

KINETICS OF GRAIN MATERIAL DRYING IN INSTALLATIONS WITH INTERMITTENT ENERGY SUPPLY BY MICROWAVE AND INFRARED RADIATION

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Abstract. In both microwave and infrared grain treatment methods, selective heating of the moist material occurs since moisture (water) components selectively absorb energy with greater intensity, ensuring targeted energy delivery, as only the water content heats up rather than the structural matrix of the material. Since moisture is evenly distributed throughout the material volume, heating occurs uniformly throughout the body. Based on the analysis of typical generalized equations of coupled heat and mass transfer, mathematical models of the grain material drying process in the microwave electromagnetic field and infrared radiation were formulated. Using experimental data on grain drying, parametric identification of the developed mathematical models for the drying process dynamics under intermittent MW and IR energy supply was performed. An algorithm for calculating unsteady drying regimes was developed. The MW-IR dryer ensures environmentally friendly grain drying with increased energy efficiency. The influence of operating parameters on the drying kinetics in a dryer with MW and IR energy supply was determined. Rational parameters of microwave-IR treatment: microwave power – 600 W/dm³, IR: 940 W/m² – for the first period; 1130 W/m² – for the second period; 1210 W/m² – for the third period. Experimental studies confirmed the high efficiency of electromagnetic energy supply to the drying material – the intensity of moisture removal was more than twice as high compared to convective drying. It is established that the use of a combined energy supply in the process of grain material drying reduces specific energy consumption and intensifies moisture removal without overheating the material.

Keywords: selective volumetric heating, periodic irradiation methods, parametric model identification, energy-efficient grain processing

KINETYKA SUSZENIA MATERIAŁÓW ZIARNISTYCH W INSTALACJACH Z PRZERYWANYM ZASILANIEM ELEKTRYCZNYM WYKORZYSTUJĄCYCH PROMIENIOWANIE MIKROFALOWE I PODCZERWONE

Streszczenie. Zarówno w przypadku obróbki ziarna za pomocą mikrofal, jak i promieniowania podczerwonego dochodzi do selektywnego ogrzewania wilgotnego materiału, ponieważ składniki wilgoci (woda) pochłaniają energię w sposób selektywny i z większą intensywnością, co zapewnia ukierunkowane dostarczanie energii, ponieważ ogrzewa się wyłącznie woda, a nie struktura materiału. Ponieważ wilgoć jest równomiernie rozłożona w całej objętości materiału, ogrzewanie przebiega jednolicie w całej masie. Na podstawie analizy typowych równań ogólnych dotyczących sprzężonego przenoszenia ciepła i masy sformułowano modele matematyczne procesu suszenia ziarna w polu elektromagnetycznym mikrofalowym i promieniowaniu podczerwonym. Wykorzystując dane eksperymentalne dotyczące suszenia ziarna, przeprowadzono identyfikację parametryczną opracowanych modeli matematycznych dynamiki procesu suszenia przy przerywanym dostarczaniu energii mikrofalowej i podczerwonej. Opracowano algorytm obliczania niestabilnych reżimów suszenia. Suszarnia MW-IR zapewnia ekologiczne suszenie ziarna przy zwiększonej efektywności energetycznej. Określono wpływ parametrów roboczych na kinetykę suszenia w suszarni zasilanej energią mikrofalową i podczerwoną. Optymalne parametry obróbki mikrofalowo-podczerwonej: moc mikrofalowa – 600 W/dm³, podczerwień: 940 W/m² – w pierwszym okresie; 1130 W/m² – w drugim okresie; 1210 W/m² – w trzecim okresie. Badania eksperymentalne potwierdziły wysoką wydajność dostarczania energii elektromagnetycznej do suszonego materiału – intensywność usuwania wilgoci była ponad dwukrotnie wyższa w porównaniu z suszeniem konwekcyjnym. Stwierdzono, że zastosowanie kombinowanego zasilania energią w procesie suszenia ziarna zmniejsza jednostkowe zużycie energii i intensyfikuje usuwanie wilgoci bez przegrzewania materiału.

