INFLUENCE OF HEAT CARRIER VELOCITY ON DRYING KINETICS OF CAPILLARY-POROUS MATERIALS UNDER COMBINED CONVECTIVE AND DIRECT ELECTRIC HEATING

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Abstract. The study investigates the effect of heat carrier velocity on drying kinetics of capillary-porous colloidal materials under combined energy supply, integrating convective and direct electric heating. Apple raw material was selected as a representative plant-based material with a well-developed capillary-porous structure. The experiments were conducted at a heat carrier temperature of 40 °C, an electric field strength of 30 $V \cdot cm^{-1}$, and an air velocity of 0.2–1.5 $m \cdot s^{-1}$. Time-dependent profiles of moisture content, moisture removal rate, material temperature, electric current, and specific electrical resistance were obtained, enabling a comprehensive analysis of heat and mass transfer as well as electrophysical processes during drying. To generalize the experimental data on drying kinetics, an exponential model was applied, demonstrating high adequacy (R^2 = 0.9904-0.9964). It was established that the drying rate constant varies within the range of 0.016-0.028 min^{-1} and reaches its maximum at a heat carrier velocity of 0.4 $m \cdot s^{-1}$. Under this condition, the drying time is approximately 132 min, which is 5.7% shorter compared to the regime at 0.2 $m \cdot s^{-1}$, whereas increasing the velocity to 1.5 $m \cdot s^{-1}$ results in an increase in the drying time of about 38%. It is shown that increasing the air velocity up to the optimal value enhances the drying process, while further increase leads to a decrease in the material temperature by 28%, electric current by 20-27%, and the moisture removal rate by 24%. It was found that variations in the heat carrier velocity affect the electrical conductivity of the material, as reflected in changes in specific electrical resistance, thereby determining the intensity of internal heat generation within the sample. The obtained results provide a basis for substantiating rational operating conditions for combined drying and can be used to improve the energy efficiency of dehydration processes for capillary-porous materials.

Keywords: combined drying, plant raw materials, direct electric heating, drying kinetics, electrophysical parameters, energy efficiency.

Introduction

Drying processes are among the most energy-intensive operations in the processing of plant-based raw materials, as well as in the food and bioenergy industries. According to various estimates, drying operations account for up to 10-15% of the industry's total energy consumption, which necessitates improving the energy efficiency of drying technologies and optimising the process parameters. Capillary-porous colloidal materials, which comprise a significant proportion of plant raw materials, are particularly challenging to dehydrate. Their structure is characterised by the presence of capillaries, cellular pores and various forms of moisture binding, which results in a complex mechanism of heat and mass transfer during drying [1; 2].

Traditional convective drying methods, which are widely used in industry, have a number of significant drawbacks: a considerable duration of the process, high specific energy consumption and uneven heating of the material. In this case, the main energy supply is provided from the surface of the material, which limits the rate of internal mass transfer and may lead to overheating of the surface layers [3]. In this regard, considerable attention is being paid to the development of intensified drying technologies, in particular methods involving volumetric energy supply to the material.

One promising approach to improving the efficiency of the process is the use of electrophysical drying methods, which involve passing electric current through the material or exposing it to an electromagnetic field. Such methods ensure internal (volumetric) heat generation directly within the material, which significantly accelerates the dehydration process. In particular, research has shown that the use of direct electrical heating allows for a significant reduction in the drying time of plant raw materials and improves the energy efficiency of the process [4; 5]. Furthermore, electrical influence can induce electroplasmolysis of cellular structures, which increases the permeability of cell membranes and facilitates the removal of intracellular moisture [6].

Further development of energy-efficient drying technologies involves the use of combined methods that integrate several energy transfer mechanisms – both surface and volumetric. Combined drying methods allow the advantages of convective heat and mass transfer to be combined with internal heating of the material, which promotes a more uniform temperature distribution and intensifies internal mass transfer. The scientific literature describes various variants of such technologies, in particular the combination of convective drying with microwave, infrared or electric heating [7-11]. Studies show that the use of combined methods allows for a significant reduction in the process duration, a decrease in specific energy consumption, and improvement in the quality of the dried product.

