# Modeling Some Drying Characteristics of High Moisture Potato Slices in Fixed, Semi Fluidized and Fluidized Bed Conditions

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## ABSTRACT

Drying properties of high moisture potato slices with initial moisture content of about 4.06 (db) under thin layer fixed, semi fluidized and fluidized bed conditions were studied. Drying air temperatures of 40, 50, 60 and 70°C were applied in experiments using a laboratory fluidized bed convective dryer. In order to predict the drying behavior of potato slices, seven thin layer drying models were applied from where finally Midilli *et al.* model was selected as the suitable one, based on comparative indices. Effective moisture diffusivity of the potato slices varied between $4.29\times10^{-9}$ and $15.70\times10^{-9}$ $m^2$ $s^{-1}$ for fixed and fluidized bed conditions, respectively. Moisture diffusivity values of the slices were increased as the drying air temperature levels increased. Activation energy values varied between 15.88 and 24.95 kJ $mol^{-1}$. Minimum and maximum values of activation energy were obtained at minimum fluidized and fixed bed conditions, respectively. Consumption of specific energy for thin layer drying of high moisture potato slices was obtained between $0.45\times10^5$ and $1.64\times10^5$ (kJ $kg^{-1}$). Increase in the drying air temperature in each bed condition caused increase in energy consumption. The maximum value of energy consumption was obtained at fluidized bed conditions.

Keywords: Drying, Diffusivity, Midilli model, Potato slices, Semi fluidized bed.

## INTRODUCTION

Dehydration is defined as moisture removal process during heat and mass transfer. Moisture transfer can occur in two forms, surface evaporation and internal liquid vapor diffusion (Meziane, 2011). Heat transfer rate depends on many such following factors: drying air temperature, air flow rate, air relative humidity, surface area of the agricultural and food material as well as the local or partial pressure. Moisture transfer rate is also governed by the physical properties of the food and agricultural material, applied temperature, moisture content as well as the material structure. The most popular form of energy transfer from a heat source to the food and to an agricultural material is through convection. In this method, heat transfer is directly conducted using a source of hot air flow.

Many investigators have studied the drying characteristics of potato and of different agricultural and food materials through thin layer drying. These include potato (Leeratanarak *et al.*, 2006; Hassini *et al.*, 2007; Bondaruk *et al.*, 2007; Wang *et al.*, 2010), candle nuts (Tarigan *et al.*, 2006), onion slices (Pathare and Sharma, 2006), azarole fruit (Koyuncu *et al.*, 2007), plums (Goyal *et al.*, 2007), broad beans (Hashemi *et al.*, 2009), milky mushroom (Arumuganathan *et al.*, 2009) as well as red beet slices (Kaleta and Górnicki, 2010).

Potato (*Solanum tuberosum*) has been widely cultivated in Iran with a production

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of about 4.7 million tons in 2008 (FAOSTAT, 2008). Due to high initial moisture content, the harvested potato is spoiled with micro-organisms injurious to human health, several weeks past harvest. Potato sun drying procedure takes time during which the crop could be contaminated by molds, dust, insects, and sand particles. To avoid these problems, quicker, safer, more uniform and controllable drying methods are needed (Gornicki and Kaleta, 2007; Krokida *et al.*, 2003). Fluidized bed drying could be an appropriate option in drying of potato slices.

Air fluidization process is defined as floating of a particulate in the current of an air flow. Air flow of a low flow rate forms a fixed bed condition. Gradual increasing of air flow rate, leads to creation of a minimum fluidized bed condition (semi fluidized bed). Following that a bubbling condition is created and then particulate materials start to be transported. Minimum fluidized bed, is a special point in fluidization process in which such particular characteristics, as, a maximum value of pressure drop, counterbalance of particles' weight and loss of the frictional force among particles occurs. Bubbling condition causes turbulence in movement of material particles. Pneumatic conveying of the particles occurs in the transportation stage (Kunii and Levenspiel, 1991; Brooker *et al.*, 1992; Karbassi and Mehdizadeh, 2008).

Theoretical, semi-theoretical and empirical models are employed to predict the drying time of food and agricultural products in a thin layer mode. Precise prediction of potato drying time is important to reduce the drying damage as well as the energy consumption, and to increase the drying capacity (Doymaz and Pala, 2002). Drying time of food and agricultural products is greatly affected by the material characteristics, air velocity and air temperature (Erenturk and Erenturk, 2007).

Effective moisture diffusivity, activation energy and specific energy consumption of food and agricultural products are important parameters for optimum design and application of a dryer (Kingsly *et al.*, 2007). Although much information has been reported regarding the modeling of drying kinetics, effective moisture diffusivity, activation energy and specific energy consumption for various food and agricultural products, but no published material is available concerning comparison of these drying parameters in fixed, semi fluidized and fluidized bed conditions as regards high moisture content potato slices.

The main goals of this study were to: (1) modeling the drying kinetics of high moisture potato slices under fixed, semi fluidized and fluidized bed condition of thin layer drying process (2) determination, and a comparison of the effective moisture diffusivity, activation energy and specific energy consumption values for high moisture potato slices during drying in different bed conditions (fixed, semi fluidized and fluidized bed) and in thin layer drying process (3) presentation of empirical models to describe the dependence between these factors and input parameters (air temperature and air velocity).

