AGRICULTURAL AND FOOD SCIENCE

Vol. 19 (2010): 127–135.

Drying characteristics and kinetics of fluidized bed dried potato

Sushant B. Bakal[1*], Kishor H. Gedam[1] and Gyanendra Prakash Sharma[2]

[1]*CRDT, Indian Institute of Technology, New Delhi – 110016, India*
[2]*Department of Processing & Food Engineering, CTAE, Maharana Pratap University of Agriculture and Technology, Udaipur – 313001 (Raj), India.*
** e-mail: sbbakal@yahoo.co.in*

In developed countries, more than 50% potatoes are consumed as processed products. As drying is the vital phenomenon in processing, it is necessary to investigate the drying characteristics and its kinetics. In this experimental study, drying kinetics of potato in two different shape of cuboidal and cylindrical with three aspect ratio was investigated as a function of drying conditions. Experiments were conducted using air temperatures of 50, 60 and 70 °C, at velocity of 7 ms^{-1}. The experimental moisture data were fitted to Page and Simple models, and a good agreement was observed. The Page model gave better fit than Simple exponential model. In the ranges covered, the values of the effective moisture diffusivity, D_{eff} were obtained between 2.278×10^{-9} to 3.314×10^{-8} m^2s^{-1} from the Fick's diffusion model. Using $D_{eff,}$ the value of activation energy (E_a) was determined assuming the Arrhenius-type temperature relationship.

Key-words: Cuboidal and cylindrical shape, Aspect ratio, drying kinetics, Page's and Simple Model

Introduction

The potato (*Solanum tuberosum*) is an important food crop of the solanaceae family commonly grown for its starchy tuber. It is a grown in about 150 countries throughout the world. India is the third largest country in world in production of potato, after China and Russian Federation. It is produced on an area of 1.4 million hectare having production of 25 million tonnes with productivity 17.86 per hectare in 2006.

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Manuscript received January 2009

Potato is a widely used vegetable in all over the world as food item. Modern food technologists have developed variety of food products which are manufactured from potato. The popular potato products are potato chips, potato powder, potato flakes, potato granules, etc. Potato granules are used for preparation of different variety of crispy food products like namkeen, bhujiya, soup curry and snack foods. It can be used for making sweetened food. There are few organised and several private sectors engaged to produce potato granules with other processed food products. The demand is increasing day by day due to population growth and food habit changes by man due to fast life. The new entrepreneur may enter in this field with other types of food and processed items.

Drying is one of the oldest methods of food preservation and it represents a very important aspect of food processing. Hot air drying is the most common method used to preserve the agricultural products in most of the tropical countries. However this technique is extremely weather dependent and has problem of contamination with dust, soil, insects etc. and also drying time required is quite long. The keeping quality of potato slices can be enhanced by drying adequately and with subsequent proper packaging.

The cost of dried product depends on the drying process. Therefore it is necessary to dry the product with minimum cost, energy and time. Fluidized bed drying, due to intensive heat and mass transfer between the drying air and particles being dried, results in shortening of the drying time. Among various drying methods, fluidized bed drying is very convenient method for heat sensitive food materials as it prevents these products from overheating due to uniform heat transfer quality (Giner and Cavelo 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 2002).

Though, there is a lot of work done on the drying of fruits and vegetables, but the information is scanty on the drying kinetics of vegetables particularly on potato. Therefore the present investigation was undertaken to study the effect of product shape on drying kinetics of potato particulates, to study the drying behaviour with the help of models and to estimate the Arrhenius activation energy during potato drying.

Material and methods

The fluidized bed drying of potato particulates were investigated in fluidized bed dryer installed in the Department of Processing and Food Engineering, College of Technology and Engineering, MPUAT, Udaipur. The table top fluidized bed dryer as shown in Figure 1 (Make Sherwood Scientific Ltd. Cambridge, England) was used in present study. The dryer consists of centrifugal blower to supply air, an electric heater and an air filter. The air temperature was controlled by means of proportional controller. An air flow rate of 7 m s^{-1} as measured with an anemometer, was used during the experiments. The samples were dried in the perforated cylindrical

