Mathematical Modeling of Thin-Layer Drying of Hygroscopic Material (*Solanum tuberosum*) in Fabricated Tunnel

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Abstract To investigate the characteristics of fresh potato in tunnel drying, an experimental setup of tunnel dryer was fabricated and installed in the laboratory. The samples of the potato for the drying were prepared in cubic shape of $10 \times 10\times 10\ mm^3$. For the modeling of drying kinetics, drying data were observed at temperature of 50, 55, 60, 65, 70 and 75 °C, and data were fitted to different drying models. The selected models were tested based on model energy efficiency (EF), reduced chi square and root mean square error (RMES) to select best fit of drying model. Results of the model nearly equal to modified page model with lower RMSE and reduced chi square value compared to page model. The observed data were fitted on Newton model, page model and modified page model. On the basis of experimental constant, modified page model was selected. In validation process, the model gave the maximum energy efficiency value **0.9823**, reduced value of chi square **0.0015** and minimum RMSE value **0.0323** at larger range of drying air temperature 45–60 °C.

Keywords Drying · Drying model · Air velocity · Moisture ratio tunnel dryer

1 Introduction

Potato is the fourth largest food crops in the world. Potato is member of Solanaceae family of the many plant stem solarium species, in which it is most widely cultivated. In 2014, worldwide production of potato (*S. tuberosum*) was more than 388 million tones which was consumed as food by people and used as animal feed and as potato starch in medicament industries [1]. The leading potato producers of the world are China, European Union, India, Russia, Ukraine, USA, Germany and

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Bangladesh, etc. India's potato production was estimated around 47 million tones in year 2014. In industry, the drying machinery has been widely used for processing of food products. During the drying of food materials, the food goes with undesirable changes that have negative effect on the food products.

Food drying is one of the oldest methods of processing and preserving food for later use. Food can be dried in the sun, in an oven or in a food dehydrator by using the right combination of warm temperature, low humidity and air current [2]. The common drying method is sun drying which has so many disadvantages. The traditional sun drying methods often yield poor quality, since the product is not protected against dust, rain, wind or even against birds, insects, rodents and domestic animals while drying. Soiling, contamination with microorganisms, formation of mycotoxins and infection with disease causing germs are the result [3].

Drying is one of the necessary processes for the preservation of agricultural products such as fruits and vegetables. This process enhances the life of agricultural products and their storage life and minimizes losses during storage life. Drying process reduces the shipping and transportation costs [4]. The thermal kinetics during drying the relationship between moisture ratios and drying instants was determined [5]. Based on the Lewis proposal, Newton's Law of Cooling

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -k(M - M_0) \tag{1}$$

Thus, the main objective of this research is to develop an experimental drying setup cubical shape potatoes samples and to validate with existing drying models [6].

2 Materials and Methods

2.1 Materials

The fresh potatoes were collected from the near market in May–June. The full-size average dimension of potatoes was found 50–60 mm in length and 20–30 mm in width. The potatoes which were selected for the study were completely washed and peeled sliced into $10 \times 10 \times 10$ mm^3 using sharp knife [7].

2.2 Method

The experimental setup for carrying out the thin-layer drying is shown in Fig. 1. It consists of three main units: humidifier unit, air heating unit and drying unit. Humidifier is constructed by GI sheet in two cylindrical parts and is joined together by means of an air-tight flange joint. The lower part of the humidifier is of 0.3 m diameter and 1 m height. A float valve is used in order to maintain a desired level of water in the lower portion of the humidifier. An overhead water tank is used to supply water to the humidifier unit. The air suction tunnel, 3 m long and 106 mm in diameter, is connected to the humidifier through an orifice meter just above the water level to measure the flow rate of drying air. The lower part of the humidifier is also provided with a water level indicator, a drain valve, two electric immersion heaters each of 2 kW capacity and a water pump and a 12 mm diameter perforated spray tube. It was intended that the atmospheric air be given a water bath by means of a fine spray produced in the humidification chamber using the perforated tube and the water pump to humidification to a desired dew point. At the top of the humidifier, two sets of louvers are provided to trap the water droplets from the moist air as shown in Fig. 1.

Humidifier unit is attached to the suction side of the blower. The drying air preparation unit was installed in three parts. The mid portion is a 1-m-long cylindrical shape with two diffusers at each end. Two heaters of 2-kW capacity each and three heaters of 1 kW capacity each are fitted into the cylindrical portion to raise the temperature of the air, coming out from the humidifier, to a desired value.