Słowa kluczowe: selektywne ogrzewanie objętościowe, metody okresowego napromieniowania, identyfikacja modeli parametrycznych, energooszczędne przetwarzanie ziarna

Introduction

For the long-term stable storage of grain crops (ear crops, grain crops, oilseeds), immediate cleaning and drying to a safe storage moisture level are essential. The drying process is the most energy-intensive stage in the technological preparation and processing of grain materials. Traditional grain drying methods rely on organic fuel to heat the drying agent in grain dryers. The heat is transferred to the grain material via convective heat transfer (convective energy supply to the moist material), while moisture is removed from the surface through convective mass exchange and carried away by the saturated drying agent from the drying zone.

A significant drawback of this method is that a large amount of drying agent is required to deliver the necessary heat to the material due to its low heat capacity. Moreover, the heat from the drying agent is not fully utilized, with up to 40% being lost along with the exhausted drying agent. This leads to inefficient thermal energy consumption in modern convective drying systems. To improve energy efficiency, it is advisable to reduce the amount of drying agent to a level sufficient for moisture absorption and removal. A significant reduction in the drying agent volume can be achieved by employing alternative energy supply methods for grain material drying [6].

Heating and drying various types of grain using microwaves improves time and energy savings. The physiological quality variation of the seeds submitted to microwave drying is known to some extent. In this context, some authors have reported excellent performance using this technique, on germination rates, after drying. The commercial use of microwave drying in seeds is irrelevant, which motivates more extensive research on the benefits and challenges of this technique that can increase its insertion in the post-harvest handling steps of agricultural products [7].

The traditional drying method (convective hot air drying) was compared with new drying methods such as infrared drying (IRD) and infrared hot air drying (IRHAD) for the production of coconut flakes. As a result, the IRHAD method is the optimal choice for the production of coconut flakes because it offers improved biochemical properties, improved drying kinetics and favourable physical characteristics [17].

Recent studies show similar trends in improving the homogeneity of temperature fields and reducing energy consumption in combined MW-IR systems. The combined application of microwave and infrared drying enhances drying efficiency and optimizes energy use. Microwave heating penetrates the material deeply, heating the interior through the vibration of water molecules, while infrared primarily heats the surface, rapidly increasing the temperature [20].



1. Problem identification

A promising direction for improving grain drying technology and equipment, reducing unproductive energy losses, minimizing exhaust gas emissions into the atmosphere, and ensuring the environmental safety of the final product is the targeted application of energy to the moisture contained in the grain material. This can be achieved through the energy supply of an ultra-high frequency electromagnetic field and infrared radiation (IR) [4, 17, 18].

The authors also investigated the principles of microwave heating, the problem of inhomogeneity, and modern approaches (including pulsed/controlled periodic power delivery methods for more uniform volumetric heating) [10]. Experimental results of combined modes (microwave radiation + hot air) of rice drying, evaluation of moisture removal intensification and energy efficiency, as well as identification of parametric models are presented by the authors [21].

The authors [14] found that the combined treatment with infrared and microwave radiation effectively promotes starch pregelatinization and protein denaturation, thereby changing the functional properties of the resulting flour and reducing its viscosity. This combined approach not only accelerates the drying process, but also preserves the nutritional value of the grain [14, 16].

The results of the review showed that the radiant heating mechanism using infrared radiation and the volumetric heating mechanism using microwaves and radio frequencies support the heating of the material and the process of moisture diffusion within the material. As a result, the drying process has achieved high efficiency, the drying time has been significantly reduced, and the quality of dried products has improved both in terms of sensory qualities and nutritional value. The study of the application of infrared radiation, microwaves and radio frequencies in drying technology has great scientific, technological and practical significance [9].

A promising approach involves the use of a combined drying technology, specifically intermittent microwave (MW) drying in combination with infrared irradiation of the material. In the intermittent energy supply method (MW and IR), both drying techniques' drawbacks are mitigated, namely, significant moisture gradients during microwave heating, which hinder moisture movement toward the surface, and temperature gradients in the material during IR heating, which also slow down moisture migration while rapidly dehydrating and overheating the surface.

