Experimental Investigation of the Drying Kinetics of Corn in a Packed and Fluidized Bed

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ABSTRACT: *In this paper, experimental data on the drying kinetics of corn in a packed and fluidized bed are presented. Experimental research was conducted on a laboratory apparatus. Corn was used as a material because of its significance in agriculture and the food industry. An analysis of the influence of the operational parameters (the drying medium velocity i. e. the fluidization number, the drying medium temperature and the height of a packed bed) on the drying kinetics of corn, was performed. The experiment shows that increasing the fluidization number and the velocity of the drying medium, has no significant influence on the drying kinetics of corn, except during the initial period of drying.*

KEY WORDS: *Corn; Drying kinetics; Packed bed; Fluidization.*

INTRODUCTION

High energy consumption in drying industry has distinguished drying as an energy demanding function with immense industrial importance [1, 13]. One of the modern drying procedures is drying of material in a fluidized bed without [3] or with inert particles [2]. This subject has been of special interest during the last decades with more papers dedicated to is. The fluidization phenomenon has attracted the attention of numerous researchers [5, 10]. Its appliance in various technological operations stems from its excellent properties, which are reflected in: intensive mixing of solid particles, a high contact-surface between gas and solid particles, an almost constant temperature in the entire bed, as well as simple insertion and removal of the material from the bed [4, 10]. In many operations in a fluidized bed heat exchange occurs between gas and solid particles that include the exchange of matter and possibly some chemical reactions. Drying of a material in a fluidized bed is most frequently performed by using heated humid air, which in this case has two roles, as a drying medium and as a fluidizing medium for solid particles of the material. In the fluidized bed the non-sticky grained, paste and liquid materials can be dried.

Production of corns such as maize has a great economic importance due to the large quantity of starch, corn syrup, ethanol, oil and other products. Corns are characterized by high initial moisture content at harvest. Hence drying becomes an essential operation before storage [14]. The main aim of this paper is to provide the experimental data on the drying kinetics of the corn ZP-704

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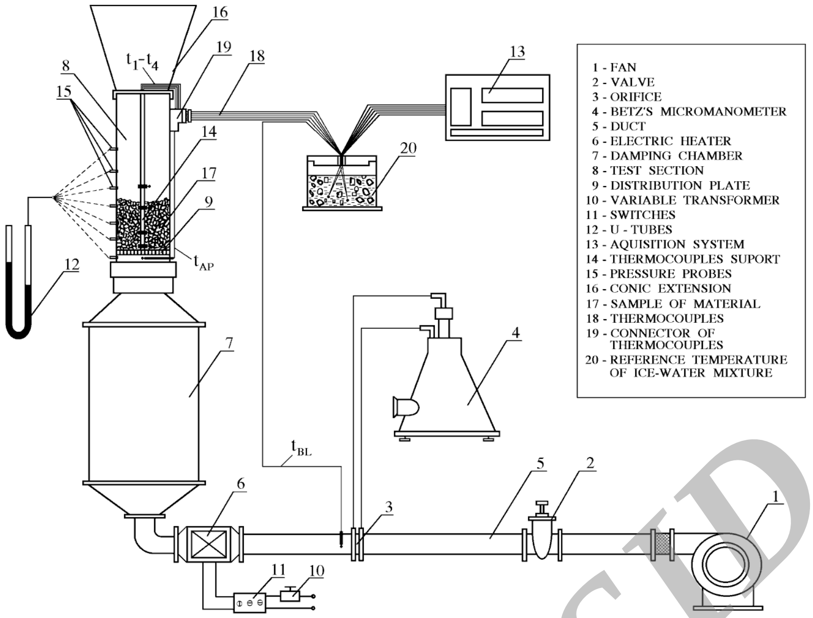

Fig. 1: Schematic layout of experimental apparatus.