## MATERIALS AND METHODS

### Experimental Points

Three experimental points of drying were selected on the fluidization curve (Figure 1). Initially the pressure drop of potato slices was determined at different air flow velocities. Fan speed was gradually increased using an inverter (Vincker VSD2) and parameters of pressure drop *vs.* air velocity were recorded using a multifunction measurement device (Standard ST-8897). Net static pressure drop of the potato slices was recorded as the difference between total static pressure drop between potato cubes and bed plate.

About 40±1 g potato slices were used as sample for fluidization and drying experiments. Maximum value of static pressure drop (point B in Figure 1) in fluidization curve of potato slices is known
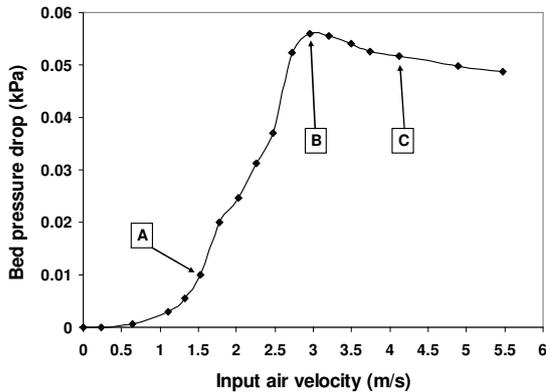
**Figure 1.** Fluidization curve of potato slices and selected points for modeling: (A) Fixed bed (1.53 m s$^{-1}$), (B) Semi fluidized bed (2.96 m s$^{-1}$) and (C) Fluidized bed (4.12 m s$^{-1}$).

as minimum fluidization point or semi fluidized bed (Kunii and Levenspiel, 1991). An experimental point in fixed bed domain was determined with air velocity of about 1.53 m s$^{-1}$ (point A in Figure 1). Also experimental point C with air velocity of about 4.12 m s$^{-1}$ was selected as the fluidized bed condition. All the drying experiments were conducted at these points.

**Drying Process Experimental Setup**

Fresh potato tubers (cv. *Agria*) were supplied from a local farm in Hamedan, Iran. The tubers were cut into slices with thicknesses of 3 mm. The slices were stored in a refrigerator at +4±1°C. Ambient air temperature and air relative humidity of laboratory room ranged from 24 to 29°C and 22 to 34%, respectively. The four parameters of inlet and outlet temperatures of the drying chamber, ambient air temperature and air relative humidity were recorded during the experiments. A laboratory fluidized bed dryer was employed in performing the drying experiments (Figure 2). Following turning on of the dryer, about 30 minutes was required for the dryer to reach the steady state. About 40±1 g potato slices were loaded into the dryer chamber and drying experiment started. Three bed conditions (fixed bed at 1.53 m s$^{-1}$, semi fluidized bed at 2.96 m s$^{-1}$ and

fluidized bed at 4.12 m s$^{-1}$) accompanied by four air temperatures of 40, 50, 60, and 70°C were applied in the drying experiments. In order to find out the moisture content of the potato samples during the drying process, weight of samples was initially measured. Through online weighing using a digital balance of 0.01 g accuracy and then
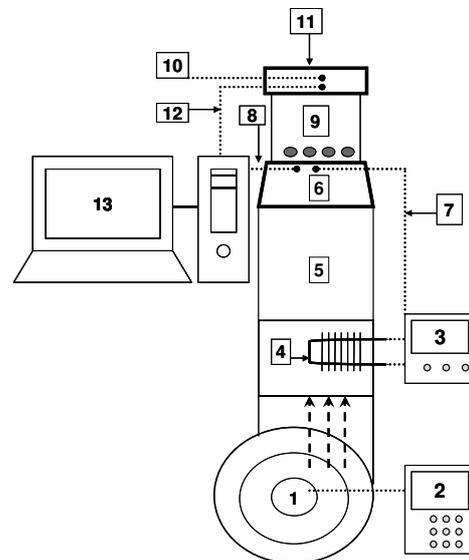


**Figure 2.** Schematic diagram of laboratory scale fluidized bed dryer: (1) Fan and electrical motor; (2) Inverter; (3) Thermostat; (4) Electrical heater; (5) Mixing chamber; (6) Diffuser; (7) Thermocouple; (8) Input air temperature recorder; (9) Drying chamber; (10) Air velocity sensor; (11) Chamber cap; (12) Outlet air temperature recorder; (13) Computer.

moisture content calculated. Initial and final moisture contents of potato samples were determined by gravimetric method at 70°C and after 24 hours (AOAC, 2002). Initial moisture content of the samples was about 4.06 (db). Drying was continued until a final moisture content of about 0.10 (db) attained. Drying experiments were conducted in three replications.

## Process and Parameter Modeling

Moisture ratio of potato slices in thin-layer drying is determined as follows:

$$MR = \frac{M - M_e}{M_i - M_e} \qquad (1)$$

Where, $MR$ stands for the moisture ratio, $M$ is the moisture content at any specified time (% db), $M_i$ and $M_e$ represent the initial and equilibrium moisture contents, respectively (% d.b.).

