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# DRYING KINETICS AND MATHEMATICAL MODELING OF FAR-INFRA RED VACUUM DRYING OF SOME VEGETABLES AND FRUITS

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**Abstract:**
In this paper the drying kinetics of far-infrared vacuum drying of some vegetables and fruits are presented. The experimental data of drying kinetics were obtained on experimental drying setup designed to imitate industrial dryer. Two well-known thin layer drying models from scientific literature were used to approximate the experimental data of drying kinetics in terms of moisture ratio. The performed statistical analysis shows that the model of Aghbashlo gives the best results for approximation of experimental drying data.

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## 1. INTRODUCTION

Drying is the most common method for preservation of food materials. This process improves the food stability, since it reduces considerably the water and microbiological activity of the material and minimizes physical and chemical changes during its storage [1]. The traditional method which is used in drying of fruits and vegetables through sunlight is not common nowadays it takes more time leading to a low-quality product with microbial growth and low process capability [2]. From the other side convective hot-air drying is the most widely used method for the production of dehydrated fruits and vegetables. The main disadvantages of this classical drying process are the low dehydration capacity of the dried materials and the material color changes during drying [3]. For better quality of dried fruits and vegetables, vacuum freeze - drying technique is used. However, the freeze-drying process has two major disadvantages: large energy demand, lengthily drying time and consequently high production costs [3]. Increasing concern for product quality and the need for minimized processing and energy costs led to a more detailed study of drying of food materials. In recent years, far-infrared drying method is very popular alternative method for drying of variety food materials. In the process of infrared radiation drying, the energy in the form of electromagnetic wave is absorbed directly by the product without loss to the environment leading to considerable energy savings, uniform temperature distributions in the product during drying, and a reduced necessity for air flow across and keeping good product quality [4]. The use of infrared radiation in drying processes, has more advantages compared to hot air convective drying, such as: high energy efficiency, uniform heating of material, acceleration of drying process or decreasing of drying time and improved dried product quality [5]. Although infrared radiation can accelerate drying process, heat-sensitive materials, such as agricultural materials and foods, could be damaged or degraded along with the quality decreasing, if radiation intensity is not properly applied [6]. Since most fruits and vegetables are heat-sensitive in nature and easily degrade at the presence of oxygen, it is desirable to be able to dry at low

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temperature and low oxygen content to preserve the quality [7]. In vacuum drying of food, moisture within the product being dried evaporates at lower temperatures (lower than 100 °C) giving better product quality, especially in the cases of foods or agricultural products, which are heat-sensitive in nature [6]. Due to the high energy consumption in this method, vacuum drying can be used for highly sensitive and high value-added products [8]. With combined advantages of both drying methods, high-energy efficiency of the drying process is enhanced and degradation of dried product quality is also reduced [8]. In scientific literature several researches experimentally, investigated vacuum far-infrared drying of various food products and plants: banana [9], carrot [6], dogwood (cornusofficinalis) [7], mushrooms [3,10-12]; onion [5], red pepper [13], pistachios [14], potato [8,15], apple [16]. The objectives of this paper were experimental research of drying kinetics of far-infrared vacuum drying of potato and apple slices and mathematical modeling of drying curves.

## 2. EXPERIMENTAL SETUP AND PROCEDURES

### 2.1. Experimental setup

The experimental data set of thin-layer drying kinetics of potato and apple  slices at different heater temperatures and different vacuum pressures were obtained on the experimental setup apparatus, (Fig.1), designed to imitate industrial dryer [17]. The experimental setup consisted of two basic units. The first unit was composed of vacuum pump (1) with separator (2) and vacuum chamber (3) with vacuum meter (4), temperature controller (5) and vacuum regulator (6). The second unit contained micro-thermocouples (8), load cell (9), data acquisition system (12) and personal computer (14). The required temperature in the vacuum chamber was maintained by regulation of the resistance of the heaters (11) with 28-segment programmable temperature controller in which over temperature protection is incorporated with included PID precise temperature control with temperature fluctuation of ±1 °C. The required temperature in the chamber and drying time were set by this controller. When the temperature was achieved, the samples (7) were put on the shelf (10), in the vacuum chamber. The vacuum pressure in the chamber was achieved by single step rotary vane vacuum pump, type EQ-2XZ. The vacuum pressure in chamber was kept constant during single experiments, while its value was regulated with the vacuum regulator (6). The transient temperatures of drying samples were measured with three micro-thermocouples (8) placed in the mid-plane of the drying samples. The micro-thermocouples were connected to data acquisition system contained of computer interface (12), type IDRN-ST, 24-bit A/D converter (13), type OMB-DAQ-2408 and data acquisition software.