(a well-known corn hybrid with the following physical properties: d_p = 7,1 mm; ρ_p = 1135 kg/m^3; ε_{mf} = 0,37) in a packed and fluidized bed, under various drying regimes. On the basis of experimentally determined drying kinetic curves of corn in the packed bed, the elementary height of corn bed has been determined, and by generalization of experimental data on the drying kinetics for the elementary bed of corn, the analytical relation for the inside mass transfer coefficient has been determined [9]. As with many other authors, an analysis of the quality of the product is performed at the end of the drying process [15]. In the fluidization of fine and coarse materials one should always take into account the velocity of corse elutriation. Many authors have analyzed this issue and obtained empirical correlations that can be used to predict the elutriation of particles [11].

EXPERIMENTAL SECTION

Various existing methods used for drying include constant temperature drying in the range 30 °C to 90 °C. One of the methods used is the microwave drying of corn [7].

For the experimental investigation of the drying kinetics of corn, the apparatus, schematically shown in Fig. 1, was used.

The fan (1) moved the air through the duct (5), in which the devices for measurements and control were mounted. The needed air-flow rate was heated in the heater (6) up to a desired temperature and introduced into the damping chamber (7) providing appropriate distribution of air across the cross-sectional area in the test section.

The test section of apparatus (8) had the circular cross section, 120 mm in inner diameter and 530 mm in height, made of transparent plexiglass 5 mm in thickness, in order to make the process visible. The distribution plate (9) had to enable both the uniform distribution of air and the nice fluidization (the occurrence of “dead” zones of solid particles is unwanted in the fluidized bed). The distribution plate was made of plexiglass 4 mm in thickness with 690 holes 1,5 mm in diameter which were at 4 mm distance between each other. In order to improve the quality of fluidization, three textile sheets were placed below the distribution plate.

Temperatures were measured by six appropriate situated K-type thermocouples (18) (chromel - alumel) 0,2 mm in diameter, which were connected with the Hewlett Packard acquisition system (13). Air temperature behind the orifice was measured by thermocouple t_{BL}, and air temperature below the distribution plate by thermocouple t_{AP}. During the investigation of the drying kinetics of corn in the packed bed, thermocouples (t_1, t_2, t_3) were inserted inside the corn grains and these grains were placed at the bottom, the middle of the height and the top of the bed. In order to prevent conductive loses, the thermocouple leads were inserted through a few corn grains.

In fluidized bed experiments the thermocouples (t_1, t_2, t_3) are immersed in the bed and placed along the axis of test section (Fig. 1). The assumption is that the thermocouples measure the temperatures of corn grains in the fluidized bed, i.e.: thermocouple t_1 at the bottom of bed, thermocouple t_2 at the middle of the height of the bed, and thermocouple t_3 at the top of the bed. Air temperature above the corn bed is measured by thermocouple t_4.

Each experimental run had three periods. In the first period, the initial moisture content of corn was determined and the quantity of corn needed to achieve the desired height of the packed bed was determined. At the same time, by running the fan, and by regulation of both the air flow rate and the power of electric heater, the steady operating conditions of apparatus were achieved. After reaching the desired temperature of the drying medium, the test section was mounted on the damping chamber (Fig. 1), and the second period of drying started. During the experimental run the corn-grain temperatures were measured along the height of the bed and also the temperature of the drying medium was measured above the bed. At certain time intervals (five minutes at the beginning and ten and fifteen minutes in the latter periods of the experimental run) the test section was disconnected from the dumping chamber and the instantaneous mass of the test section together with the material was registered. The break of the experimental run was usually five to ten seconds. After reaching the moisture content of corn from 0,10 kg/kg (d.b.) to 0,12 kg/kg (d.b.) the experimental run was stopped. From the dried corn four samples were taken. One sample was used in analyzing the quality of dried grains, and other three were dried in the laboratory dryer (the third period) in order to obtain the boundary moisture contents of corn.

Firstly, a set of experiments were carried out with a variable height of the packed bed (100 mm, 70 mm, 50 mm, 40 mm, 30 mm, 20 mm, 15 mm, and 10 mm) and other experimental parameters constant (initial air temperature $t_o \approx 70$ °C; air velocity $V_o \approx 1{,}05$ m/s). On the basis of these experimental data the elementary height of the corn bed was determined.

After that, the drying kinetic curves of the elementary corn bed were determined experimentally for variable temperatures and air velocities.