Thin-layer drying section consists of three sections: an air chamber, a base plate with five openings and an exposure chamber. The cylindrical air chamber is a fitted with a 300 diffuser at 0.5 m height. The material drying unit is connected to the air preparation unit with the help of a 900, 150 mm pipe bend to the diffuser. A 3-mm-thick mild steel base plate having five equi-spaced holes, each of 185 mm diameter, is fitted to the top of the plenum chamber. The openings are provided with rubber gaskets to prevent any leakage of air from the sides when drying pans are placed over them. To smooth functioning, placement of the drying pans, four small

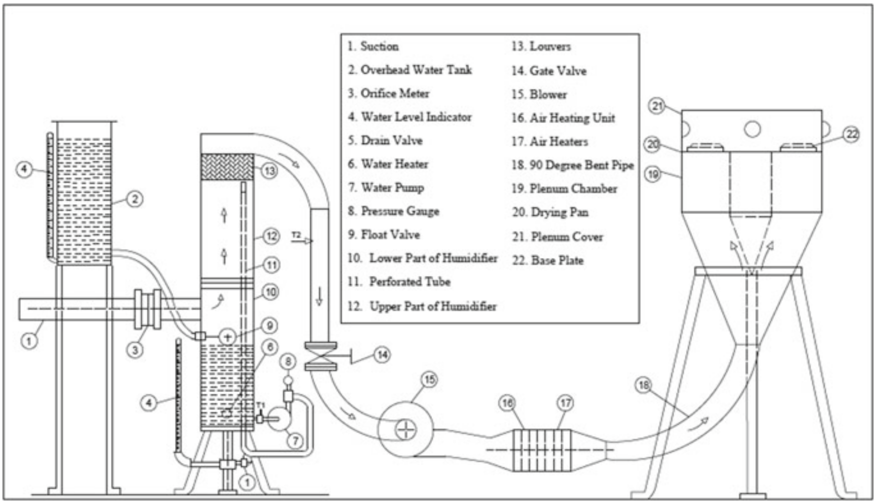

Fig. 1 Schematic diagram of thin-layer experimental setup

bearings are arranged to the plate toward each of the openings. During the experiments, temperature, velocity and relative humidity of drying air are recorded every 90 min. The temperature and relative humidity sensors are located at the inlet of the fan (T, RH), upstream (T1, RH1) and downstream of the tray (T2, RH2). The anemometer is located at the exit of the tunnel. The air was allowed to flow in the tunnel over the potato cubes with average velocity of 1 m/s, with 65% initial moisture content of potato on dry basis. With the time, the weight of the potato was observed to decrease gradually, and the humidity also decreased with the time. During the experiment, only drying temperatures are variable, and all other parameters are fixed.

3 Result and Discussion

The loss in weight during drying at different temperatures was converted into moisture contents (% d.b.). The relationship between moisture content and drying time for different temperatures is calculated. The moisture ratio was calculated from the moisture contents (% d.b.), the initial moisture content and the equilibrium moisture content at different temperature with time interval of 9 h. From the plot of moisture ratio versus drying time at different temperatures, it was observed that moisture ratio decreased rapidly during the first 8 h of drying as compared to the latter part of drying because of higher availability of free water during initial stages [8].

Variation in moisture ratio with time at different temperatures 50, 55, 60, 65, 70 and 75 °C was recorded. When a semilogarithmic plot of moisture ratio versus drying time was plotted at various temperatures, it results that drying time was reducing with increase in temperature. The value of drying coefficient was given by the slope of straight line, and the intercept gives the natural logarithmic value at different temperatures. Half-life method [9] was used in the calculation of drying coefficient K and plotted in Fig. 2.

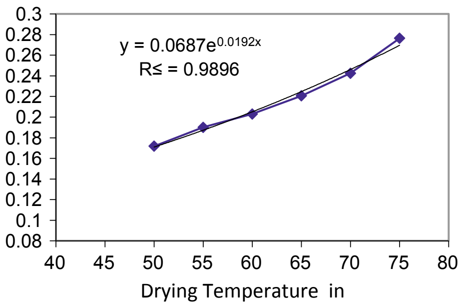

Fig. 2 Exponential graph of drying coefficient "K"

Hence the exponential model was fitted best with the following equation

$$K = 0.0687e^{0.0192T} \tag{2}$$

where "T" is the drying air temperature in °C.

Thus, the existing model Eq. (1) is modified for the experimental model using Eq. (2), and we get model drying equation for the experimental setup.

$$\frac{(M - M_e)}{(M_o - M_e)} = \exp^{-\left(0.0687e^{0.0192T}\right)t} \tag{3}$$

where

t is the drying time in hours,
M_o initial moisture content,
M_e is equilibrium moisture content, and
M is moisture content after t time [10].

The value of drying coefficient is calculated from Eq. (2) (model parameter) for page model at 50 °C results that the energy efficiency is high at $n = 1$. Therefore, for $n = 1$ page model also gives the maximum energy efficiency. Again, model was tested for the modified page model at varying value of n, and this model also results the maximum energy efficiency at $n = 1$ at 50 °C as shown in Table 1.

Here in Table 2, all tested drying model values of chi square, RMSE and energy efficiency are shown [6].

From Table 2, it can be observed that lower value of RMSE is at 45–60 °C, and graph in Fig. 3 shows that energy efficiency is higher in the range of 45–60 °C for modified page model. These results show that the model was best fitted to the modified page model.