At the same time, the efficiency of combined drying depends to a large extent on the process operating parameters, among which the velocity of the heat transfer fluid plays an important role. Changes in hydrodynamic conditions affect both the intensity of convective heat and mass transfer and the temperature regime of the material, which, in turn, determines the intensity of internal electric heating and the course of electrophysical processes within the material. Despite a significant number of studies in the field of intensified drying methods, the issue of the influence of the heat transfer fluid velocity on the drying process of capillary-porous materials under conditions of combined energy supply has not been sufficiently investigated.

In this regard, the aim of this work is to investigate the effect of the heat transfer fluid velocity on the drying kinetics of capillary-porous colloidal materials under combined energy supply, which combines convective heating and direct electrical heating of the material.

Materials and methods

The study of the effect of the heat transfer fluid velocity on the drying process of capillary-porous colloidal materials under combined energy supply is a logical continuation of previous experimental work on combined methods of supplying energy to the material being dried [7; 12; 13].

The capillary-porous colloidal material used in the studies is apple raw material. This material is typical of the processing industry and allows the modelling of drying processes for similar colloidal systems.

We investigated the drying process using a specially designed experimental setup, the schematic diagram of which is shown in Fig. 1.

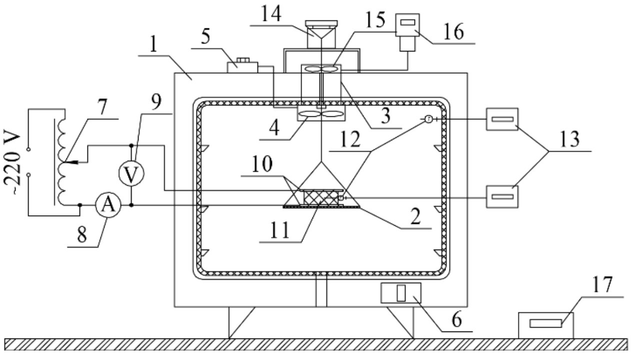

Fig. 1. **Schematic diagram of the experimental setup:** 1 – convective dryer SNOL-2.5 (Ukraine); 2 – mesh tray; 3 – ventilation ducts; 4 – fan; 5 – fan speed controller; 6 – air temperature controller in the chamber; 7 – autotransformer LATR-2.5 (Ukraine); 8 – milliammeter E536 (Ukraine); 9 – voltmeter D5081 (Ukraine); 10 – mesh electrodes for direct electric heating; 11 – test sample; 12 – thermocouples THA (chromel–alumel) (China); 13 – temperature indicators VC61A (China); 14 – electronic scales; 15 – vane anemometer sensor; 16 – anemometer Flus ET-965 (China); 17 – timer

The experiments were conducted under the following operating conditions: air temperature in the drying oven – 40 °C; average electric field strength of direct electric heating – 30 $V \cdot cm^{-1}$; velocity of the heated heat carrier (air) – 0.2-1.5 $m \cdot s^{-1}$. Pre-prepared apples were cut into disks with a height of 0.005 m and a diameter of 0.028 m.

During drying, measurements were taken of the mass, material temperature and the current passing through the sample. The electrical resistance of the raw material during the dehydration process was determined using an ammeter-voltmeter. Measurements were taken at set intervals depending on the dynamics of the process. To prepare the samples, identical parameters (mass, linear dimensions) were maintained, as confirmed by virtually identical initial electrical resistance.

Experimental data were processed using methods of mathematical statistics with the application of Microsoft Excel software. Each experiment was performed in triplicate ($n = 3$), and the average values of the studied parameters were determined. To assess the variability of experimental data within a single regime, the standard deviation and coefficient of variation were calculated. It was established that the coefficient of variation did not exceed 5%, indicating high reproducibility of the results.

To evaluate the effect of heat carrier velocity on the drying kinetics and electrophysical properties of the material, correlation analysis was applied. Statistical significance of the differences was assessed at a significance level of $p \leq 0.05$.

Based on the data obtained, calculations were performed for the moisture content, the rate of moisture removal and the specific electrical resistance of the material.

The current values of the material moisture content were determined using the following expression:

$$X_i = \frac{M_i - M_{abs}}{M_{abs}}, \tag{1}$$

where X_i – current moisture content of the material, kg·kg^{-1};
M_{abs} – dry matter content of the material, kg;
M_i – current mass of the sample, kg.

