.98	14.5
	60	2.340	0.99	13.2	1.33	2.476	0.98	12.9
	70	2.600	0.99	14.4	1.29	2.691	0.98	13.8
1:2	50	1.745	0.96	10.8	1.39	1.971	0.97	8.3
	60	2.230	0.98	12.9	1.31	2.386	0.98	10.8
	70	2.729	0.97	14.0	1.28	2.523	0.98	8.76
1:3	50	1.689	0.96	18.8	1.38	1.772	0.98	9.10
	60	2.201	0.98	13.7	1.31	2.493	0.97	18.4
	70	2.610	0.98	20.0	1.25	2.645	0.98	21.2

were calculated. The plot of $\ln MR$ versus drying time give a straight line with negative slope and the slope became steeper with increase in drying air temperature Fig. 2. Moisture diffusivities were calculated from the slopes of these straight lines using Eqs. 3 and 4. The coefficient of regressions of linear relationship and moisture diffusivities evaluated for various process conditions are given in Table 2.

For all aspect ratios of cuboidal and cylindrical potato, moisture diffusivity increased with increase in temperature as also observed by Afzal and Abe (1998) during infrared drying of potato. This is because the product temperature

increased with increase in drying air temperature and moisture diffusion is an internal process which very much depends on product temperature (Singh and Heldman 1984). Shape and temperature had significant ($p \leq 0.05$) effect on moisture diffusivity.

The activation energy from moisture diffusivity of drying data was calculated, using Arrhenius type Eq. 6 with replacement of reference value of drying constant k_0 with coefficient of diffusivity (D_0) and the values were presented in Table 3. Activation energy decreased with increase in aspect ratio for both cuboidal and cylindrical shapes.

Fig. 3 Comparison of experimental and calculated moisture ratio of potato particulates (Aspect ratio=1:1) at 50 °C

Modeling of drying behaviour of potato In order to determine the moisture content as function of drying time, a simple (exponential) and Page model using Marquardt method of non-linear regression procedure in SY-Stat were initially fitted. For adequacy of model fit coefficient of determination (R^2) and mean absolute error percentage, (MAE %) (Rosello et al. 1997; Madamba et al. 1996; Noomborn and Verma 1986; Palipane and Driscoll 1994) were calculated and presented in Table 4. The moisture ratio versus drying time was plotted as shown in Fig. 3. The coefficient of determination (R^2) and MAE % was determined using non-linear regression analysis of software SAS (1985) 12.0 version.

Temperature affected the drying constant in exponential (k_s) and Page model (k_p). The drying constant in exponential (k_s) and Page model (k_p) increased with increase in drying temperature for all aspect ratios. The k_s increased from 0.818 to 2.631 h^{-1} as air temperature increased from 50 to 70 °C for cuboidal shaped potato (aspect ratio =1:1). The k_p increased from 2.092 to 2.923 h^{-1} , for cylindrical shaped (aspect ratio =1:1) potato for the same increase in temperature. Similar results were found for other aspect ratios as well. For both exponential and Page models, the highest value of drying constant k_p and k_s were observed as 2.923 h^{-1} and 2.729 h^{-1} , respectively. Temperature had more pronounced effect on Page model. The value of 'n' in the Page model was non significant ($p>0.05$) with temperature for cuboidal as well as cylindrical shape. Page model gave better fit than simple (exponential) model, when the values of R^2 and MAE % were compared. Energy activation values estimated from diffusivity data were very close to energy activation values from drying kinetics data.

Conclusion

The moisture content in potato decreased with increase in drying air temperature for cuboidal as well as cylindrical shaped potato. The fluidised bed drying of potato took place in the falling drying rate period. The drying rate

decreased with decrease in moisture content of potato at different air temperatures for both the shapes of potato. The moisture diffusion coefficient increased with increase in thickness of sample. The moisture diffusivity increased with increase in drying air temperature for both the shapes of potato. Drying constants in exponential and Page models increased with increase in air temperature. As aspect ratio and diameter to length ratio ratio increased, drying constants in exponential and Page models decreased due to higher surface area per unit volume. Page model gave better fit than simple (exponential) model for the fluidized bed drying conditions under study. Energy activation values estimated from diffusivity data were very close to energy activation values from drying kinetics data.

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