TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
MECHANICS | MECHANIKA
2-M/2016

STANISLAV RUDOBASHTA*, GALINA ZUEVA**, VJACHESLAV DMITRIEV***

THEORETICAL AND EXPERIMENTAL BACKGROUNDS OF OSCILLATING INFRARED DRYING DISPERSED MATERIALS

TEORETYCZNE I EKSPERYMENTALNE PODSTAWY OSCYLACYJNEGO SUSZENIA PROMIENNIKOWEGO MATERIAŁÓW SYPKICH

A b s t r a c t

The research on the influence of the initial moisture content of seeds, of the duration of IR drying, of temperature regime on the effect of stimulation and keeping the effect with time, was carried out. A mathematical model for the dynamics of heating a seed layer, taking into account the moisture evaporation, is developed. Paper presents experimental data on mass conductivity properties for a dried layer of seeds, the recommendations for process equipment design are given.

Keywords: drying, kinetic calculation, zone method, dispersed materials

S t r e s z c z e n i e

W pracy analizowano wpływ początkowej zawartości wilgoci w nasionach, czasu trwania suszenia IR oraz zakresu temperatur na stymulację jakości nasion oraz utrzymywanie efektu stymulacji. Zaproponowano model matematyczny dynamiki ogrzewania warstwy nasion uwzgledniający odparowanie wilgoci. Przedstawiono dane eksperymentalne przewodności masowej dla warstw suszonych nasion oraz wytyczne projektowania urządzeń.

Słowa kluczowe: suszenie, obliczenia kinetyczne, metoda strefowa, materiały sypkie

DOI:

* Prof. PhD. Stanislav Rudobashta, Department of Heat Engineering, Hydraulics and Enterprises Energy Supply, Russian State Agrarian University.

** Prof. PhD. Galina Zueva, Department of Higher and Applied Mathematics, Ivanovo State University of Chemistry and Technology.

*** Prof. PhD. Vjacheslav Dmitriev, Department of Security and Legal Order, Tambov State Technical University.

1. Introduction

Infrared drying of various materials is frequently used in practice [1-4], thus for drying heat-sensitive materials in order to prevent overheating, an oscillating mode in temperature must be used. It was found in [5] that the oscillating IR drying of the vegetable seeds carried out under conditions of the temperature range from t_{min} = 34^{o}C till t_{max} = 40^{o}C causes significant seeds stimulation. Research on the influence of the initial moisture content of seeds, of the duration of the IR drying on the effect of stimulation, were carried out in [6], as well as the research on keeping with time the stimulating effect. The mathematical model, which allows to calculate the dynamics of the heating material layer irradiated by an oscillating electromagnetic field – taking into account the evaporation of moisture from it is developed in [7], numerical experiments to study on the basis of the model the influence of technological parameters on the dynamics of layer heating are carried out in [8, 9]. They showed the possibility of the model in the organisation of the drying process. The calculations have been done in [8, 9] for a monolayer of seeds, but with mass conductivity data for isolated seeds. However, to reduce the size of the dryer for oscillating IR drying, the seeds must be dried in the bed. There are no data on mass conductivity of seeds in a layer, so the aim of this work is to obtain experimental data on mass conductivity of seeds in a layer, to describe these data with a function of moisture content and temperature of material, to compare the results for a layer with the data on mass conductivity of individual seeds, to develop an engineering method for calculating the kinetics of seeds oscillating infrared drying using these data and to calculate the industrial machine on its base.

2. Experimental study of seed layer mass conductivity

The mass conductivity of a seed layer was investigated with the zonal method – by receiving the drying curves with the exclusion of external diffusion resistance, and their processing by the method of splitting into a number of concentration zones and defining the value of mass conductivity coefficient for each of them by the solution of a linear differential equation of mass conductivity in a regular process mode. Drying curves were obtained when the drying agent (air) at velocity of 5 m/s had three different temperatures: 40, 50 and 60°C. As the object of the study "Stuttgarter Risen" onion seeds have been chosen because there are data on mass conductivity for a single seed, which could be compared to the results of the research.