To generalize the experimental data on drying kinetics, the moisture content–time relationships were approximated using an exponential model:

$$X_i = X_0 \cdot e^{-k\tau}, \tag{2}$$

where X_0 – initial moisture content, kg·kg^{-1};
k – drying rate constant, min^{-1}.

Moisture removal rate:

$$u_i = \frac{\Delta m_i}{\Delta \tau_i}, \tag{3}$$

where u_i – moisture removal rate, kg·min^{-1};
Δm_i – amount of moisture removed, kg;
$\Delta \tau_i$ – drying time at that stage of the process, min.

The electrical resistivity of the material was determined, taking into account the linear shrinkage coefficient, using the following formula:

$$\rho_i = R_i \frac{\Delta m_i}{\gamma l_0^2 \left(1 + \beta_l X_i\right)^2}, \tag{4}$$

where ρ_i – electrical resistivity of the material, Ohm·m;
R_i – electrical resistance of the material, Ohm;
γ – density of the material, kg·m^{-3};
l_0 – initial height of the material layer, m;
β_l – linear shrinkage coefficient.

Linear shrinkage coefficient:

$$\beta_l = \frac{l_{abs} - l_0}{l_0 X}, \tag{5}$$

where l_{abs} – height of the material layer at the end of drying, m.

Results and discussion

The summarised results of the experiments are presented as graphs showing the time dependence of moisture content, moisture removal rate, temperature at the centre of the samples, direct electric heating current, and the specific electrical resistance of the material layer (Figs. 2–4).

Analysis of the drying curves (Fig. 2) shows that increasing the air velocity to 0.4 m·s^{-1} contributes to a certain intensification of the drying process. In particular, at a velocity of 0.4 m·s^{-1}, the drying time is 132 minutes, which is 5.7% less compared to the regime with an air velocity of 0.2 m·s^{-1}. A further increase in air velocity leads to a decrease in the intensity of the drying process. It has been established that increasing carrier velocity from 0.4 to 1.5 m·s^{-1} is accompanied by a 38% increase in the drying time.

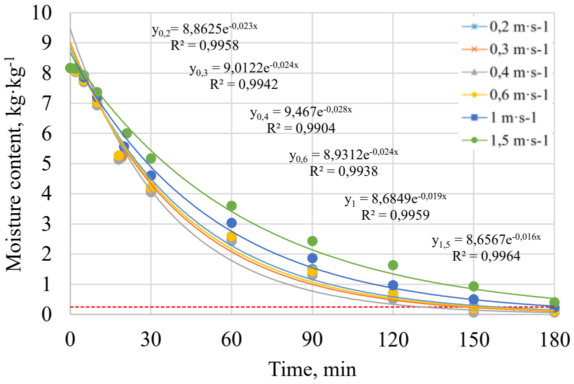

Fig. 2. **Dependence of the moisture content of the material during the drying process at a heat carrier velocity of 0.2-1.5 m·s^{-1}**

For mathematical processing of the experimental data on drying kinetics, the moisture content–time relationships were approximated using the exponential model (5). The obtained values of the coefficient of determination R^2 = 0.9904-0.9964 indicate a high adequacy of the proposed model. It was established that the drying rate constant k varies within the range of 0.016-0.028 min^{-1} and reaches its maximum at a heat carrier velocity of 0.4 m·s^{-1}. This confirms that the highest intensity of moisture removal is achieved under this regime. With further increase in air velocity, the value of k decreases, which is consistent with the experimentally observed slowdown of the drying process due to the enhanced cooling effect of the heat carrier.

At the initial stage of the process, a sharp rise in material temperature is observed for all the modes under investigation (Fig. 3, *a*). Maximum temperatures are reached after 15-20 minutes of drying. The highest sample temperature, 57 °C, was recorded at a carrier velocity of 0.2 m·s^{-1}.

As the air velocity increases, the maximum material temperature gradually decreases. Thus, at velocities of 0.3-0.6 m·s^{-1}, the peak temperature values are 50-55 °C, whereas at velocities of 1-1.5 m·s^{-1}, they decrease to 41-47 °C. This is explained by the intensification of convective heat transfer between the material surface and the air flow, which intensifies heat removal from the sample.