Intermittent irradiation with electromagnetic waves of different wavelengths ensures an optimal temperature distribution, facilitating intensive moisture movement toward the surface, where it effectively evaporates.

2. Research objective

The objective of this study is to develop and validate a mathematical model of combined MW-IR grain drying to quantitatively assess the impact of energy supply parameters (heating application sequence, power levels, and cycle durations) on dehydration kinetics, specific energy consumption, and the material's temperature profile, thereby enabling the determination of energy-efficient drying modes while adhering to technological temperature constraints.

3. Materials and methods

The influence of infrared radiation and ultra-high frequency electromagnetic fields on grain materials is determined by the electromagnetic nature of radiation in both cases. This allows the quantitative description of the heat and mass transfer dynamics in the drying process under IR and MW energy supply using a unified system of differential equations developed by O. V. Lykov [5]. The primary distinction is based on representing the internal heat source generated within

the material due to the absorption of electromagnetic radiation (of different wavelengths) and the boundary conditions describing its interaction with the surrounding environment.

It is known [2, 3] that for MW heating, it is advisable to use the heat conduction equation with an internal heat source, whereas for IR heating, the intensity of heat supply should be considered in the boundary conditions (second-order conditions).

According to the fundamental characteristics of MW and IR heating, valid solutions for the non-stationary differential equations obtained by O.V. Lykov for MW heating are as follows:

$$\frac{\theta(r, \tau) - \theta_0}{t_c - \theta_0} = 1 + \frac{Po}{6} \left(1 + \frac{2}{Bi} - \frac{r^2}{R^2} \right) + \sum_{n=1}^{\infty} \left(1 + \frac{Po}{\mu_n^2} \right) \cdot A_n \frac{R \cdot \sin \mu_n \frac{r}{R}}{r \cdot \mu_n} \exp \left(-\mu_n^2 \frac{a}{R^2} \tau \right) \quad (1)$$

for IR heating:

$$\frac{\theta(r, \tau) - \theta_0}{\theta^* - \theta_0} = 1 - \sum_{n=1}^{\infty} A_n \frac{R \cdot \sin \mu_n \frac{r}{R}}{r \cdot \mu_n} \exp \left(-\mu_n^2 \frac{a}{R^2} \tau \right) \quad (2)$$

$$Q^* = t_c + \frac{Q_F}{\alpha}$$

for the change in moisture content of a spherical grain kernel:

$$\frac{U(r, \tau) - U_p}{U_0 - U_p} = \sum_{n=1}^{\infty} A_n \frac{R \cdot \sin \mu_n \frac{r}{R}}{r \cdot \mu_n} \exp \left(-\mu_n^2 \frac{a_m}{R^2} \tau \right) \quad (3)$$

where, θ_0 , $\theta(r, \tau)$, t_c – initial material temperature, current material temperature, ambient temperature; U_0 , $U(r, \tau)$, U_p – initial, current, and equilibrium moisture content of the grain; $Bi = \frac{\alpha \cdot R}{\lambda}$,

$Bi_m = \frac{\beta \cdot R}{a_m}$ – Bio criterion for heat and mass transfer;

$Po = \frac{q_v R^2}{\lambda(t_c - \theta_0)}$ – Pomerantsev criterion; R , r – radius

of the body and current radius; a , a_m – thermal diffusivity and moisture diffusivity coefficients; α , β – heat and mass transfer coefficients; λ – thermal conductivity coefficient; $q_v = 0.555 E^2 f \cdot \epsilon' \cdot tg \delta$ – internal heat generation power during MW irradiation; Q_F – intensity of the IR source; ϵ' – dielectric permittivity of the material; E – electric field intensity; $tg \delta$ – dielectric loss factor; μ_n – roots of the characteristic equation $\mu_n = (Bi - 1) \cdot tg \mu_n$;

$A_n = (-1)^{n+1} \frac{2Bi \sqrt{\mu_n^2 + (Bi - 1)^2}}{\mu_n^2 + Bi^2 - Bi}$ – wave amplitude.