The experimental investigations of drying in the fluidized bed were performed for three various corn-bed heights: 50 mm, 100 mm, and 150 mm.

The velocity of air related to the total cross section area of the apparatus (V_o) was varied in the range of 2,25 m/s to 6,00 m/s. For each bed height the flow situations with three fluidization numbers ($K_1 \approx 1{,}5$, $K_2 \approx 2{,}6$, and $K_3 \approx 4{,}0$) were simulated.

For each height of the bed and each fluidization number three temperatures of the drying medium (60 °C, 70 °C and 80 °C) were achieved.

Since the initial moisture content of corn was not constant in all experiments, in order to analyze the influence of a fluidization number on the drying kinetics of corn in the fluidized bed, three experimental runs with the same initial corn-moisture content, the same drying-medium temperatures for various fluidization numbers, were performed. For all above regimes the drying curves and temperature curves were obtained and shown in diagrams.

RESULTS AND DISCUSSION

Before performing the experiments on the drying kinetics of corn, the basic bed characteristics were determined. The minimal fluidization velocity was determined experimentally, from the fluidization curve. The minimum fluidization velocity (V_{mf}) is the drying medium velocity at which the bed of material is transferred to the fluidized state. This velocity is used for the fluidization number determination. The fluidization number is the ratio of the operating velocity and the minimum fluidization velocity ($K = V_o/V_{mf}$) of the drying medium and is a measure of the fluidization intensity. The minimum fluidization velocity for corn hybrid ZP-704 with the moisture content 0,1 kg/kg (d.m.) is $V_{mf} = 1{,}5$ m/s.

Determination of the height of the elementary corn bed

The elementary material bed is defined as a material bed in which a change in drying of the material and the drying medium parameters over the height (thickness) can be considered as linear and differentially small. The study of the kinetics of thick material layer drying is more complex, because the change of parameters of the material and the drying medium in the layer are not even nearly linear. Therefore, the thick material bed is seen

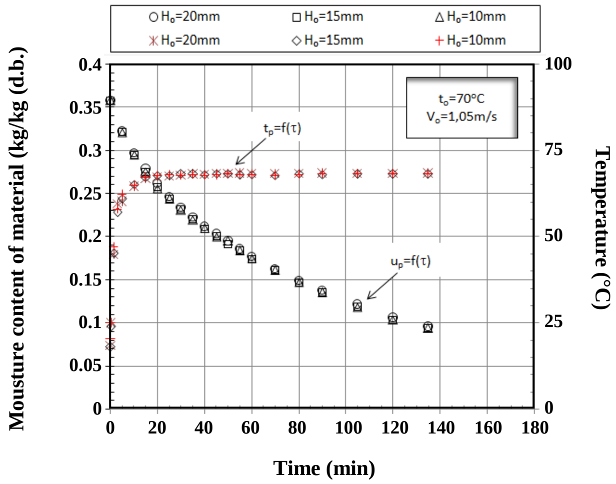

Fig. 2: Drying kinetic curves of corn in the packed bed.

as a series of elementary beds with defined and mathematically described heat and mass transfer for each layer [6]. Therefore, the thick layer of material drying kinetics curve is determined with "layer by layer" balance equations.

The height of an elementary bed is the height of that bed of material which has identical drying kinetic curves as the beds with smaller heights. In Fig. 2 the experimentally drying kinetic curves of corn in the packed beds (20 mm, 15 mm, and 10 mm) are shown. Since the drying kinetic curves of corn for the bed heights of 15 mm and 10 mm are almost identical, the corn bed with 15 mm in height was accepted as the elementary one.

Determination of the inside mass transfer coefficient

In order to find the drying velocity of a material, it is necessary to know the inside mass transfer coefficient of the moisture.

For practical determination of the inside mass transfer coefficient the following expression can be used:

$$k_{un} = \frac{\dfrac{\Delta M}{\Delta \tau}}{\bar{M} - M_e} \qquad (1)$$

where all the parameters on the right side of this relation are determined by experiment.