During drying of potato slices in a fluidized bed method, $M_e$ values were relatively small compared to $M$ and $M_i$. Equation (1) was therefore simplified as follows (Doymaz, 2004):

$$MR = \frac{M}{M_0} \qquad (2)$$

Seven mathematical models of thin layer drying were employed to fit the experimental drying curves (Table 1). Model coefficients and values of indices were calculated using nonlinear regression of Curve Expert software (ver. 1.4). Three indices were applied to determine the supremacy of mathematical models. These included correlation coefficient ($R^2$), Chi-square ($\chi^2$) and root mean square error ($RMSE$). As for the most suitable model, $\chi^2$ and $RMSE$ values should assume the lowest while $R^2$ the highest (Demir *et al.*, 2004). These parameters are estimated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}[MR_{exp,i} - MR_{pre,i}]^2}{\sum_{k=1}^{N}\left[\frac{\sum_{k=1}^{n}MR_{pre,i}}{N} - MR_{pre,i}\right]^2} \qquad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \qquad (4)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{\frac{1}{2}} \qquad (5)$$

Where, $MR_{exp,i}$ is the experimental moisture ratio of $i^{th}$ data, $MR_{pre,i}$ stands for the predicted moisture ratio of $i^{th}$ data, $N$ is the number of observations and $z$ the number of drying constants.

## Effective Moisture Diffusivity

Fick's diffusion equation for slab geometry particles was used for computation of the effective moisture diffusivity of

**Table 1.** Thin layer drying models used in drying of high moisture potato slices.

| Model | Equation [d] | References |
|---|---|---|
| Demir *et al.* | $MR = a\exp(-kt)^n + b$ | DEMIR *et al.* (2007) |
| Logarithmic | $MR = a\exp(-kt) + c$ | Doymaz (2004) |
| Midilli *et al.* | $MR = a\exp(-kt^n) + bt$ | Midilli *et al.* (2002) |
| Page | $MR = a\exp(-kt^n)$ | Zhang and Litchfield (1991) |
| Two-term exponential | $MR = a\exp(-kt) + (1-b)\exp(-kct)$ | Sharaf-Elden *et al.* (1980) |
| Wang and Singh | $MR = 1 + at + bt^2$ | Wang and Singh (1978) |
| Logistic | $MR = a/(1 + b\exp(kt))$ | Cihan *et al.* (2007) |

[d] *a; b; c; k; $k_0$; $k_1$; and n stand for drying constants.*

potato slices. Assuming negligible external mass transfer resistance, uniform initial moisture distribution and constant slab thickness, the solution of Fick's equation proposed by Crank (1975) is presented as follows:

$$MR = \frac{M - M_e}{M_i - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(\frac{-D_{eff}(2n-1)^2 \pi^2 t}{4L^2}\right)$$

(6)

Where, $MR$ stands for moisture ratio (decimal), $M$ is moisture content at any point of time ($kg_{water}/kg_{dry\ mater}$), $M_i$ is the initial moisture content ($kg_{water}/kg_{dry\ mater}$), $n$ represents the number of terms taken into consideration, $t$ denotes the drying time (s), $D_{eff}$ is effective moisture diffusivity ($m^2\ s^{-1}$) and finally $L$ is the average half thickness of potato slices (m).

Due to the drying time of the potato slices being relatively long, so according to Kingsly *et al.* (2007) the first term of Equation (6) has been considered for the calculation of $D_{eff}$:

$$\ln(MR) = \ln\left(\frac{M - M_e}{M_i - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff}\pi^2 t}{4L^2}\right)$$

(7)

$MR$ can be obtained as follows:

$$MR = \left(\frac{8}{\pi^2}\right) \exp\left(\frac{\pi^2 D_{eff} t}{4L^2}\right)$$

(8)

As Arrhenius type of equation can be used for computation of activation energy (Babalis and Belessiotis, 2004):

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right)$$

(9)

For obtaining $E_a$, Equation (9) can be linear as follows:

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right)$$

(10)

Where, $E_a$ is activation energy ($kJ\ mol^{-1}$), $R$ is universal gas constant ($8.3143\ kJ\ mol^{-1}\ K^{-1}$), $T$ stands for absolute air temperature (K), and $D_0$ represents the pre-exponential factor of the equation ($m^2\ s^{-1}$).

According to Equation (10), $\ln(D_{eff})$ was plotted against $1/T$ and then three linear models were fitted to the experimental data.

Specific energy consumption ($E_S$) for drying of potato slices was calculated using the following model (Zhang *et al.*, 2002):

$$E_S = Qt\frac{(T_{in} - T_{am})}{60m_v V_h}(C_{Pa} + C_{Pv}h_a)$$

(11)

where $E_S$ is specific energy consumption ($kJ\ kg^{-1}$), $C_{Pv}$ and $C_{Pa}$ stand for the specific heat capacity of vapor and air, respectively, (1004.16 and 1828.8 $J\ kg^{-1}\ °C^{-1}$), $Q$ is inlet air to drying chamber ($m^3\ s^{-1}$), $t$ the total drying time (s), $h_a$ is the absolute air humidity ($kg_{vapor}/kg_{dry\ air}$), $T_{in}$ and $T_{am}$ are inlet air to drying chamber and ambient air temperatures, respectively, (°C), $m_v$ is the mass of water removed (kg) and $V_h$ the specific air volume ($m^3/kg$).