The average values of the parameters $\bar{\theta}(\tau)$, $\bar{U}(\tau)$ are determined by integrating functions (1)-(3) using the standard formulas:

$$\bar{\theta}(\tau) = \frac{3}{R^3} \int_0^R r^2 \theta(r, \tau) dr; \quad \bar{U}(\tau) = \frac{3}{R^3} \int_0^R r^2 U(r, \tau) dr$$

By integrating equations (1)-(3) and considering only the first terms of the series, after the appropriate transformations [13, 15], we obtain the equations for heating and dehydration kinetics in the following form:

- for drying in a microwave field:

$$\frac{d\bar{\theta}(\tau)}{d\tau} = K_{T1} (t_c - \theta(\tau)) + Q_{T1} \quad (4)$$

- for drying in an infrared field:

$$\frac{d\bar{\theta}(\tau)}{d\tau} = K_{T2}(t_c - \theta(\tau)) + Q_{T2} \quad (5)$$

- for the change in moisture content (dehydration kinetics):

$$\frac{d\bar{U}(\tau)}{d\tau} = -K_c(\bar{U}(\tau) - U_p) \quad (6)$$

where

$$K_{T1} = 3Bi \frac{a}{R^2}; Q_{T1} = \frac{\alpha}{\lambda} \left(1 + \frac{Bi}{5}\right) \cdot q_v = \frac{1}{\rho c} \left(1 + \frac{Bi}{5}\right) \cdot q_v$$

$$K_{T2} = 3Bi \frac{a}{R^2}; Q_{T2} = \frac{3\alpha}{R\lambda} Q_F \quad (7)$$

$$K_c = 3Bi_m \frac{a_m}{R^2} \quad (8)$$

Equations (1)-(6) are used to determine the unknown criteria Bi , Bi_m and coefficients a , a_m by solving inverse heat conduction problems [6], provided there are experimental data on temperature and moisture content variations over time.

4. Research results

Analytical solutions to the differential equations (4)-(6) are presented as dependencies $\theta_{1,2}(\tau)$, $U_{1,2}(\tau)$ in the following form.

- for MW heating (subscript 1) and for IR heating (subscript 2):

$$\Theta_{1,2}(\tau) = t_c + \frac{Q_{T1,2}}{K_{T1,2}} - \frac{Q_{T1,2} + K_{T1,2}(t_c - \Theta_0)}{K_{T1,2}} \exp[-K_{T1,2} \cdot \tau] \quad (9)$$

$$U_{1,2}(\tau) = U_p + (U_0 - U_p) \exp[-K_{c1,2} \cdot \tau] \quad (10)$$

Substituting equation (7) into equation (9), we obtain:

- for MW heating:

$$\Theta_1(\tau) = t_c + t_{T1} + (\Theta_0 - t_c - t_{T1}) \exp[-K_{T1} \cdot \tau] \quad (11)$$

where

$$t_{T1} = \frac{R^2 q_v}{15\lambda} + \frac{R \cdot q_v}{3\alpha} \quad (12)$$

- for IR heating:

$$\Theta_2(\tau) = t_c + t_{T2} + (\Theta_0 - t_c - t_{T2}) \exp[-K_{T1} \cdot \tau] \quad (13)$$

where

$$t_{T2} = \frac{q_F}{\alpha} \quad (14)$$

Experimental studies were conducted using a laboratory setup described in research [1]. The material was dried in cassettes; the average temperature was measured with a thermometer, surface temperature with a pyrometer, and moisture content was determined by the change in grain weight in the cassette.

Figures 1 and 2 present experimental data points (2, 4) and graphical dependencies (1, 3) of the change in average temperature and moisture content over time during microwave (Fig. 1) and infrared irradiation (Fig. 2). The calculated curves were obtained using equations (10), (11), and (13), with coefficient values determined according to the methodology [11].