The practical determination of the coefficient k_{un} is achieved by differencing of the experimentally determined curves of the elementary bed of material drying kinetics. Values of the mean temperature and moisture content of the material during the drying process are experimentally determined, based on the known parameters of the drying medium. Based on the acquired data, knowing the value of the equilibrium moisture content M_e for each measurement point, the value of the coefficient k_{un} of dried material is calculated, according to Eq. (1).

The equilibrium moisture content of corn as a function of temperature and relative humidity of the drying air is determined by Eq. (2) [6]:

$$M_e = \left[-\frac{\ln(1-RH)}{0,0397\,t^2 + 1,2585\,t + 160,57} \right]^{0,375} \qquad (2)$$

where t is the drying air temperature in °C and RH is the relative humidity of drying air as a decimal.

The analytic relation for this coefficient (k_{un}) can be obtained by a generalization of the experimental data on the drying kinetics in the elementary bed of material [6, 9].

Fig. 3 shows the drying curves of the elementary corn bed as a function of the air temperature.

The analytical relation for the inside mass transfer coefficient is obtained in the form Eq. (3):

$$k_{un} = 8,34357 \cdot 10^{-4} \left(\frac{\bar{M}}{M_o} \right)^{0,709126} \left(\frac{\bar{t}_p}{t_{po}} \right)^{-0,723053} \qquad (3)$$

Analysis of the influence of operation parameters on the drying kinetics of corn

In order to perform the analysis of the influence of the operating parameters on the drying kinetics in a fluidized bed, the summarizing diagrams for three different values of one parameter were established.

Fig. 4 shows the drying curves as a function of the air temperature, Fig. 5 shows the same curves as a function of the packed bed height, and Figs. 6 and 7 the drying curves as a function of the fluidization number. In each figure, the operation parameters are presented.

On the basis of the experimental results one can conclude as follows:

- With an increasing of the fluidizing air temperature the drying process becomes much faster. These results were obtained by other authors [16]. For instance, for fluidization number K ≈ 4,0 and for the packed bed height H_o = 150 mm with an increase in the fluidizing air temperature from 60 °C to 80 °C, the drying time for

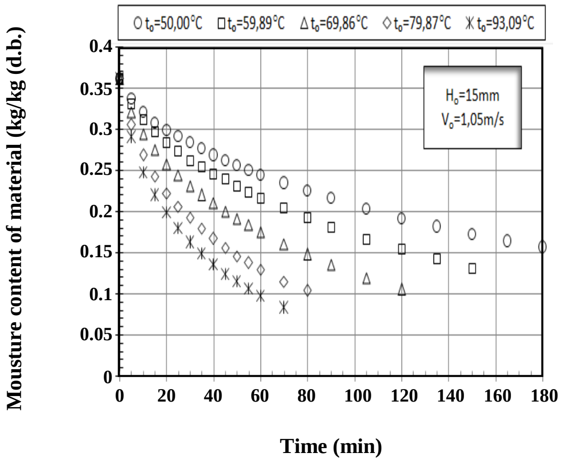

Fig. 3: Drying curves of corn in the elementary bed as a function of the air temperature.

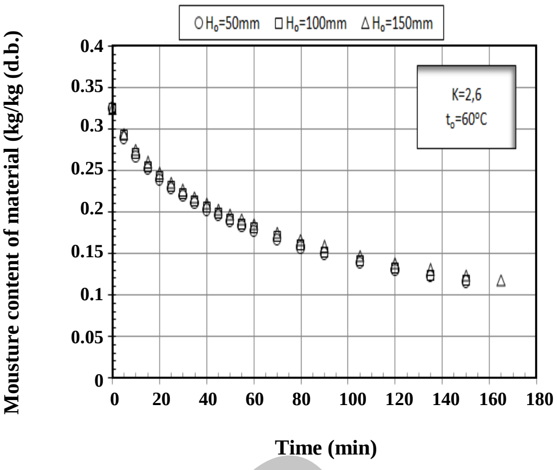

Fig. 5: Drying curves of corn in the fluidized bed as a function of the packed bed height.