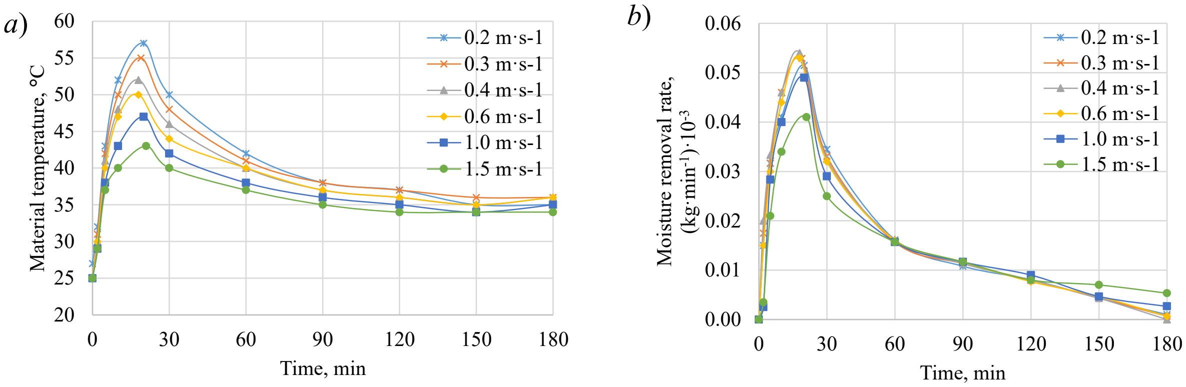

Fig. 3. **Dependences of the material temperature (*a*) and moisture removal rate (*b*) at a heat carrier velocity of 0.2-1.5 m·s^{-1}**

After reaching the maximum, the temperature of the material gradually decreases and, after 90-120 minutes of the process, stabilises within the range of 34-37 °C, regardless of the carrier velocity. This temperature profile is due to a reduction in the moisture content of the material and a decrease in the intensity of internal heat generation during direct electric heating.

The research has shown that increasing the carrier velocity from 0.2 to 1.5 m·s^{-1} reduces the maximum material temperatures during drying by 28% and ensures a more uniform temperature distribution during the final stage of the process.

An analysis of the dependence of moisture removal rates on time during combined drying (Fig. 3, *b*) indicates that the carrier velocity significantly influences the intensity of the mass transfer process. At the initial stage of drying, a sharp increase in the moisture removal rate is observed for all studied regimes, which is associated with the heating of the material and the intensification of evaporation of free moisture from the surface of the samples. Maximum values of the moisture removal rate are reached at 15-20 minutes in the process. The highest drying intensity is observed at a heat carrier velocity of 0.4 m·s^{-1}, where the maximum moisture removal rate is 0.054·10^{-3} kg·min^{-1}. At velocities of 0.2-0.3 m·s^{-1}, the peak values are slightly lower, which is explained by less intense convective heat and mass transfer between the material surface and the air flow.

A further increase in the heat carrier velocity beyond 0.4 m·s^{-1} leads to a decrease in the maximum moisture removal rate. In particular, at a velocity of 1.5 m·s^{-1}, the maximum drying rate was the lowest among the tested conditions and amounted to 0.041·10^{-3} kg·min^{-1}, which is 24% lower compared to the 0.4 m·s^{-1} condition. This can be explained by the increased cooling effect of the air flow, which lowers the material temperature and, consequently, the intensity of moisture evaporation.

The dependencies of the electric current of direct electric heating and the electrical resistance of the material during combined drying at different heat carrier velocities in the drying oven are shown in Fig. 4. In all cases, an intense increase in current is observed at the start of drying for all heat carrier velocities studied (Fig. 4, *a*). Maximum current values are reached in the range of 0.12-0.16 A. The highest values are characteristic of lower heat transfer fluid flow rates (0.2-0.3 m·s^{-1}), whereas as the air velocity increases to 1-1.5 m·s^{-1}, the peak current values decrease.

After reaching a maximum, between 20 and 60 minutes into the process, a sharp decrease in current is observed for all drying modes. During this period, intense evaporation of moisture takes place, leading to a reduction in the material electrical conductivity. As a result, the current strength quickly decreases to values of around 0.03-0.04 A. At the same time, the differences between the curves for different heat carrier velocities gradually decrease, indicating a reduction in the influence of hydrodynamic conditions on the material's electrophysical parameters as it dries.