The comparative analysis of the experimental moisture ratio and the predicted moisture ratios based on modified page model $\mathrm{MR} = \exp^{(-Kt)^n}$ at drying air temperature 50 °C gave the value of experimental constant $n = 1$ and drying coefficient $K = 0.0687e^{0.0192T}$ (Fig. 4).

Table 1 Modified page model at 50 value of n

Temp	0.8	0.9	1	1.1	1.2	1.3
χ^2	0.002499	0.001647	**0.001569**	0.002105	0.003114	0.004474
R.M.S.E.	0.034099	0.032153	**0.032316**	0.034438	0.038677	0.045654
EF	**0.971404**	**0.981305**	**0.982345**	**0.976507**	0.965537	0.950904

Source: At different value of n, optimum values are highlighted

Table 2 Values of RMSE, χ^2 and EF for all model

Model	Temp	χ^2	R.M.S.E.	EF
Newton model MR = $\exp^{(-Kt)}$	45	0.002636	0.040902	0.967858
	50	0.001448	0.032316	0.982345
	55	0.001458	0.032696	0.982216
	60	0.002539	0.038809	0.969041
	65	0.004554	0.051156	0.944476
	70	0.007365	0.064292	0.910197
	75	0.010838	0.080846	0.867848
Page model MR $= \exp^{(-Kt)^n}$	45	0.002856	0.040902	0.967858
	50	0.001569	0.032316	0.982345
	55	0.00158	0.032696	0.982216
	60	0.002751	0.038809	0.969041
	65	0.004933	0.051156	0.944476
	70	0.007979	0.064292	0.910197
	75	0.011741	0.080846	0.867848
Modified page MR $= \exp^{[-(Kt)^n]}$	45	0.002856	0.040902	0.967858
	50	0.001569	0.032316	0.982345
	55	0.00158	0.032696	0.982216
	60	0.002751	0.038809	0.969041
	65	0.004933	0.051156	0.944476
	70	0.007979	0.064292	0.910197
	75	0.011741	0.080846	0.867848

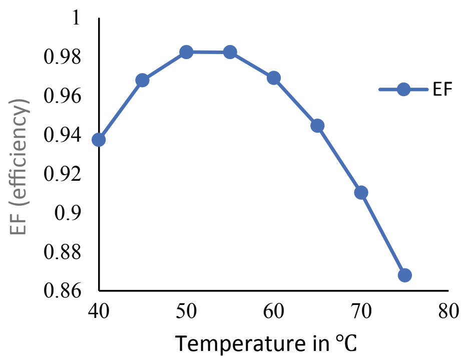

Fig. 3 Value of EF versus temperature based on modified page model at experiment temperature 50 °C

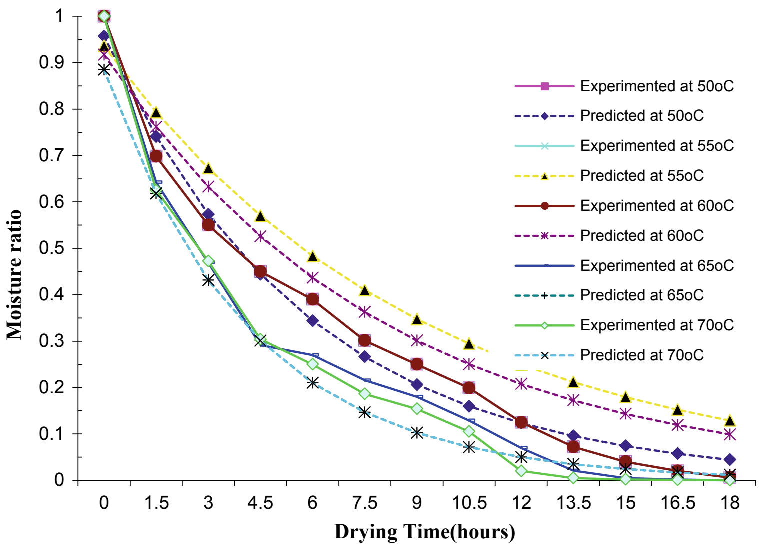

Fig. 4 Experimental and predicted moisture ratio versus time by modified page model

4 Conclusion

Thin-layer drying characteristics of *S. tuberosum* were investigated at various drying temperatures of air in tunnel dryer. The obtained data were fitted into drying models, namely Newton's model, page model and modified page model and were compared on the basis of their statistical coefficients such as root mean square error (RMSE), chi square (χ^2) and efficiency (EF). The result showed that the predicted values were very close to experimental values. It was also found that out of all these models the values of RMSE and chi square were found lowest, and values of EF were found highest at particular temperature and in larger range value of constants $n = 1$ on modified page model. The modified page model was found to be in good agreement with the experimental results $\chi^2 = 0.0015$, RMSE = 0.0323 and EF = 0.9823 for all drying temperatures taken up in the present study.

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