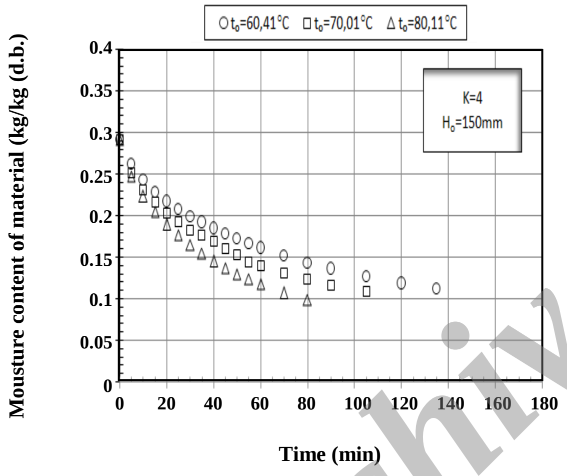

Fig. 4: Drying curves of corn in the fluidized bed as a function of the air temperature.

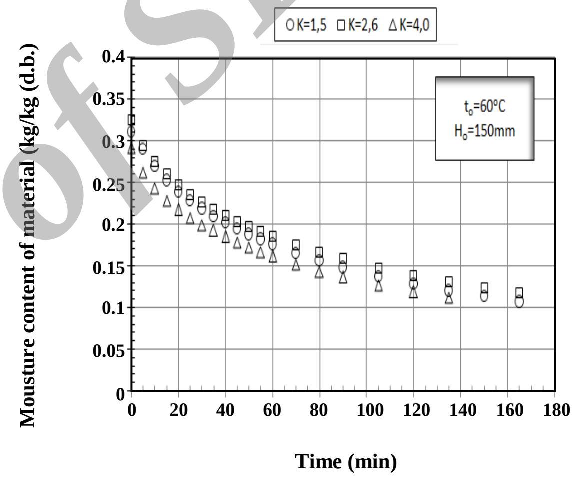

Fig. 6: Drying curves of corn in the fluidized bed as a function of the fluidization number.

obtaining the moisture content in corn of 0,11 kg/kg (d.b.) is shorter for almost 75 min (Fig. 4);

- Variation of the packed bed height of corn has small effect on the drying kinetic curves (Fig. 5); it can be explained by good mixing of the corn grains in the fluidized bed, where one must have in mind that the experiments were performed on an apparatus of small dimensions with correspondingly small packed bed heights of corn;
- increasing the fluidization number has no greater effect on the drying curves of corn, except in the initial period of the drying process (Fig. 6 and Fig. 7);
- Fig. 8 presents the temperature curves (measured by thermocouple t_2) as a function of the fluidization number.
- Variation of the overall temperature of air and particles of the fluidized bed is very small, except in the initial period of the drying process (Fig. 8).
- Fig. 9 presents the drying kinetic curves of corn, in the packed (V_0 = 1,05 m/s) and fluidized bed (V_0 = 3,9 m/s (K=2,6) and V_0 = 6,0 m/s (K=4,0)) for the air temperature of 70 °C and the packed bed height of H_o = 50 mm.

Besides the fact that in the compared experiments on the drying kinetic in the packed and fluidized bed the initial moisture content of material was not the same, one can conclude that the drying process in the fluidized bed is the more intense one, especially in the initial period of the process.

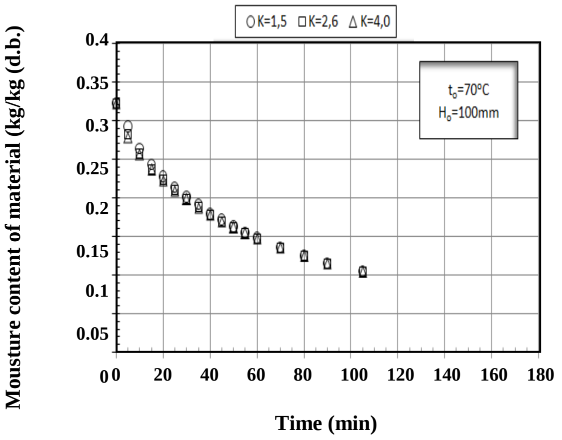

Fig. 7: Drying curves of corn in the fluidized bed as a function of the fluidization number.