Analysis of the time dependence of the electrical resistivity of the material during combined drying (Fig. 4, *b*) shows a characteristic change in this parameter throughout the entire dehydration process and its dependence on the heat carrier velocity. In the first 20 minutes of drying, a sharp decrease in the electrical resistivity to 9-20 Ohm·m is observed.

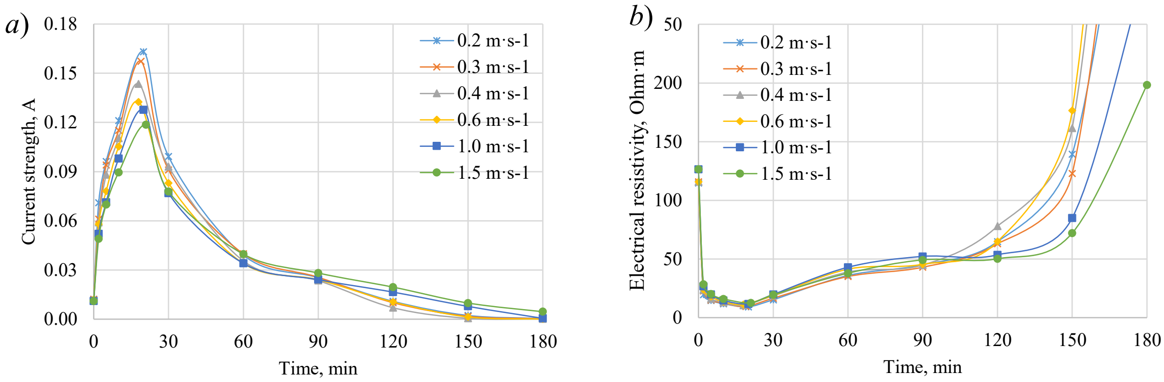

Fig. 4. **Dependences of the electric current during direct ohmic heating (*a*) and the specific electrical resistance of the material (*b*) at a heat carrier velocity of 0.2-1.5 m·s^{-1}**

After reaching minimum values, a gradual increase in electrical resistivity is observed for all drying modes. This is associated with a decrease in the moisture content of the material, which leads to a reduction in the electrical conductivity of the layer. The most intense increase in resistance occurs in the final stage of the process (120-150 minutes), when bound forms of moisture predominate in the material structure. The effect of the heat carrier velocity is most evident in the final stage of drying. At lower air velocities in the range of 0.2-0.4 $m \cdot s^{-1}$, a more abrupt increase in electrical resistivity is observed, whereas at higher velocities (1-1.5 $m \cdot s^{-1}$) this process occurs more gradually. This is explained by differences in the rate of moisture removal and the drying temperature regime, which determine the material's electrical conductivity properties.

The obtained dependencies of material temperature, electric current, and specific electrical resistance exhibit a non-monotonic behavior and cannot be adequately described by simple analytical models. This is due to the complex interaction of convective heat transfer, internal electric heating, and changes in the electrical conductivity of the material during dehydration. At the same time, these dependencies can be used for qualitative analysis and for substantiating the selection of rational operating conditions for combined drying.

Statistical processing of the experimental data revealed strong correlations between the studied parameters. In particular, pronounced negative correlation was observed between the heat carrier velocity and the maximum material temperature ($r = -0.98$), while a strong positive correlation was found between the material temperature and electric current ($r = 0.97$). An inverse relationship between specific electrical resistance and electric current was also identified ($r = -0.95$), confirming the decisive role of the electrophysical properties of the material in determining the intensity of the drying process. The obtained results indicate a statistically significant effect of heat carrier velocity on drying kinetics and electrophysical parameters of the material ($p \leq 0.05$).

The results obtained indicate that in the combined drying method, the nature of the influence of the heat carrier velocity differs significantly from that in traditional convective drying. In classical convective drying processes, an increase in the air velocity typically leads to an intensification of heat and mass transfer at the material surface, which contributes to an increase in the drying rate. However, in the case of combined energy supply, where mechanisms of surface convective heating and volumetric electric heating act simultaneously, an increase in the heat carrier velocity can have a dual effect.

On the one hand, increasing the air velocity promotes the intensification of external heat and mass transfer between the material surface and the surrounding environment. This manifests itself in an increase in the heat transfer coefficient and improved conditions for moisture evaporation from the material surface. On the other hand, an excessive increase in the heat carrier velocity leads to an intensification of the cooling effect of the air flow, which reduces the material temperature and, consequently, the intensity of internal electric heating.