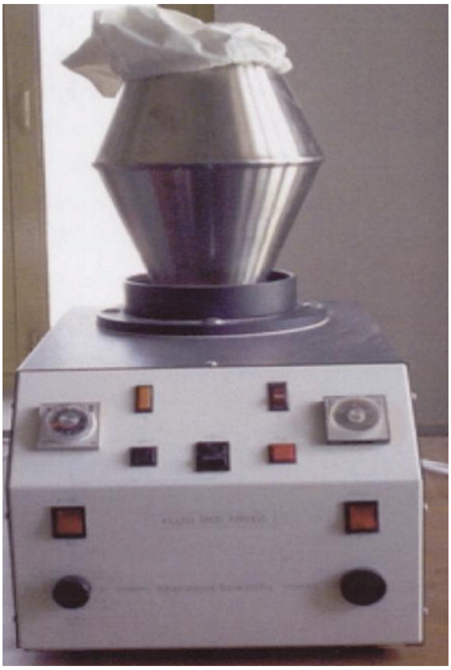

Fig. 1. Fluidized Bed Dryer

chamber. The air was circulated by variable speed blower and heated by electricity. Potatoes procured from the local market were used in the studies. At the start of each experiment, potatoes were washed under tap water, peeled and cut into cuboidal with aspect ratio (area:lenght, A:L ratio) of 1:1 (5 mm × 5 mm × 5mm), 1:2 (5 mm × 5 mm × 10 mm) and 1:3 (5 mm × 5 mm × 15 mm) and cylindrical shape with aspect ratio (diameter:lenght, D:L ratio) as 1:1 (5 mm × 5 mm), 1:2 (5 mm × 10 mm) and 1:3 (5 mm × 15 mm) using sharp stainless steel knife. Three batches of potatoes were prepared for each shape (cuboidal and cylindrical) and each ratio (1:1, 1:2, 1:3). Three drying temperatures such as 50 °C, 60 °C and 70 °C were used at 7 ms^{-1} air velocity.

The potato samples were immersed, immediately after cutting in a sodium metabisulphite solution (0.1% w/w) for 15 min to prevent browning which may otherwise take place 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 according to AOAC (1995) method. The 10 g potato particulates were weighted with an electric balance (±0.001g), for moisture determination and kept in the vacuum oven at 70 °C and 13.3 kPa. After that potato particulates were transferred from the vacuum oven to the desiccators (containing silica) to cool. Moisture content was determined as the loss in weight of the potato particulates. The drying of potato particulates were finalized when the moisture content decreased to 6% from an initial value of 80.7% wet basis (wb) (400% dry basis). The product was cooled for 10 minutes after drying and kept in air glass jars.

Modeling

The Simple 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 as the Simple model and is as follows

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

where,

MR = Moisture ratio
k_s = drying constant for Simple model
t = time

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

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

where,

k_p = drying constant for Page model.

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

The diffusion equation of potato particulates for cuboidal shape

$$MR = \left[\frac{M - M_e}{M_0 - M_e}\right] = \sum_{n=1}^{\infty} \frac{4}{\beta_n^2} \exp\left[-\frac{\beta_n^2 D_{eff}}{r_c^2}\right]$$

$$= \frac{8}{\Pi^2} \exp\left[-\frac{\Pi^2 D_{eff} t}{L^2}\right] \tag{3}$$

The diffusion equation of potato particulates for cylindrical shape

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

$$= \frac{4}{\beta_1^2} \exp\left[-\frac{\Pi^2 D_{eff} t}{r_c^2}\right] \tag{4}$$

where,

MR = Moisture ratio
M = Final moisture content (% db)
M_0 = Initial moisture content (% db)
M_e = Equilibrium moisture content (% db)
β = Roots of Bessel moisture content
D_{eff} = Diffusion function (m^2s^{-1})
L = Slab thickness (mm)
n = Positive integer

r_c = Cylindrical radius
t = Time (h)

A general form of equation can be written in logarithmic form

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

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

The dependence of drying constants for Simple (k_s) and Page's (k_p) model of the two models was evaluated, using Arrhenius type equation as given below

$$K = K_0 \exp\left[\frac{-E_a}{RT}\right] \qquad (6)$$

where,
K = Drying constant, h^{-1}
k_0 = Reference value of drying constant, h^{-1}
E_a = Energy activation, kJ mol^{-1}
R = Universal gas constant, J $mol^{-1}K^{-1}$
T = Absolute temperature, K

Parameters k_0 and E_a were estimated using drying constant and its reference value, respectively.

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 ratio 1:1 at temperatures (50 °C, 60 °C and 70 °C) were presented in Figure 2 and 3**.** Similar trend was found for other aspect ratios 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, 1.66 h at 50 °C and lowest 1.5 h at 70 °C irrespective of product shape and its aspect ratio. It was observed, for cuboidal shape of potato, that when aspect ratio increased from 1:1 to 1:3 at given air temperature, the drying time also increased. A similar trend for increase in drying time was also observed for cylindrical shaped potato. The effect of shape on drying time was not significant as per the ANOVA carried out.