## RESULTS AND DISCUSSION

### Mathematical Modeling of Drying Kinetics

Decreasing of potato slices moisture content against drying time at different temperatures and in the various bed conditions is depicted in Figure 3. Based on these results, air temperature was the most important in drying of potato slices. With increase in air temperature, drying time was decreased. This is due to applying energy at a higher rate to the bed of potato slices and consequently increase in draying rate. These results are similar to those of such previous studies, as: peach slices (Kingsly *et al.*, 2007), soybean (Rafiee, 2009), plum slices (Goyal *et al.*, 2007) and mushroom (Arumuganathan *et al.*, 2009; Gorjian, 2011). With regard to the drying curves (Figure 3), falling rate period took place in all the drying processes of high moisture potato slices. Similar patterns have been observed in drying of quercus (Tahmasebi *et al.*, 2011).
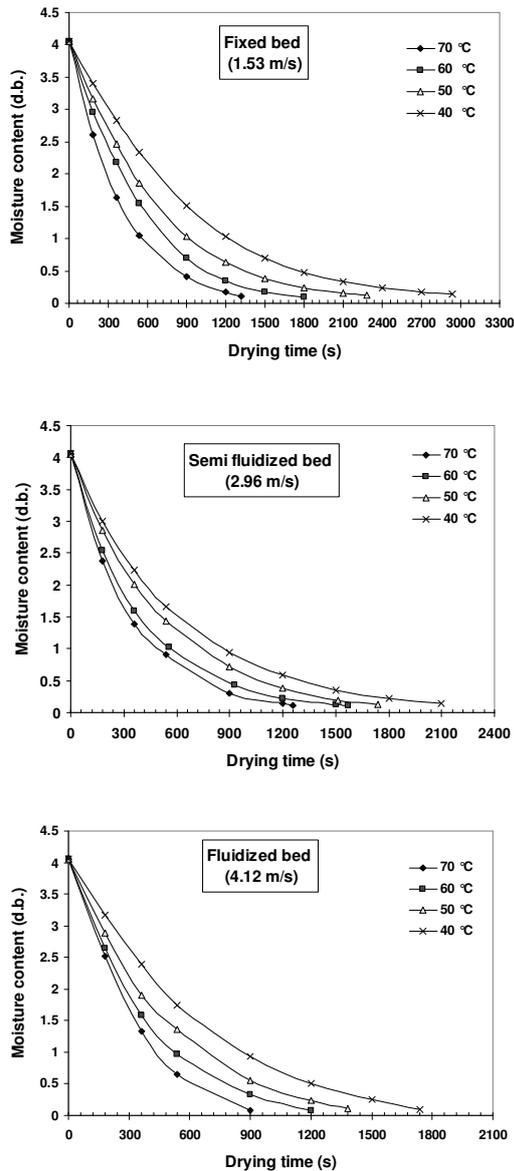
**Figure 3.** Moisture contents of high moisture potato slices in different bed conditions and at different drying air temperatures.

The kinetic drying of potato slices at different bed conditions and air temperatures was predicted using seven mathematical models to evaluate their suitability and to select the most appropriate model. Indices of $R^2$, $\chi^2$ and *RMSE* are presented in Table 2. All $R^2$ values of Midilli *et al.*, Page, and Wang and Singh models were obtained as

greater than 0.99. Results indicated that the Midilli *et al.* model presents the most suitable performance in prediction of high moisture potato slices' drying behavior, due to the fact that $R^2$ values for all the drying temperatures being the highest, while $\chi^2$ and *RMSE* values the lowest. Midilli *et al.* model coefficients for all bed conditions and air temperatures are presented in Table 3. Results indicate that the $R^2$ value for all the predicted moisture ratio values against the experimental ones for all bed conditions and temperatures was 0.9995. This also proved that the Midilli *et al.* model benefits from the proper accuracy in moisture rate prediction of high moisture potato slices.

**Effective Moisture Diffusivity**

Potato drying experiments were continued until moisture content of samples reached about 0.10 (db). *Ln(MR)* values versus drying time (s) in different temperatures and bed conditions have been presented in Figure 4. Increase in air temperature caused increase in slope of lines. Equation (4) was used to calculate the $D_{eff}$ Values. The highest value of $D_{eff}$ was obtained at fluidized bed condition with air velocity of 4.12 m s$^{-1}$ (Figure 5). This is assumed as due to the most effective contact between air flow and potato slices. Hence increase in air velocity caused increase in $D_{eff}$ values. Minimum values for $D_{eff}$ were obtained as $4.29 \times 10^{-9}$ m$^2$ s$^{-1}$ for fixed bed (1.53 m s$^{-1}$), and air temperature of 40°C. The maximum value of $D_{eff}$ ($1.57 \times 10^{-8}$ m$^2$ s$^{-1}$) belonged to fluidized bed with air velocity of 4.12 m s$^{-1}$ and air temperature of 70°C.