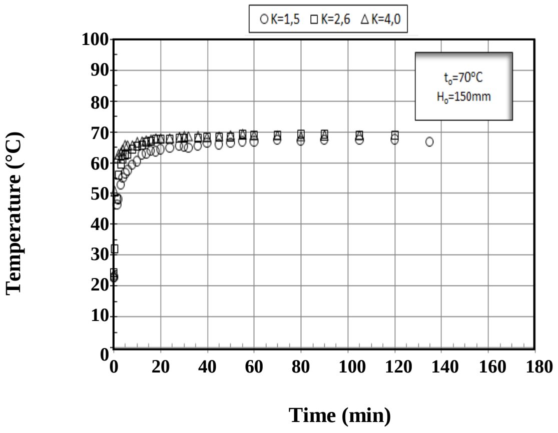

Fig. 8: Variation of bed temperature (overall temperature of air and particles) during the drying of corn in the fluidized bed as a function of the fluidization number.

CONCLUSIONS

During the investigation of the drying kinetics of corn, 49 experimental runs were carried out. On the basis of the drying kinetic experimental data of corn in the packed bed (8 runs), the height of the elementary bed was determined (H_o = 15 mm). By generalization of the experimental data on the drying kinetics of the elementary corn bed (11 experimental runs), the analytic relation for the inside mass transfer coefficient for moisture was obtained.

It is found that an increase in the fluidization number and the velocity of the drying medium has no significant influence on the drying kinetics of corn, except in the initial period of drying, when a more intense drying process will occur for the higher fluidization number. These results coincide with the results of other authors who have also investigated the corn drying in a fluidized bed under the following conditions: inlet hot air temperatures of 120 °C to 200 °C, superficial air velocities of 2.2 m/s to 4 m/s, bed depths of 4 cm to 12 cm, [8].

At the end of each of the experiments on the drying kinetics of corn in the fluidized bed a representative sample of around thirty grains was taken randomly. To determine the appearance of cracks in the dried grain of corn, each grain was observed first visually, and then under a 10x magnifying glass. It was determined that the majority of grains (around 92 %) had cracks in them. It can be concluded that the degree of fluidization has a great influence on the shape, size, and number of cracks in the corn grain. At higher values of the degree of fluidization the cracks in the cron grain are much more prominent, particularly in those grains that were dried in the higher layer. On the basis of the obtained results the influence of air temperature on the appearance of the dried grain of corn was also examined. With an increase in air temperature from the initial value of 60 °C to the final value of 80 °C, the number of cracked grains also rose to 15 %. Similar conclusions have also been reached by other authors [17].

Nomenclature

d_p	Equivalent diameter of particle, m
H_o	Height of packed bed, m
k_{un}	Inside mass transfer coefficient, 1/s
K	Fluidization number
RH	Relative humidity of drying air
t_o	Air temperature at the inlet in bed, °C
t_p	Material temperature, °C
t_{po}	Initial temperature of material, °C
M	Moisture content of material reduced on dry basis, kg/kg (d.b.)
M_o	Initial moisture content of material reduced on dry basis, kg/kg (d.b.)
M_e	Equilibrium moisture content of material reduced on dry basis, kg/kg (d.b.)
V_{mf}	Minimal fluidization velocity, m/s
V_o	Superficial air velocity, m/s
ε_{mf}	Porosity of bed at minimal fluidization velocity
ρ_p	Density of material, kg/m^3
τ	Time, min

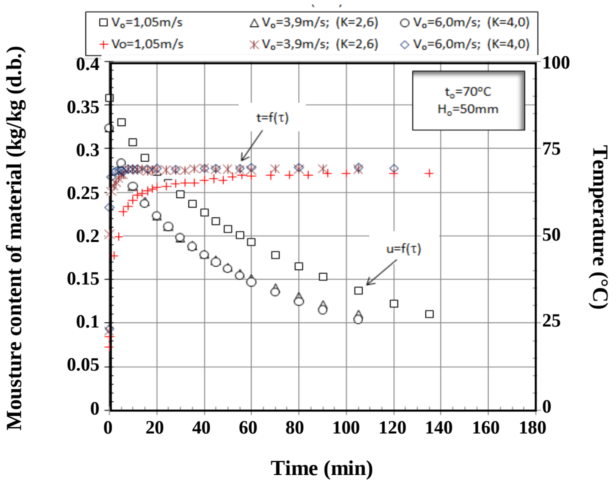

Fig. 9: Comparison of the drying kinetic curves of corn in the packed and fluidized bed.