**Fig.1.** Experimental far-infrared vacuum setup
1-vacuum pump, 2-separator, 3-vacuum chamber, 4-vacuum meter, 5-temperature controller, 6-vacuum regulator, 7-samples, 8-micro-thermocouples, 9-load cell, 10-shelf, 11-heaters, 12-data acquisition system,13-24 bit A/D converter, 14-personal computer

The measurement of sample's mass changes with time was enabled with load cell type OMEGA LCL 040, which was connected to data acquisition system. The temperature and mass changes were registered on personal computer.

### 2.1 Procedures

The potatoes variety ”Carrera” and apples variety ”Golden Delicious” separately were used in the experimental part of the research. The samples were stored in a refrigerator at 4 °C until usage. To prepare samples, the potatoes and apples were washed, peeled and sliced in order to obtain uniform samples with thickness of $3±10^{-1}$ mm, before being reduced to a cylinder form with diameter of $43±10^{-1}$ mm. The initial moisture content of fresh slices and the final moisture content of dried samples were determined gravimetrically by hot air oven method at 105 °C and atmospheric pressure for a period of 24 h.

## 2. MATHEMATICAL MODELLING OF DRYING CURVES

Two thin-layer mathematical models given in Table 1 were used to approximate experimental data of the drying kinetics of potato and apple slices.

**Table 1.** Thin-layer mathematical drying models*

| Model | Equation | Name of model | References |
|---|---|---|---|
| *M*01 | MR = exp(-$k_1\tau/(1+k_2\tau)$) | Aghbashlo | [18] |
| *M*02 | MR = Aexp(-$k_1\tau$+ $B\tau^{0.5}$)+C | Jena and Das | [19] |

*A, B, C parameters, $k_1$, $k_2$, drying constants, τ drying time

In these models, the moisture ratio (*MR*) is defined by the following equation.

$$MR = (M - M_{eq}) / (M_0 - M_{eq}). \quad (1)$$

Because of the values of equlibrium moisture content, $M_{eq}$ are relatively small compared to those of moisture content of material, *M* or initial moisture content, $M_0$, so the error involved in the simplification is negligible. Thus moisture ratio was then calculated as:

$$MR = M/M_0. \quad (2)$$

In order to estimate and select the best thin-layer drying model performance index, ϕ was calculated. The value of performance index, ϕ was calculated on the basis of calculated values for coefficient of determination, $R^2$, the root mean squared error, *RMSE* and the mean relative deviation, *MRD* [20].

$$\phi = \frac{R^2}{RMSE \cdot MRD}. \quad (3)$$

Higher values of performance index, ϕ indicate that thin-layer model better approximates the experimental data. The D'Agostino-Pearson test of normality is the most effective procedure for assessing a goodness of fit for a normal distribution [21]. This test is based on the individual statistics for testing of the population of skewness, $z_1$ and kurtosis, $z_2$, respectively. The test statistic for the D'Agostino-Pearson test of normality is computed with equation [21]:

$$\chi^2 = z_1^2 + z_2^2. \quad (4)$$

The $\chi^2$ statistics has a chi-squared distribution with 2 degrees of freedom (df). The tabled critical 0.05 chi-square value for df = 2 is $\chi^2_{.05}$ = 5.99. Therefore, if the computed value of chi-square is equal to, or greater than, either of the aforementioned values, the null hypothesis can be rejected at the appropriate level of significance [21], i.e. the thin-layer model should be rejected. The best model that is describing the thin-layer drying characteristics of potato and apple slices has to be chosen on the basis of higher, ϕ value and lower, $\chi^2$ value [17].