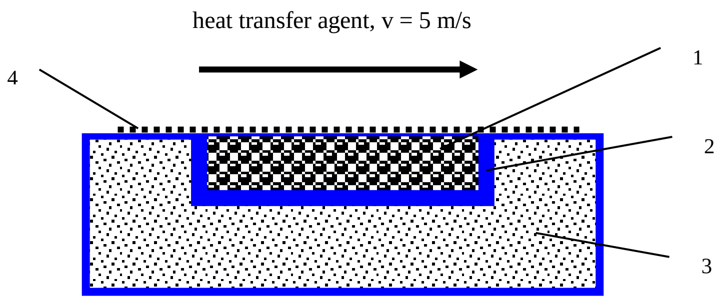

Fig. 1. Measuring cell for studying the kinetics of drying the seed layer
1 – layer of seeds; 2 – cell; 3 – thermal insulation; 4 – mesh

The measuring cell was designed as a cell filled with seeds, 5 mm high and 50 mm in diameter, situated in a substrate of foamed polyurethane (Fig.1).

The top layer was covered with a thin brass mesh (wire thickness of 0.12 mm, cell size of 1.5 mm), which prevents seeds from being blown-off by the air flow. A single "Stuttgarter Risen" onion seed is a limited cylinder with a diameter d = 1.7 mm and a length l = 0.9 mm (equivalent diameter d_{eq} = 1.57 mm). Thermocouples HC with 0.08 mm diameter electrodes were placed into three seeds, which measure the changes in seeds' temperature while drying. The seeds with embedded thermocouples were placed in three basic layers: the upper, middle and lower (bottom layer) (Figure 2.).

A measuring cell was placed into a working chamber of a dryer (Fig. 1), which was an air thermostat with air circulating inside it and driven by a fan. Air in the thermostat is dried by means of silica gel, which allowed to maintain a low moisture content that is close to zero. The set-up was equipped with an electric air heater, with TRM202 temperature regulators working HC with thermocouple. The air temperature was measured and maintained with an accuracy of ±0.1°C. A layer weight in the drying process was measured by AB 210-01 EDO electronic balance with accuracy of 1 mg cell without extraction of cell with seeds from a drying chamber, measuring time should not exceed 10 seconds.

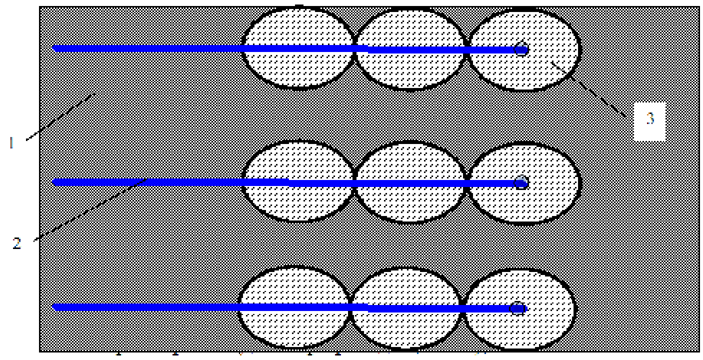

Fig. 2. The layout of thermocouples in the layer of seeds:
1 – a layer of seeds; 2 – thermocouple; 3 – seed

The analysis of drying curves of onion seed layer, obtained at different air velocities, showed that at velocity of 5 m/s external diffusion resistance is completely eliminated and the drying process is limited by the internal diffusion resistance, which makes it possible to determine the dependence of the mass conductivity ratio on the seeds' moisture content from drying curve by zonal method [10].

Fig. 3 illustrates the drying curves obtained when the velocity of the drying agent is 5 m/s, and Fig. 4 shows the experimental heating thermogram of elementary layers of seeds, obtained for drying agent at 50°C (at other temperatures of the drying agent, they have a similar form).