For the experimental data presented in Fig. 1, the identification of MW heating kinetics was conducted under the initial conditions: $t_c = 20^\circ\text{C}$; $\theta_0 = 20^\circ\text{C}$; $U_0 = 0.25 \text{ kg/kg}$. The coefficients determined for equation (10) are: $t_{T1} = 46^\circ\text{C}$; $K_{T1} = 3.5 \cdot 10^{-3} \text{ 1/s}$. The thermophysical parameters from equations (7) are: $q_v = 457 \text{ W/dm}^3$; $Bi = 0.041$. The drying kinetics was identified using equation (10) with $K_{c1} = 1.08 \cdot 10^{-3} \text{ 1/s}$; $U_0 = 0.25 \text{ kg/kg}$, $U_p = 0.1 \text{ kg/kg}$.

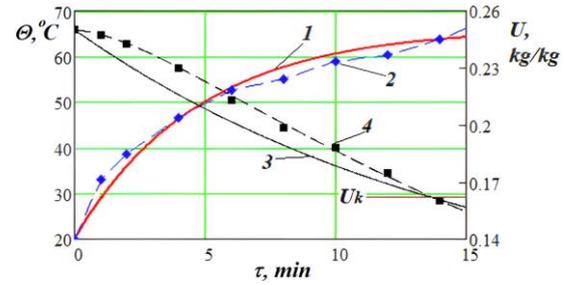


Fig. 1. Experimental curves with data points (◆,■) and the calculated curves (—) based on equation (11) for temperature kinetics $\theta(\tau)$ – 1, 2, and equation (10) for moisture content $\bar{U}(\tau)$ – 3, 4 as functions of exposure time to microwave radiation. The grain volume is $V_g = 0.2 \text{ m}^3$, and the magnetron power is $P = 120 \text{ W}$

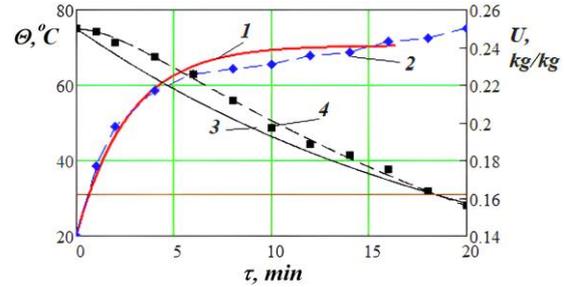


Fig. 2. Experimental curves with data points (◆,■) and the calculated curves (—) 1 – dependence of temperature change $\theta(\tau)$ and 3 – dependence of moisture content $\bar{U}(\tau)$ on the time under infrared radiation exposure

For the experimental data presented in Fig. 2, the identification of IR heating kinetics was performed under the initial conditions: $t_c = 20^\circ\text{C}$; $\theta_0 = 20^\circ\text{C}$; $U_0 = 0.25 \text{ kg/kg}$. The coefficients determined for equation (13) are: $t_{T2} = 50.4^\circ\text{C}$; $K_{T2} = 6.2 \cdot 10^{-3} \text{ 1/s}$. The thermophysical parameters from equations (7) are: $q_F = 567 \text{ W/m}^2$; $Bi = 0.072$. The drying kinetics was identified using equation (10) with $K_{c2} = 0.8 \cdot 10^{-3} \text{ 1/s}$; $U_0 = 0.25 \text{ kg/kg}$, $U_p = 0.1 \text{ kg/kg}$.

The use of microwave radiation (Fig. 1) allows drying grain at a higher speed compared to other types of energy supply, which is explained by the effect of barodiffusion [5]. The average drying speed per process for microwave drying (Fig. 1) is $1.094 \cdot 10^{-4} \text{ kg/s}$ and for IR drying (Fig. 2) is $8.037 \cdot 10^{-5} \text{ kg/s}$, the difference is 26.5% with the same full power of the drying units.

Equations (10), (11), and (13) with experimentally identified coefficients provide sufficient accuracy for engineering calculations (Figs. 1, 2) and can be used for modelling heating and drying processes with MW and IR energy supply. The multiple correlation coefficient between experimental and theoretical data is $R^2 = 0.96-0.97$.

For the mathematical description of drying processes in continuous-operation installations, material movement must be considered, meaning changes in its parameters along the coordinate in the direction of movement.