## 3. RESULTS AND DISCUSSION

The experimental moisture content data obtained at different heater temperatures, 120, 140, 160, 180 and 200 °C and different absolute vacuum pressures, 20, 40, 60 and 80 kPa for potato [15] and apple [16] were converted to the moisture ratio, MR, and then fitted to the two thin-layer drying models given in Table 1. Because the regression method, estimation method, the initial step size, the start values of parameters, convergence criterion and form of the function have significant influence on accuracy of estimated parameters [22], a large number of numerical experiments were performed. The method of indirect non-linear regression and estimation methods of Quasi-Newton, Simplex, Simplex and quasi-Newton, Hooke-Jeeves pattern moves, Hooke-Jeeves pattern moves and quasi-Newton, Rosenbrock pattern search, Rosenbrock patternsearch and quasi-Newton, Gauss-Newton and Levenberg-Marquardt from computer program StatSoft Statistica (Statsoft Inc., Tulsa, OK, http://www.statsoft.com), were used in numerical experiments. On the basis of thin-layer data of quince and each model from Table 1, the average values of: coefficient of determination, $R^2$, root mean squared error, *RMSE*, mean relative deviation, *MRD*, performance index, ϕ and $\chi^2$ were calculated. When the value for coefficient of determination obtained from different estimation methods was different, the greatest value was accepted as relevant. After that, the thin layer models were ranked on the basis of average values of performance index, $\phi_a$, Table 2.

**Table 2.** Statistic summary of the regression analysis*

| Model | $R_a^2$ | $RMSE_a$ | $MRD_a$ | $\phi_a$ | $\chi_a^2$ | Rank | Materials |
|---|---|---|---|---|---|---|---|
| M01 | 0.9997 | 0.0056 | 0.2017 | 1322.8 | 1.3324 | 1 | potato |
| M02 | 0.9979 | 0.0155 | 0.9739 | 291.41 | 2.1483 | 2 | potato |
| M01 | 0.9999 | 0.0048 | 0.0690 | 6613.7 | 1.1219 | 1 | apple |
| M02 | 0.9986 | 0.0190 | 0.5774 | 174.50 | 1.1932 | 2 | apple |

*"a" average values were calculated for five temperature of heater's and four absolute vacuum pressures

From Table 2, it is evident that model *M*01 i.e. Aghbashlo model, has the highest value of average performance index $\phi_a$ = 1322.8 and lowest average chi-squared value $\chi_a^2$ = 1.3324 for potato and $\phi_a$ = 6613.7 and $\chi_a^2$ = 1.1219 for apple. So, this model may be selected to represent the thin layer drying behavior of potato and apple slices for all drying conditions. In accordance with statistical criteria, the Aghbashlo model is able to correlate the experimental values of drying kinetic of potato slices with 0.56 % average root mean squared error and with 0.48 % average root means squared error for apple. The estimated values of parameters for the Aghbashlo model at different heater temperatures and different absolute vacuum pressure in chamber for potato and apple are given in Table 3.

**Table 3.** Non-linear regression parameters

| t [°C] p [kPa] | $k_1$ | $k_2$ | t [°C] p [kPa] | $k_1$ | $k_2$ |
|---|---|---|---|---|---|
| 120 20 | 0.0098 | -0.0036 | 120 20 | 0.0127 | - 0.0055 |
| 120 40 | 0.0093 | -0.0036 | 120 40 | 0.0121 | - 0.0055 |
| 120 60 | 0.0086 | -0.0036 | 120 60 | 0.0116 | - 0.0055 |
| 120 80 | 0.0080 | -0.0035 | 120 80 | 0.0110 | - 0.0055 |
| 140 20 | 0.0095 | -0.0057 | 140 20 | 0.0131 | - 0.0073 |
| 140 40 | 0.0102 | -0.0053 | 140 40 | 0.0131 | - 0.0067 |
| 140 60 | 0.0090 | -0.0052 | 140 60 | 0.0130 | - 0.0065 |
| 140 80 | 0.0093 | -0.0048 | 140 80 | 0.0130 | - 0.0061 |
| 160 20 | 0.0195 | -0.0044 | 160 20 | 0.0203 | - 0.0098 |
| 160 40 | 0.0174 | -0.0047 | 160 40 | 0.0194 | - 0.0095 |
| 160 60 | 0.0155 | -0.0050 | 160 60 | 0.0188 | - 0.0091 |
| 160 80 | 0.0135 | -0.0051 | 160 80 | 0.0178 | - 0.0091 |
| 180 20 | 0.0185 | -0.0084 | 180 20 | 0.0245 | - 0.0119 |
| 180 40 | 0.0170 | -0.0083 | 180 40 | 0.0240 | - 0.0112 |
| 180 60 | 0.0149 | -0.0083 | 180 60 | 0.0240 | - 0.0104 |
| 180 80 | 0.0134 | -0.0081 | 180 80 | 0.0239 | -0.0097 |
| 200 20 | 0.0248 | -0.0083 | 200 20 | 0.0344 | - 0.0120 |
| 200 40 | 0.0224 | -0.0088 | 200 40 | 0.0327 | - 0.0115 |
| 200 60 | 0.0209 | -0.0088 | 200 60 | 0.0320 | - 0.0108 |
| 200 80 | 0.0171 | -0.0091 | 200 80 | 0.0310 | - 0.0103 |

As shown in Fig.2 and Fig.3 a good match was found between experimental and calculated values with the model of Aghbashlo.