Consideration of the thermograms allows to come to two conclusions: 1) the temperature in each layer varies throughout the process of drying, so the drying is characterised by non-isothermal internal mass transfer; 2) heating curves for different elementary layers of a material, despite the small thickness of the entire layer (5 mm), differ substantially. The values of mass conductivity coefficient k, m^2s^{-1} according to each concentration zone were calculated by a zonal method using drying curves, shown in Fig. 3 [10]. The changes in the value of the mass conductivity coefficient during the process calculated by zones are shown in Fig. 5.

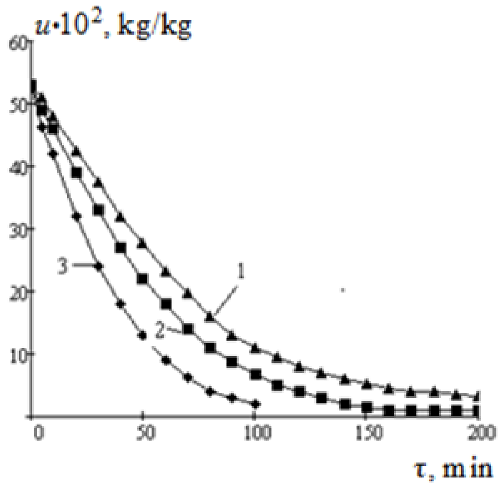

Fig. 3. The convective drying curves of a wet dense layer of "Stuttgarter Risen" onion seeds $u{\cdot}10^2$, kg/kg (air velocity 5 m/s; 1 – $t_{d.a}$ = 40°C; 2 – $t_{d.a}$ = 50°C; 3 – $t_{d.a}$ = 60°C)

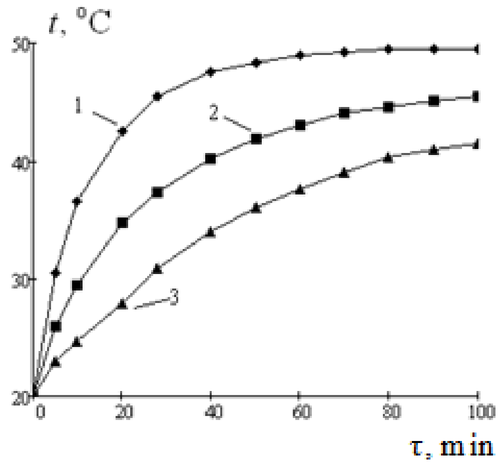

Fig. 4. Heating thermograms of elementary seeds layers at $t_{d.a}$ = 50°C:
1 – top layer; 2 – middle layer; 3 – bottom layer

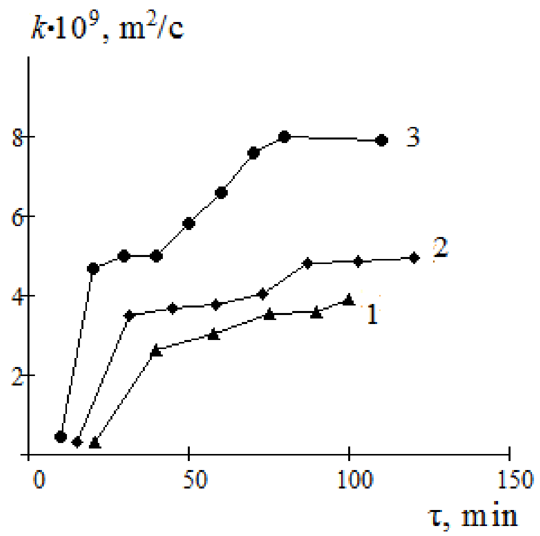

Fig. 5. Changing with time mass conductivity ratio while drying at air temperature:
1 – 40°C; 2 – 50°C; 3 – 60°C