Table 1. Observations of drying conditions and drying time

Cuboidal shape			Cylindrical shape		
A:L[1]	Air temperature (°C)	Drying time (h)	D:L[2]	Air temperature (°C)	Drying time (h)
1:1	50	1.66	1:1	50	1.66
	60	1.63		60	1.65
	70	1.5		70	1.51
1:2	50	1.7	1:2	50	1.71
	60	1.65		60	1.65
	70	1.5		70	1.53
1:3	50	1.75	1:3	50	1.75
	60	1.68		60	1.7
	70	1.51		70	1.5

[1] Aspect ratio A:L = area: length ratio, 1:1 = 5 mm × 5 mm × 5mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.

[2] Aspect ratio D:L = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm) and 1:3 = 5 mm × 15 mm.

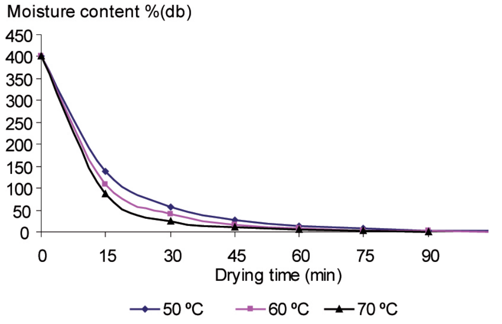

Fig. 2. Drying curves of moisture content with drying time at different temperature (Cuboidal shape with aspect ratio 1:1.)

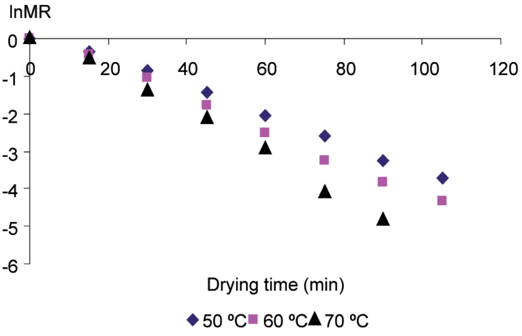

Fig. 4. Drying curves of moisture ratio (MR) with drying time at different temperature (Cuboidal shape with aspect ratio 1:1).

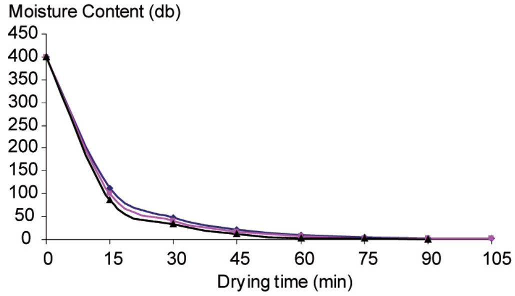

Fig. 3. Drying curves of moisture content with drying time at different temperature (Cylindrical shape with aspect ratio 1:1).

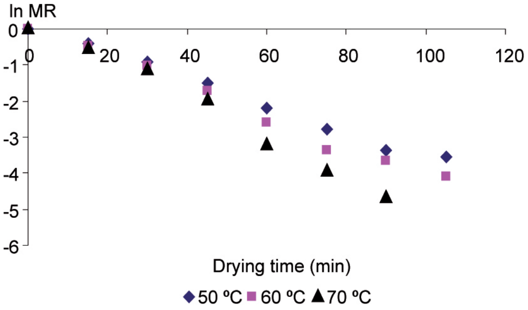

Fig. 5 Drying curves of moisture ratio (MR) with drying time at different temperature (Cylindrical shape with aspect ratio 1:1).

The drying curves of moisture ratio versus drying time for drying of potato cuboidal and cylindrical particulates for aspect ratio 1:1 at temperatures (50 °C, 60 °C and 70 °C) were presented in Figure 4 and 5. From the plot of MR versus drying time gives straight line with negative slope. The slope became steeper with increase in drying air temperature.

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 analyzed and moisture ratio at every 15 minute interval was calculated. From the plot of MR versus drying time gives straight line with negative slope. The slope became steeper with increase in drying air temperature. Moisture diffusivities were calculated from the slopes of these straight lines using Eq. 3 and 4. The coefficient of determination and moisture diffusivities evaluated for various process conditions are given in Table 3.