Using the transformation $dy/d\tau = V$, where V is the material movement speed, we obtain:

$$\Theta_{1,2}(y) = t_c + t_{T1,2} + (\Theta_0 - t_c - t_{T1,2}) \exp\left[-\frac{K_{T1,2}}{V} y\right] \quad (15)$$

$$U_{1,2}(y) = U_p + (U_0 - U_p) \exp\left[-\frac{K_{c1,2}}{V} y\right] \quad (16)$$

These equations describe the temperature and moisture content changes of the material during movement through the drying installation under MW and IR heating.

Let's consider the grain drying process under normal operating conditions of a belt dryer [12]. In this scenario, the drying regime is steady-state (stationary), meaning that at every point in the working space (material on the belt), its temperature and moisture content remain constant over time, and the heating and dehydration processes are stationary.

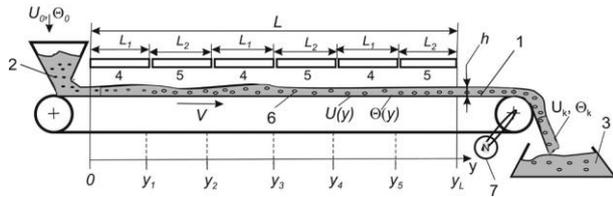


Fig. 3. The schematic diagram of the drying installation: 1 – belt conveyor; 2 – loading hopper; 3 – dry grain hopper; 4 – magnetrans (microwave emitters); 5 – infrared emitters; 6 – grain layer; 7 – electric drive. Dimensions L_1 i L_2 – the lengths of the zones where microwave and infrared radiation are applied; L – total drying zone length; h – the height of the grain layer on the conveyor

The schematic diagram of the drying installation is shown in Fig. 3 (the complete dryer diagram is provided in reference [8, 19]).

In this setup, the grain layer moves at a constant speed, and the power outputs of both the microwave generators and infrared emitters remain steady over time. The initial temperature and moisture content in the grain are uniform over the height of the layer, which is equal to their average values. The ambient temperature is assumed to be constant both in time and space.

The algorithm for calculating the grain drying process under alternating microwave and infrared irradiation involves sequential computations using equations (15) and (16) for zones L_1 and L_2 , as shown in Fig. 4. In this approach, the terminal values of parameters $\theta_i(y)$ and $U_i(y)$ for each subsequent zone L_2 after zone L_1 $\theta_{i+1}(y+1)$ and $U_{i+1}(y+1)$ will be terminal values of the preceding zone.

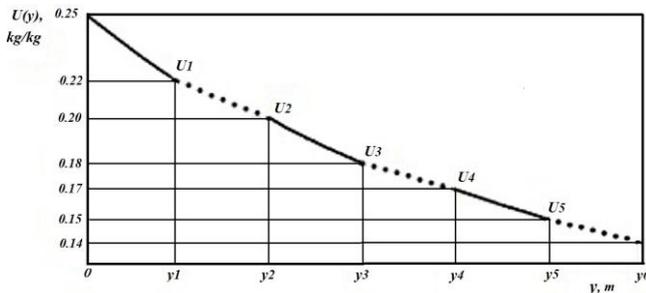


Fig. 4. Kinetics of alternating MW-IR drying

An example of the calculated kinetics of alternating heating and dehydration of grain is presented in Fig. 5.

For 1, 4, the supplied microwave power is 600 W/dm^3 , IR: 940 W/m^2 for the first period; 1130 W/m^2 for the second period; 1210 W/m^2 for the third period. For 2, 3, the supplied microwave power is 600 W/dm^3 , and the air speed is 0.2 m/s .

For each cycle of IR energy supply, the power of IR heaters was determined by formula (14) to compensate for the heat flow of energy losses to the external environment from the surface of the heated grain. In addition, with this approach, in the IR cycle, the grain kernel temperature is equalized along the radius (Fig. 6).