As can be observed from Figure 5, the most effective factor affecting the $D_{eff}$ values in high moisture potato slices is air temperature. Increase in air temperature caused increase in $D_{eff}$ values. Similar results regarding the effect of drying air temperature on effective moisture

**Table 2.** Values of statistical model parameters for thin layer drying of potato slices in different bed conditions.

| Model | Air temperature (°C) | $R^2$ | | | $\chi^2$ | | | RMSE | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1.53 m s⁻¹ | 2.96 m s⁻¹ | 4.12 m s⁻¹ | 1.53 m s⁻¹ | 2.96 m s⁻¹ | 4.12 m s⁻¹ | 1.53 m s⁻¹ | 2.96 m s⁻¹ | 4.12 m s⁻¹ |
| Demir *et al.* | 40 | 0.9928 | 0.9966 | 0.9912 | 0.0084 | 0.0028 | 0.0070 | 0.0748 | 0.0394 | 0.0597 |
| | 50 | 0.9928 | 0.9948 | 0.9932 | 0.0071 | 0.0039 | 0.0047 | 0.0652 | 0.0441 | 0.0448 |
| | 60 | 0.9916 | 0.9942 | 0.9966 | 0.0069 | 0.0047 | 0.0035 | 0.0587 | 0.0448 | 0.0341 |
| | 70 | 0.9974 | 0.9964 | 0.9868 | 0.0018 | 0.0026 | 0.0722 | 0.0277 | 0.0333 | 0.1201 |
| Logarithmic | 40 | 0.9928 | 0.9966 | 0.9910 | 0.0084 | 0.0028 | 0.0071 | 0.0793 | 0.0432 | 0.0666 |
| | 50 | 0.9928 | 0.9954 | 0.9906 | 0.0071 | 0.0035 | 0.0065 | 0.0704 | 0.0467 | 0.0609 |
| | 60 | 0.9916 | 0.9942 | 0.9960 | 0.0069 | 0.0047 | 0.0023 | 0.0656 | 0.0541 | 0.0339 |
| | 70 | 0.9966 | 0.9964 | 0.9860 | 0.0024 | 0.0026 | 0.0071 | 0.0370 | 0.0385 | 0.0533 |
| Midilli *et al.* | 40 | 0.9996 | 0.9994 | 0.9998 | 0.0004 | 0.0003 | 0.0000 | 0.0163 | 0.0129 | 0.0031 |
| | 50 | 0.9994 | 0.9990 | 0.9994 | 0.0005 | 0.0006 | 0.0003 | 0.0173 | 0.0173 | 0.0113 |
| | 60 | 0.9992 | 0.9994 | 0.9998 | 0.0005 | 0.0004 | 0.0000 | 0.0158 | 0.0141 | 0.0018 |
| | 70 | 0.9998 | 0.9988 | 1 | 0.0001 | 0.0007 | 0.0000 | 0.0002 | 0.0173 | 0.0000 |
| Page | 40 | 0.9992 | 0.9982 | 0.9934 | 0.0007 | 0.0013 | 0.0051 | 0.0241 | 0.0317 | 0.0618 |
| | 50 | 0.9992 | 0.9982 | 0.9956 | 0.0006 | 0.0013 | 0.0030 | 0.0219 | 0.0312 | 0.0462 |
| | 60 | 0.9988 | 0.9992 | 0.9962 | 0.0008 | 0.0006 | 0.0023 | 0.0244 | 0.0212 | 0.0391 |
| | 70 | 0.9986 | 0.9984 | 0.9972 | 0.0010 | 0.0011 | 0.0013 | 0.0267 | 0.0280 | 0.0297 |
| Two-term exponential | 40 | 0.9898 | 0.9954 | 0.9842 | 0.0120 | 0.0038 | 0.0125 | 0.1000 | 0.0543 | 0.0968 |
| | 50 | 0.9904 | 0.9942 | 0.9890 | 0.0096 | 0.0045 | 0.0077 | 0.0876 | 0.0580 | 0.0741 |
| | 60 | 0.9890 | 0.9930 | 0.9940 | 0.0090 | 0.0057 | 0.0035 | 0.0821 | 0.0653 | 0.0483 |
| | 70 | 0.9964 | 0.9958 | 0.9787 | 0.0025 | 0.0029 | 0.0109 | 0.0422 | 0.0455 | 0.0808 |
| Wang and Singh | 40 | 0.9898 | 0.9954 | 0.9980 | 0.0119 | 0.0037 | 0.0014 | 0.0995 | 0.0536 | 0.0324 |
| | 50 | 0.9904 | 0.9942 | 0.9974 | 0.0095 | 0.0043 | 0.0017 | 0.0871 | 0.0567 | 0.0348 |
| | 60 | 0.9892 | 0.9946 | 0.9972 | 0.0089 | 0.0044 | 0.0016 | 0.0817 | 0.0574 | 0.0326 |
| | 70 | 0.9968 | 0.9960 | 0.9952 | 0.0023 | 0.0028 | 0.0024 | 0.0405 | 0.0447 | 0.0379 |
| Logistic | 40 | 0.9842 | 0.9966 | 0.9910 | 0.0188 | 0.0028 | 0.0072 | 0.1187 | 0.0432 | 0.0670 |
| | 50 | 0.9928 | 0.9954 | 0.9940 | 0.0071 | 0.0035 | 0.0270 | 0.0704 | 0.0467 | 0.1242 |
| | 60 | 0.9916 | 0.9942 | 0.9968 | 0.0069 | 0.0047 | 0.0024 | 0.0656 | 0.0541 | 0.0346 |
| | 70 | 0.9972 | 0.9964 | 0.9860 | 0.0018 | 0.0026 | 0.0071 | 0.0320 | 0.0385 | 0.0532 |