For cuboidal shape of potato having A:L 1:1, the moisture diffusivity increased from 2.27 × 10^{-9} to 3.165 × 10^{-9} m^2s^{-1} as the drying air temperature increased from 50 °C to 70 °C. Similar values of moisture diffusivities have been reported by some researchers for the food products (Madamba et al. 1996, Pinthus et al. 1997, Senadeera et al. 2003, McMinn et al. 2003, Odilio et al. 2004, Charles et al. 2005). For all aspect ratios of cuboidal potato, moisture diffusivity increased with increase in temperature. This is because the product temperature increased with increased in drying air temperature and moisture diffusion is an internal process which very much depends on product temperature (Singh and Heldman 2004).

ANOVA was carried on to study the effect of temperature and shape on moisture diffusivity. It was inferred from the ANOVA that shape and temperature had significant effect on moisture diffusivity at 5% level of confidence.

Moisture diffusivities were calculated from the slopes of these straight lines using Eq. 3 and 4. The coefficient of determination and moisture diffusivities evaluated for various process conditions are given in Table 3. The activation energy from moisture diffusivity of the drying data was calculated, using Arrhenius type Eq. 6 with replacement of the Reference value of drying constant k_0 with coefficient of diffusivity (D_0) and their values were presented in Table 4.

Modeling of drying behaviour of potato

In order to determine the moisture content as function of drying time, a Simple 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

Table 2. Regression analysis for constants and coefficients for simple and Page model.

Shape		Simple model			Page model			
	Temperature (°C)	k_s (h^{-1})	R^2	MAE (%)	n	k_p (h^{-1})	R^2	MAE (%)
Cuboidal								
A:L[1] = 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
A:L = 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
A:L = 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								
D:L[2] = 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
D:L = 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
D:L = 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

k_s = drying constant for Simple model, k_p = drying constant for Page's model, MAE = Mean absolute error temperature, n = constant.

[1] A:L = area: length ratio, 1:1 = 5 mm × 5 mm × 5mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.

[2] D:L = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm) and 1:3 = 5 mm × 15 mm.

Table 3. Effective diffusivity and regression coefficient values

Shape	Drying temperature (°C)	Regression equation	Moisture diffusivity (m^2s^{-1})	Coefficient of Determination R^2
Cuboidal				
A:L[1] = 1:1	50	y = -0.0036x + 0.014	2.277×10^{-9}	0.98
	60	y = -0.0043x + 0.013	2.721×10^{-9}	0.99
	70	y = -0.005x + 0.020	3.165×10^{-9}	0.99
A:L = 1:2	50	y = -0.0034x + 0.016	5.612×10^{-9}	0.97
	60	y = -0.0040x + 0.027	1.013×10^{-8}	0.99
	70	y = -0.0052x + 0.028	1.317×10^{-8}	0.99
A:L = 1:3	50	y = -0.0032x + 0.01	1.824×10^{-8}	0.99
	60	y = -0.0041x + 0.019	2.337×10^{-8}	0.98
	70	y = -0.0055x + 0.035	3.314×10^{-8}	0.98
Cylindrical				
D:L[2] = 1:1	50	y = -0.0036x + 0.71	2.277×10^{-9}	0.99
	60	y = -0.0047x + 0.070	2.295×10^{-9}	0.99
	70	y = -0.005x + 0.042	3.418×10^{-9}	0.97
D:L = 1:2	50	y = -0.0033x + 0.016	5.358×10^{-9}	0.98
	60	y = -0.0044x + 0.014	1.114×10^{-8}	0.99
	70	y = -0.0050x + 0.013	1.266×10^{-8}	0.97
D:L = 1:3	50	y = -0.0033x + 0.016	1.880×10^{-8}	0.99
	60	y = -0.0041x + 0.015	2.336×10^{-8}	0.99
	70	y = -0.0044x + 0.036	2.507×10^{-8}	0.99

y = In MR, dimensionless; x = drying air temperature, ºC; MR = Moisture ratio.

[1] A:L = area: length ratio, 1:1 = 5 mm × 5 mm × 5mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.

[2] D:L = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm) and 1:3 = 5 mm × 15 mm.