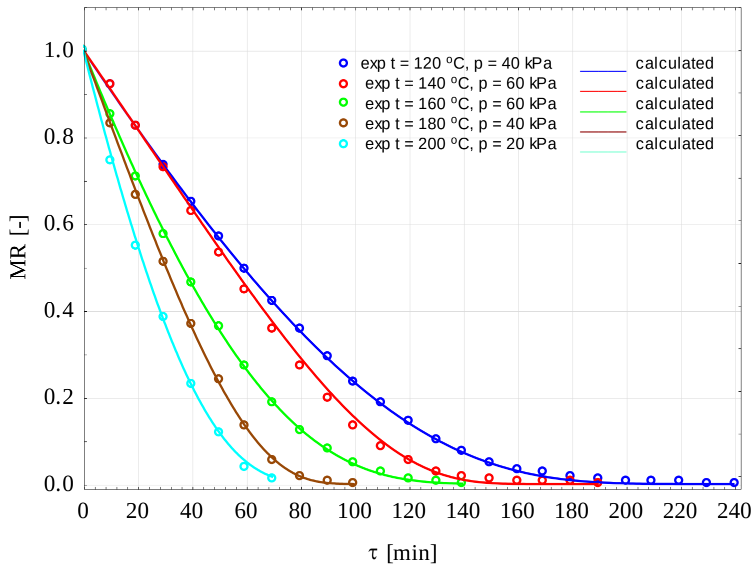


**Fig.2.** Experimental and predicted moisture ratio for different heater temperatures and different absolute vacuum pressures in chamber-potato

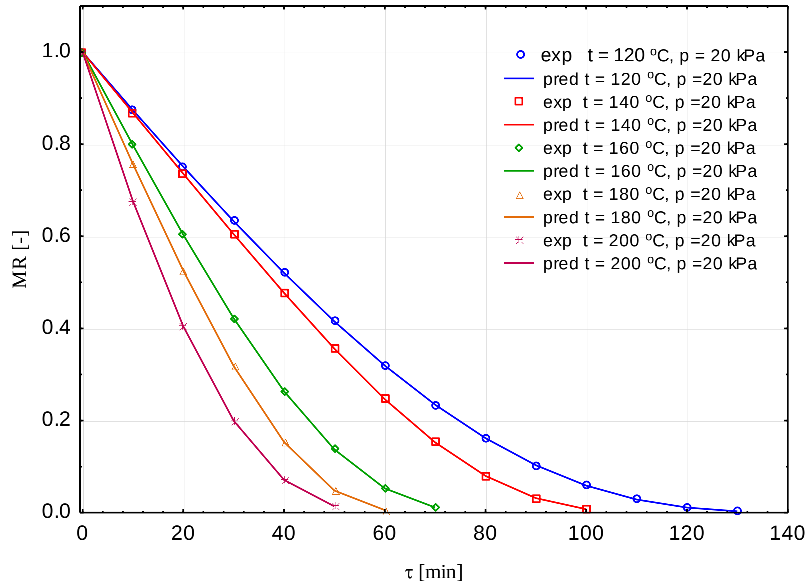


**Fig.3.** Experimental and predicted moisture ratio for different heater temperatures and different absolute vacuum pressures in chamber-apple

## 4. CONCLUSION

In the presented study, the drying kinetics of potato and apple slices under far-infrared vacuum drying was investigated. Experiments were carried out for five values of the heaters temperature and four absolute vacuum pressures in the drying chamber. The experimental drying data in terms of moisture ratio were approximated with two well known thin layer drying models. The goodness of fit for those models was determined using performance index $\phi^2$ and chi-squared value $\chi^2$. According to the results obtained from statistical analyzes it was concluded that the Aghbashlo model could adequately describe the thin layer drying behavior of potato and apple slices.

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