**Table 3.** Coefficients of Midilli *et al.* (2002) model for kinetic drying prediction of potato slices in different bed conditions.

| Temperature | Coefficients | 40°C | 50°C | 60°C | 70°C |
|---|---|---|---|---|---|
| Fixed bed | a | 0.9876 | 0.9887 | 0.9888 | 0.9970 |
| (1.53 m s$^{-1}$) | k | 0.0113 | 0.0213 | -0.0276 | -0.3130 |
| | n | 3.0303 | 4.5044 | 6.6855 | 6.1401 |
| | b | 1.6902 | 1.6323 | 1.6837 | 1.4596 |
| Semi fluidized bed | a | 0.9931 | 0.9923 | 0.9931 | 0.9958 |
| (2.96 m s$^{-1}$) | k | -0.1472 | -0.1392 | 0.0682 | -0.1539 |
| | n | 3.4069 | 4.8288 | 7.4482 | 7.3824 |
| | b | 1.4440 | 1.4995 | 1.4371 | 1.4065 |
| Fluidized bed | a | 0.9988 | 0.9967 | 0.9989 | 1.0089 |
| (4.12 m s$^{-1}$) | k | -0.6861 | -0.6643 | -0.6612 | -0.7153 |
| | n | 2.9623 | 4.5940 | 5.9814 | 15.212 |
| | b | 1.7339 | 1.6193 | 1.5067 | 1.7777 |
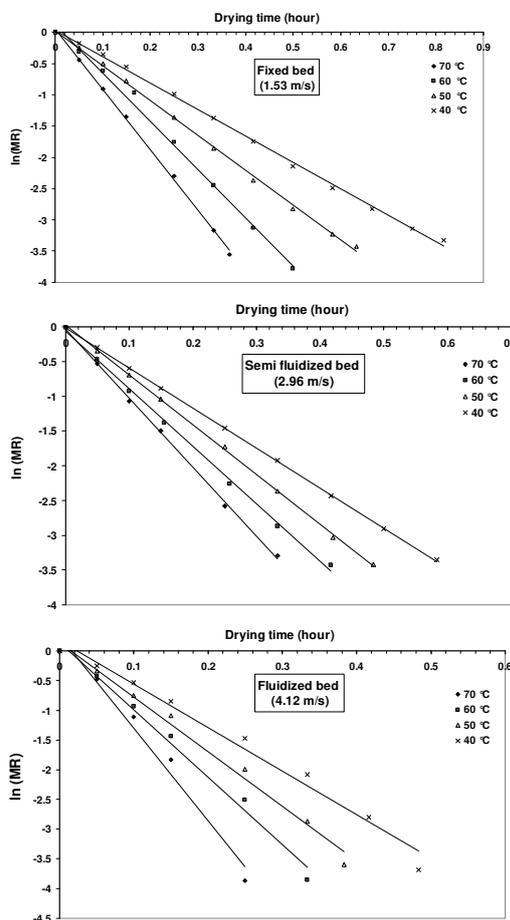


**Figure 4.** *Ln(MR)* versus time (hour) for different bed conations and drying air temperatures.

diffusivity, during convective air drying, have been reported for apricots (Doymaz, 2004), peaches (Kingsly *et al.*, 2007), mushroom (Arumuganathan *et al.*, 2009), and carrot slices (Aghbashlo *et al.*, 2009).

**Effect of Drying Conditions on $D_{eff}$**

Power models were the most fitting in prediction of $D_{eff}$ values in drying under all bed conditions. Fitted power models and related $R^2$ values are reported in Table 4. Results indicate that the minimum value of $D_{eff}$ the obtained at minimum air temperature (40°C). Also the difference between $D_{eff}$ values for different bed conditions was less than those for the drying air temperatures. This is assumed to be due to drying air temperature playing a more important role in moisture transfer in potato. Results also revealed that the effect of fluidized bed at higher air temperatures was more pronounced. Quadratic models were employed to predict moisture diffusivity values as based on different bed conditions (Table 5).

**Activation Energy Values and Models**

In the first step for computing the activation energy ($E_a$), Ln($D_{eff}$) was
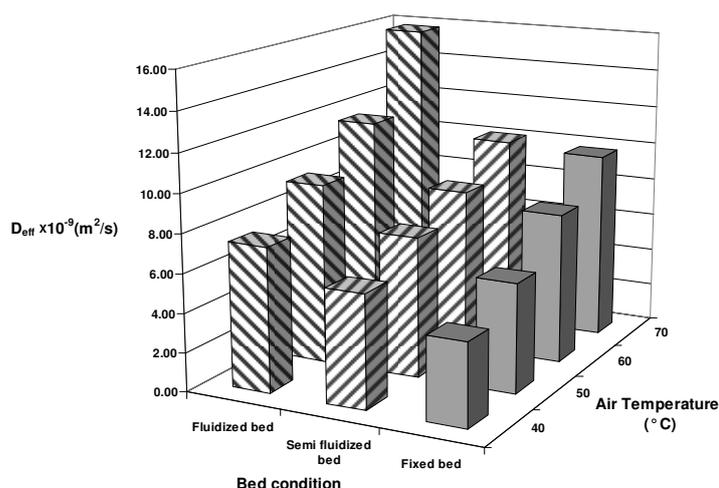
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**Figure 5.** Effect of bed conditions and air temperature on effective moisture diffusivity ($D_{eff}$) in thin-layer drying of high moisture potato slices.