Table 4. Activation Energy ($E_{a)}$) for different shapes of potato particulates drying using Experimental data and the values from model

Shape	Aspect Ratio	Experimental value		Simple model		Page's model	
		$D_0 \times 10^{-9}$	E_a kJ mol^{-1}	k_0	E_a kJ mol^{-1}	k_0	E_a kJ mol^{-1}
Cuboidal							
	A:L[1] = 1:1	2.30	24.17	401	16.19	580	18.12
	A:L = 1:2	2.32	19.95	440	19.20	610	20.86
	A:L = 1:3	2.36	18.96	490	21.28	640	22.69
Cylindrical							
	D:L[2] = 1:1	2.25	22.36	405	12.80	490	11.97
	D:L = 1:2	2.23	20.60	443	19.20	555	21.86
	D:L = 1:3	2.28	16.04	460	19.78	590	21.28

D_0 = Coefficient of diffusion; k_0 = Reference value of drying constant; E_a = Energy activation.

[1] A:L = area: length ratio, 1:1 = 5 mm × 5 mm × 5mm, 1:2 = 5 mm × 5 mm × 10 mm and 1:3 = 5 mm × 5 mm × 15 mm.

[2] D:L = diameter: length, 1:1 = 5 mm × 5 mm, 1:2 = 5 mm × 10 mm) and 1:3 = 5 mm × 15 mm.

(R^2) and mean absolute error percentage (MAE, %) (Noomborn and Verma 1986, Palipane and Driscoll 1994, Madamba et al. 1996) were calculated and presented in Table 2. The MR versus drying time was plotted as shown in Figure. 6 and 7.

The drying constant in Simple (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 (A:L 1:1). The k_p increased from 2.092 to 2.923 h^{-1}, in case of cylindrical shaped (D:L 1:1) potato for same increase in temperature. Similar results were found for all A:L as well as D:L ratios. For both Simple 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}. The ANOVA carried out to study the effect of temperature of drying air on drying constant showed that temperature had more pronounced effect on Page model. The value of 'n' in the Page model was non significant ($p > 0.05$) with the temperature for cuboidal as well as cylindrical shape. Page model gave better fit than Simple model, when the values of R^2 and MAE compared.

The activation energy of the two models was calculated, using Arrhenius type Eq. 6 and their values were presented in Table 4. It was observed that the activation energy decreases with increases in AR for cuboidal as well as cylindrical shape.

Activation energy values estimated from diffusivity data were very close to activation energy values from drying kinetics data.

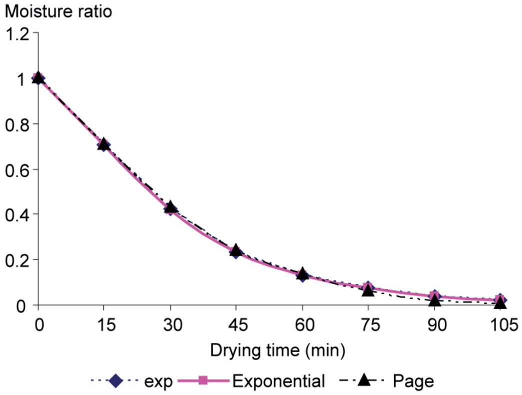

Fig. 6. Comparison of Experimental and calculated Moisture ratio of cuboidal shape potato particulates (AR = 1:1) at 50 °C.

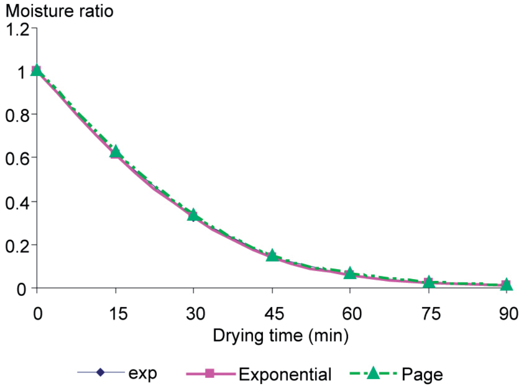

Fig.7. Comparison of Experimental and calculated Moisture ratio of cylindrical shape potato particulates (AR = 1:1) at 50 °C.

Conclusions

The effects of product shape on drying of potato particulates for fluidized bed drying were studied. The moisture content in potato decreased with increase in drying air temperature. Also when aspect ratio increased from 1:1 to 1:3 at given air temperature, the drying time increased for both cuboidal as well as for cylindrical shape of potato. The moisture diffusivity coefficient of potato particulates was in the range of 2.278×10^{-9} to 3.314×10^{-8} m^2s^{-1}. The moisture diffusion coefficient increased with increase in thickness of sample. Page model gave better fit than Simple model for the fluidized bed drying conditions under study. Activation energy values estimated from diffusivity data were very close to activation energy values from drying kinetics data.

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