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REFERENCES

[1] Abbasyadeh A., Motevali A., Ghobadian B., Khoshtaghaza M., Minaei S., Effect of Air Velocity and Temperature on Energy and Effective Moisture Diffusivity for Russian Olive in Thin-Layer Drying, *Iranian Journal of Chemistry and Chemical Engineering (IJCCE)*, **31**(1): 75-79 (2012).

[2] Hatamipour M.S., Mowla D., Correlations for Shrinkage, Density and Diffusivity for Drying of Maize and Green Peas in a Fluidized Bed with Energy Carrier Particles, *Journal of Food Engineering*, **59**: 221-227 (2003).

[3] Jovanović G., Ćatipović N., Fitzgerald T., Levenspiel O., "Fluidization", Plenum, 325-332 (1990).

[4] Lee D.H., Kim S.D., Mathematical Model for Batch Drying in an Inert Medium Fluidized Bed, *Chemical Engineering Technology* **22**: 443-450 (1999).

[5] Lykov A.V., "Heat and Mass Transfer" (Teplomasoobmen), Energia, Moscow, (1976).

[6] Milojević D., "Analysis of Heat and Mass Transfer Kinetics of Convective Drying in Dense Grained bed of Capillary-Porous Colloid Materials", M. S. Thesis, Faculty of Mechanical Engineering, University of Belgrade (1979).

[7] Nair G. R., L. Zhenfeng, Y. Garipey, V. Raghavan, Microwave Drying of Corn for the Seed Industry, *Drying Technology*, **29**: 1291-1296 (2011).

[8] Soponronnarit S., Pontornkulpanich A., Prachayawarakom S., Drying Characteristics of Corn in Fluidized Bed Dryer, *Drying Technology*, **15**:1603-1615 (1997).

[9] Stefanović M., Nešić S., "Presentation of the ITE Method for Analysis of Drying Kinetics and the Computer Program for its Application", IBK-ITE-488, Vincha - Belgrade (1984).

[10] Stojanović B., Janevski J., Stojiljković M., Experimental Investigation of Thermal Conductivity Coefficient and Heat Exchange between Fluidized Bed and Inclined Exchange Surface, *Brazilian Journal of Chemical Engineering*, **26**, 343-352 (2009).

[11] Stojkovski V., Z. Kostić, Empirical Correlation for Prediction of the Elutration Rate Constant, *Thermal Science*: **7**: 43-58 (2003).

[12] Strumillo C., Kudra T., "Drying: Principles, Applications and Design", Gordon&Breach Science Publishers, New York, USA, (1987).

[13] Abbasyadeh A., Motevali A., Ghobadian B., Khoshtaghaza M., Minaei S., Effect of Air Velocity and Temperature on Energy and Effective Moisture Diffusivity for Russian Olive in Thin-Layer Drying, *Iranian Journal of Chemistry and Chemical Engineering (IJCCE)*, **31**(1): 75-79 (2012).

[14] Srzednicki G., Driscoll R. H., Xinghe N., Daolin G., Strategies for In-store Drying Based on the Analzsis of Weather Data-Case Study, *Drying Technology*, **30**(16): 1863-1869 (2012).

[15] Estrada J. A., Litchfield J. B., High Humidity Drying of Corn: Effect on Drying Rate and Product Quality, *Drying Technology*, **15**(2): 539-554 (1997).

[16] Khanali M., Rafiee Sh., Jafari A., Hashemabadi S.H., Banisharif A., Mathematical Modeling of Fluidized Bed Drying of Rough Rice Grain, *Journal of Agricultural Technology*, **8** (3): 795-810 (2012).

[17] Abasi S., Minaei S., Effect of Drying Temperature on Mechanical Properties of Dried Corn, *Drying Technology*, **32**(7): 774-780 (2014).