3. The analysis and mathematical processing the data obtained

Examination of Fig. 5 allows to conclude the following: 1) the mass conductivity coefficient *k* changes significantly during drying, thus the calculation of drying kinetics at a constant value of *k* would result in significant errors in the determination of the drying time (estimation error arising from negligence of the change is given in [10]); 2) change in the coefficient k in the investigated drying process is due to its dependence on both moisture content and the temperature, but the effect of temperature on the coefficient k prevails over the effect of moisture, so the mass conductivity coefficient increases as the temperature of the seeds rises while drying; 3) coefficient *k* has the order of 10^{-9}, while its order is equal to 10^{-11} in drying single seed [11]. The difference in orders of mass conductivity coefficient while drying a unit seed and a seed layer is caused by the fact that during drying, a layer of vapour diffusion in areas between individual seeds plays an important role, while in a unit seed drying, vapour diffusion in spaces between individual seeds as a type of mass transfer is absent.

Since the mass conductivity coefficient *k* as the physical parameter is a function of the moisture content and temperature of the material $k = f(u,t)$, it is advisable in experimental data obtained for this coefficient to untie affecting parameters, thus it gives an opportunity to present this coefficient as a physical quantity, and not as a regime parameter, and to use it for engineering calculations. This problem was solved with the use of multidimensional (two-dimensional) function approximation procedures using the Cobb-Douglas model in the MATHCAD system [12]. As a result, the following functional dependence of the mass conductivity on the moisture content and temperature of the material was obtained, which can be used in the calculation of convective drying kinetics of a dense layer of "Stuttgarter Risen" onion seeds, blown over the surface

$$k = a_0 \cdot u^{a1} \cdot t^{a2} \cdot f(t_{d.a}/50), \tag{1}$$

where

$$a_0 = 4.12 \cdot 10^{-15};\ a_1 = 6.19 \cdot 10^{-2};\ a_2 = 3.73;$$

$$f(t_{d.a}/50) = 9.59 - 15.15 \cdot (t_{d.a}/50) + 6.50 \cdot (t_{d.a}/50)^2;$$

t – temperature of the material, °C,

$t_{d.a}$ – temperature of drying agent, °C,

U – local moisture content, kg/(kg of dry material).

Equation (1) was used to calculate the drying kinetics of onion seed layer during oscillating IR drying at layer thickness h = 5 mm, at oscillation of seeds' temperature between t_{min} = 34°C to t_{max} = 40°C, at continuous blowing of the seeds' surface by atmospheric air with temperature $t_{d.a}$ = 20°C. The calculation is performed under the condition that the temperature of the material to be dried is constant and equal to $t = (t_{min} + t_{max})/2$ = (34° + 40°)/2 = 37°C. The results of calculation and their comparison with experimental drying curve are shown in Fig. 6.

As it can be seen in the figure, the calculation of the drying curve using data on mass conductivity described by equation (1) gives a satisfactory agreement with the experiment. The same figure shows the comparison between experimental and calculated drying curves for a monolayer of onion seeds, in this calculations data on mass conductivity for individual seeds, shown in [11] are used. In this case, the calculated and experimental drying curves have satisfactory agreement, and the drying curve for a monolayer of seeds passes, as would be expected, more steeply than for the layer.

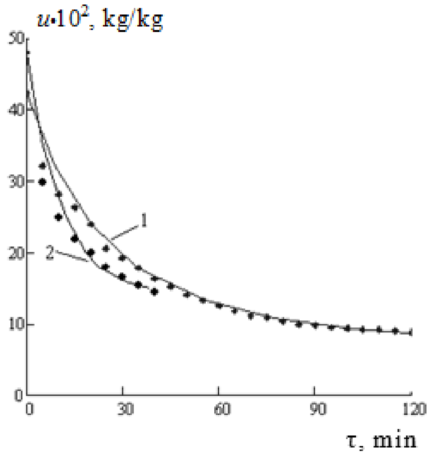

Fig. 6. Comparison of experimental and calculated drying curves of "Shtutgarer Risen" onion seeds at oscillating infrared energy supply (the line – calculation, points - experiment): 1 – dense blown layer; 2 – monolayer; t_{min} = 34°C; t_{max} = 40°C, $t_{d.a}$ = 20°C.