Fig. 5 shows that with alternating MW and IR energy supply, the temperature remains within the optimal range for grain processing, which ensures its high quality. The resulting IR power value is determined to compensate for thermal convective heat losses from the heated material to the surrounding environment, due to which a stable material temperature is maintained in the IR cycle (Fig. 5, curve 1), in comparison with alternating microwave and ventilation of the material (Fig. 5, curve 2). Drying using microwave radiation and air ventilation leads to a decrease in the material temperature during ventilation periods. Due to this, the drying coefficient, which depends on the temperature, decreases and this increases the drying exposure (Fig. 5, curve 3) and, therefore, energy consumption.

The use of alternating MW and IR energy supply enables to reduce the total drying exposure time (Fig. 5, curve 4). The average drying speed with microwave-IR energy supply is

(Fig. 5 curve 3) $5.05 \cdot 10^{-5} \text{ kg/s}$, the average drying speed with microwave-convective is $4.1 \cdot 10^{-5} \text{ kg/s}$ (Fig. 5 curve 4), which is 19% less, i.e. the productivity of the installation with microwave-IR drying is 19% higher. Increasing the power of IR heaters allows you to further reduce the drying time by up to 22%. But at the same time, the risks of local overheating of the grain, in particular, overheating of the grain endosperm, which reduces the germination of the grain and, accordingly, its quality, increase. Therefore, it is rational to supply such an amount of IR energy that will compensate for the heat loss to the environment of the heated grain in the microwave cycle, and accordingly will not lead to a decrease in the drying rate after the microwave cycle due to convective energy losses. This, in turn, increases the dryer's productivity, reduces the total energy consumption for drying compared to other options for implementing the process.

The combination of MW and IR energy supply provides a more uniform temperature distribution in the grain, preventing local overheating, which is inherent in electromagnetic energy supply. Fig. 6 shows that the unevenness of the grain temperature remains within the optimal range for processing thermolabile materials, in particular grain, which ensures the preservation of its quality.

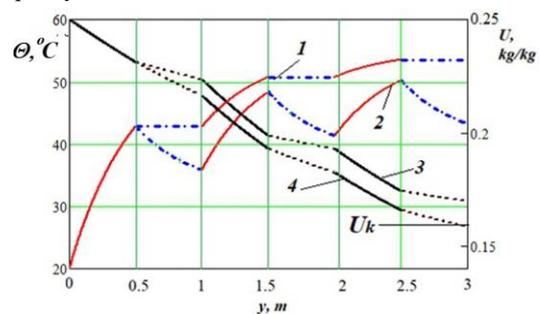


Fig. 5. Kinetics of alternating heating and drying of grain: 1, 4 – MR-IR energy supply; 2, 3 – MW – ventilation

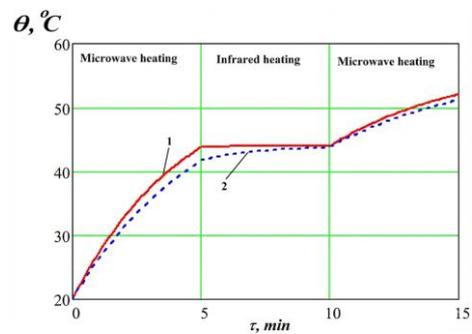


Fig. 6. Dynamics of grain kernel heating during microwave-IR energy supply: 1 – centre, 2 – surface of grain kernel

5. Conclusions

Mathematical models of heat and mass transfer kinetics under combined energy supply was developed and validated. The high correlation between the calculated and experimental data ($R^2 = 0.96$) confirms the model's adequacy, enabling its application for generalizing results and designing control algorithms for dryers.

Based on the parametric identification of the model, rational modes of intermittent drying were substantiated. The key control element was determined to be the calculation of IR radiation power that precisely compensates for convective heat losses during the pauses between MW heating cycles. This ensures the equalization of the grain kernel temperature profile and guarantees that the temperature does not exceed critical limits, which is crucial for preserving seed quality (germination capacity).

It has been demonstrated that the proposed technology provides a synergistic effect compared to the traditional "MW heating + active ventilation" scheme. The implementation of the developed modes allows for a 19–22% increase

in the drying unit's productivity due to the intensification of moisture removal while maintaining the high quality of the finished product.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship, or other, that could influence the study and its results presented in this article.

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