**Table 4.** Applied power models to $D_{eff}$ values of high moisture potato for different bed conditions.

| Bed condition | Model | $R^2$ |
|---|---|---|
| Fixed bed (V= 1.53 m s$^{-1}$) | $D_{eff} = 2 \times 10^{-11} \times T^{1.4951}$ | 0.9947 |
| Semi fluidized bed (V= 2.96 m s$^{-1}$) | $D_{eff} = 2 \times 10^{-10} \times T^{0.9524}$ | 0.9959 |
| (Fluidized bed) (V= 4.12 m s$^{-1}$) | $D_{eff} = 6 \times 10^{-11} \times T^{1.3090}$ | 0.9741 |

**Table 5.** Applied quadratic models to $D_{eff}$ values of high moisture potato for different air temperatures.

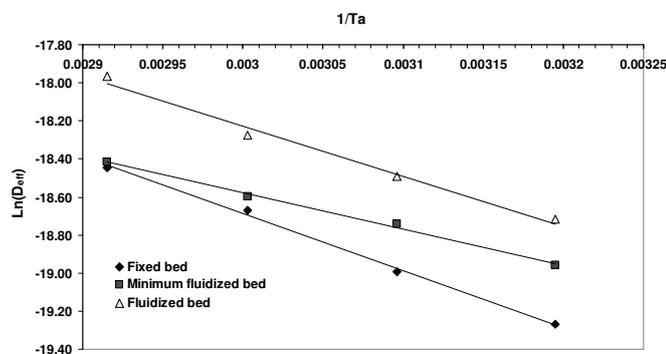| Air temperature (°C) | Model | $R^2$ |
|---|---|---|
| 40 | $D_{eff} = -10^{-10} \times v^2 + 6 \times 10^{-10} \times v + 3 \times 10^{-9}$ | 1 |
| 50 | $D_{eff} = 3 \times 10^{-10} \times v^2 - 3 \times 10^{-11} \times v - 5 \times 10^{-9}$ | 1 |
| 60 | $D_{eff} = 9 \times 10^{-10} \times v^2 - 4 \times 10^{-9} \times v + 10^{-8}$ | 1 |
| 70 | $D_{eff} = 2 \times 10^{-9} \times v^2 - 8 \times 10^{-9} \times v + 2 \times 10^{-8}$ | 1 |



**Figure 6.** *Ln($D_{eff}$)* against *1/T* at different bed conditions for thin-layer drying of high moisture potato slices.

plotted against _1/T_ for the first and second falling periods (Figure 6). Equation (10) was employed to calculate the $E_a$ values for potato slices. Table 6 shows the obtained values of $E_a$ and related $R^2$ values for different bed conditions. A general range of 12.7–110 kJ mol$^{-1}$ has been reported for $E_a$ values for food and agricultural products (Babalis and Belessiotis, 2004). Minimum and maximum values of $E_a$ for high moisture potato slices in applied drying conditions varied between 15.88 and 24.95 kJ mol$^{-1}$. Water forms in food and agricultural materials include surface and chemical ones. Due to the fact that most water in high moisture potato slices was removed at the start of the drying process, so higher energy is needed to start the evaporation process. Also unsuitable changes (physical and chemical) in potato tissue are negligible at the beginning of the drying process (Hassini _et al._, 2007). If such proper conditions as bed condition and temperature were selected for drying of potato slices, quality of the product would surely be improved. Activation energy of high moisture potato slices was relatively low as compared with other agricultural and food products. This is due to high initial moisture content (4.06 db), tissue of potato and starchy structure of potato slices. Similar results have been reported (less activation energy requirement) for banana slices during high air temperature drying (Demirel and Turhan, 2003).

A quadratic model was applied to fit the $E_a$ values of potato slices. A maximum value of $E_a$ was obtained at fixed bed drying with air velocity of 1.53 m s$^{-1}$. Semi fluidized bed condition, caused the activation energy to increase. A fitted quadratic equation to the $E_a$ values for all bed conditions is presented as follows:

$$E_a = 30.33v^2 - 63.64v + 49.19$$
$$R^2 = 1 \tag{12}$$

## Specific Energy Consumption Values and Models

Specific energy requirements for drying of high moisture potato slices were determined using Equation (11). Obtained values of $E_S$ for all bed conditions and air temperatures are presented in Figure 7. These results show that in each bed condition, with increase in air temperature, the $E_S$ value increases. Change of bed condition from fixed to fluidized bed caused an intensive increase in $E_S$ value. Maximum value of $E_S$ ($1.64\times10^5$ kJ kg$^{-1}$) was obtained at fluidized bed condition with air velocity of 4.12 m s$^{-1}$ and air temperature of 70°C. Minimum value of $E_S$ was $0.45\times10^5$ (kJ kg$^{-1}$) and obtained at fixed bed drying with air velocity of 1.53 m s$^{-1}$ and air temperatures of 40°C. Results proved that increase in air velocity and temperature caused intensive increase in $E_S$. In other words, each factor causing an increase in input energy rate also causes the specific energy to increase. Similar results have been observed for paddy (Khoshtaghaza _et al._, 2007). Three logarithmic models were employed to fit the $E_S$ values of fixed, semi fluidized and fluidized bed conditions as follows:

$$E_S = -30883\ln(T) + 46462$$
$$R^2 = 0.9873$$
$$\text{(Fixed bed)} \tag{13}$$
$$E_S = -70064\ln(T) + 60966$$

**Table 6.** Activation energy values and related correlation coefficient for different bed conditions in drying periods of high moisture potato (FFP and SFP: First and Second Falling Periods).