4. Recommendations for hardware design of oscillating infrared seeds drying and kinetic calculation of the process

The studies performed have shown that the data on mass conductivity of seeds in a layer are reliable and can be used for calculating drying kinetics. The absence of oscillations in the moisture content of seeds on the drying curve in the oscillating seeds layer IR drying, carried out in the temperature range of the material t_{min} = 34°C ... t_{max} = 40°C (Fig. 6), suggest the possibility of calculating the kinetics of this process on the basis of the solution of mass conductivity differential equation written for layer blown up on the surface, under appropriate boundary conditions of the problem – using the data in terms of mass conductivity for a layer. The calculation methods are described in [10]. To implement this method in practice, is necessary to obtain data on the mass conductivity of dried seeds, which can be obtained in the same way as it was done in this work for onion seeds.

The infrared dryer for continuous oscillating infrared drying can be carried out on the basis of a typical conveyor dryer with IR emitters located over the dried material (e.g. based on a commercial IR dryer, such as an infrared belt dryer of Russian production model UTZ-4). Equipping a corresponding dryer by automatic control system will implement an oscillating mode of infrared drying. The technique of engineering kinetic calculation has been proposed for the apparatus of this type on the basis of a developed mathematical model, using the data of mass conductivity coefficient for a layer. The aim of the calculation is to determine the necessary residence time for the seeds in the apparatus, thus providing the specified productivity, and at the same time, it allows to find the device dimensions on the stage of its design.

References

[1] Ratti C., Mujumdar A. S., *Infrared drying*, in *Handbook of Industrial Drying*, 3-rd edition. A. S. Mujumdar (Ed), CRC Press, Boca Raton, FL. 2007.

[2] Mujumdar A. S. (Ed)., *Drying'92*, Proceedings of 8-th International Drying Symposium, Elsevier, Amsterdam, 1992, 667-729.

[3] Supmoon N., Noomhorm, A. *Influence of combined hot air impingement and infrared drying on drying kinetics and physical properties of potato chips*, Drying Technology, vol. 31(1), 2013, 24-31.

[4] Bon J., Kudra T,. *Enthalpy-driven optimization of intermittent drying*, Drying Technology, vol. 25 (4), 2007, 523-532.

[5] Rudobashta S. P., Grigoriev I. V., *Impulse infrared drying the seeds of vegetables, nontraditional and rare plants*, Industrial Heat Engineering, vol. 33 (8), 2011, 85-90 (in Russian).

[6] Rudobashta S. P., Zueva G. A.; Zuev N. A., S*eeds stimulation by oscillating infrared heat treatment*, Industrial Heat Engineering, vol. 35 (7), 2013, 218-222 (in Russian).

[7] Rudobashta S. P., Kartashov E. M., Zuev N. A., *Heat-and Mass Transfer in Drying in an Oscillating Electromagnetic Field*, Theoretical Foundations of Chemical Engineering, vol. 45 (6), 2011, 830-837.

[8] Rudobashta, S., Zueva G., Zuev N., *Mathematical Modelling and Numerical*, Analysis of Oscillating Infrared Seeds Drying Process, XIII Polish Drying Symposium, Kołobrzeg, 5-6 September, 2013, 1-6.

[9] Rudobashta, S., Zueva G., Zuev N., *Mathematical modeling and numerical simulation of seeds drying under oscillating infrared irradiation*, Drying Technology, vol. 32 (11), 2014, 1352-1359.

[10] Rudobashta, S. P., *Mass transfer in the solid phase systems*, Chemistry, Moscow 1980 (in Russian).

[11] Rudobashta S. P., Zueva G. A., Dmitriev V. M., Zuev N. A., *Mass conductivity when drying colloidal capillary-porous materials*, Proceedings of the Higher Educational Institutions. Chemistry and Chemical Engineering, vol. 57 (1), 2014, 103-107 (in Russian).

[12] Ohorzin V. A., *Applied mathematics in MATHCAD system*: Schoolbook, Lany, St. Petersburg 2009 (in Russian).