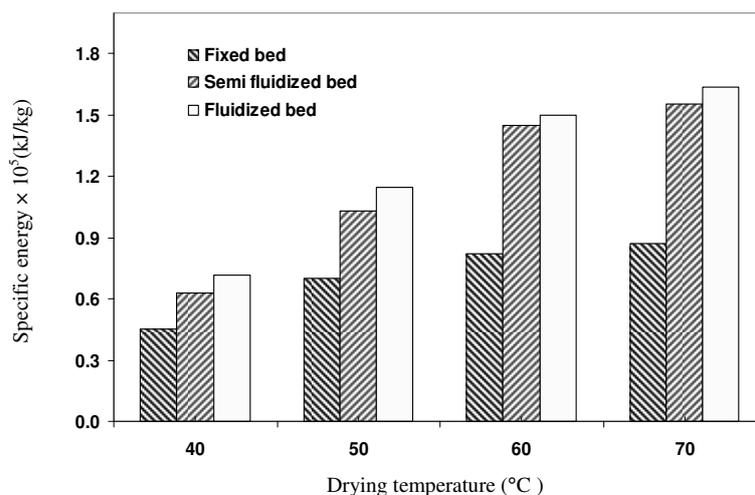|  | Fixed bed (V= 1.53 m s$^{-1}$) | Semi fluidized bed (V= 2.96 m s$^{-1}$) | (Fluidized bed) (V= 4.12 m s$^{-1}$) |
|---|---|---|---|
| $E_a$ ( kJ mol$^{-1}$) | 24.95 | 15.88 | 21.97 |
| $R^2$ | 0.9972 | 0.9964 | 0.9879 |

**Figure 7.** Specific energy consumption in thin layer drying of high moisture potato slices at different bed conditions and air temperatures.

$R^2 = 0.9813$
(Semi fluidized bed)　　　　　　　　(14)
$E_S = -68233\ln(T) + 70643$

$R^2 = 0.9936$
(Fluidized bed)　　　　　　　　　(15)

## CONCLUSIONS

Midilli *et al.* model was the most fitting for estimation of high moisture potato slices drying kinetics at fixed, semi fluidized and fluidized bed conditions.

Maximum and Minimum values of $D_{eff}$ during drying of high moisture potato slices was obtained in fluidized bed and fixed bed drying conditions, respectively. Maximum values of $D_{eff}$ at each temperature level were obtained in fluidized bed conditions.

Minimum and maximum values of $E_a$ for drying of high moisture potato slices were obtained in minimum fluidized bed and fixed bed conditions, respectively.

Maximum value of $E_S$ for drying of high moisture potato slices was found out in fluidized bed conditions. Minimum value of $E_S$ was estimated in fixed bed condition. Increase in drying air temperature in each bed condition caused an increase in $E_S$ value.

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**مدلسازی برخی مشخصه های خشک شدن سیب زمینی بسیار مرطوب در شرایط بسترهای ثابت، نیمه سیال و سیال**

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**چکیده**

خصوصیات خشک شدن قطعات بسیار مرطوب سیب‌زمینی با رطوبت اولیۀ ۴/۰۶ پایۀ خشک در شرایط لایۀ نازک بسترهای ثابت، نیمه سیال و سیال مورد مطالعه قرار گرفت. دماهای ۴۰، ۵۰، ۶۰ و ۷۰°C به کمک یک خشک‌کن بستر سیال آزمایشگاهی در آزمایشها اعمال شد. به منظور پیش بینی رفتار خشک‌شدن قطعات سیب‌زمینی، هفت مدل خشک شدن لایۀ نازک استفاده شد و سرانجام بر اساس شاخصه‌های مقایسه‌ای، مدل میدلی و همکاران به عنوان بهترین مدل انتخاب شد. پخش رطوبتی مؤثر قطعات سیب‌زمینی بین ۴/۲۹×۱۰⁻⁹ و ۱۵/۷۰×۱۰⁻⁹ m²/s بترتیب برای شرایط بسترهای ثابت و سیال محاسبه شد. مقادیر پخش رطوبتی قطعات با افزایش دمای هوا افزایش یافت. مقادیر انرژی فعالسازی بین ۱۵/۸۸ و ۲۴/۹۵ kJ/mol تغییر کرد. کمینه و بیشینه مقادیر انرژی فعالسازی بترتیب در شرایط بسترهای نیمه سیال و ثابت محاسبه شد. مصرف انرژی ویژه برای خشک کردن لایۀ نازک قطعات سیب‌زمینی بسیار مرطوب بترتیب بین ۰/۴۵×۱۰⁵ و ۱/۶۴×۱۰⁵ kJ/kg محاسبه شد. افزایش دمای هوای خشک کردن در هر شرایط بستر مواد، سبب افزایش مصرف انرژی شد. بیشترین مقدار مصرف انرژی در شرایط بستر سیال حاصل شد.