A distinctive feature of the direct electric heating process is that the amount of heat released in the material is determined by its electrical conductivity and the magnitude of the current passing through the layer. As the material temperature decreases and its electrical conductivity decreases, the current also decreases, leading to a reduction in the intensity of volumetric heat release. This explains the reduction in the rate of moisture removal at high carrier velocities, despite the improvement in external heat and mass transfer conditions.

The optimal heat carrier velocity range established in this study, at 0.4 $m \cdot s^{-1}$, indicates a balance between the two energy transfer mechanisms. In this mode, sufficiently intense convective heat transfer is ensured whilst maintaining a high material temperature and effective internal electric heating.

An important role in the initial stage of the process is played by the phenomenon of electroplasmolysis of the cellular structure of the plant raw material, which constitutes a capillary-porous system. Under the action of the electric field, the integrity of the cell membranes is partially disrupted, which contributes to an increase in the permeability of the cell walls and the release of intracellular moisture. As a result, at the initial stage of the process, there is an intense increase in the rate of moisture removal, a sharp decrease in the specific electrical resistance of the material, and an increase in the strength of the direct electric heating current. Similar effects of increased electrical conductivity in plant raw materials due to the destruction of cell membranes under the influence of an electric current have also been noted in the works of other researchers who have studied electrophysical methods of processing plant raw materials [13-15]. The further increase in the electrical resistance of the material during the drying process is associated with a decrease in the content of free moisture within the material structure. Since the electrical conductivity of plant-based raw materials is largely determined by the presence of an aqueous electrolyte, the removal of moisture leads to a sharp decrease in ion mobility and a corresponding increase in the electrical resistance. This, in turn, reduces the intensity of internal electric heating during the final stages of the process.

The obtained results are in good agreement with the findings of studies [6; 7; 12; 13], which show that the use of combined drying methods employing electrical or electromagnetic energy supply allows for the intensification of internal mass transfer and a reduction in the drying time of capillary-porous materials. At the same time, the effectiveness of such technologies is largely determined by the optimal combination of external heat transfer parameters and the intensity of internal heating.

The results of the conducted studies confirm the feasibility of using a combined drying method for capillary-porous materials, which combines surface convective heating and volumetric direct electrical heating. Optimizing the heat carrier velocity allows for effective interaction between these mechanisms and improves the energy efficiency of the drying process.

Conclusions

1. Experimental studies have shown that the heat carrier velocity significantly affects the drying kinetics of capillary-porous colloidal materials under conditions of combined energy supply, which combines convective heating and direct electrical heating of the material. It has been established that changing the air velocities in the range of 0.2-1.5 $m \cdot s^{-1}$ leads to a significant change in the duration of the process, the temperature regime, and the electrophysical parameters of the material layer.
2. It has been determined that the optimal heat carrier velocity is 0.4 $m \cdot s^{-1}$, at which the drying process is maximally intensified. In this mode, the drying duration is 132 min, which is 5.7% less than at an air velocity of 0.2 $m \cdot s^{-1}$. A further increase in the air velocity to 1.5 $m \cdot s^{-1}$ leads to a 38% increase in drying duration.
3. It was found that as the heat carrier velocity increases from 0.2 to 1.5 $m \cdot s^{-1}$, the maximum material temperature during drying decreases by 28%, from 57 °C to 41-47 °C. The highest moisture removal rate is observed at a heat carrier velocity of 0.4 $m \cdot s^{-1}$. When the air velocity is increased to 1.5 $m \cdot s^{-1}$, the maximum moisture removal rate decreases by 24% compared to the optimal operating conditions.
4. A study of the electrophysical parameters showed that, in the initial stage of the process, the direct electric heating current rises to 0.12-0.16 A, after which it decreases to 0.03-0.04 A due to a reduction in the material moisture content. At the same time, an increase in the heat carrier velocity leads to a decrease in peak current values. It was established that during the first 20 minutes of the process, the electrical resistivity of the material decreases to minimum values of 9-20 Ohm·m. Subsequently, as the moisture content decreases, the electrical resistivity gradually increases, reflecting a decrease in the electrical conductivity of the layer being dried.
5. The results obtained show that an excessive increase in the heat carrier velocity during combined drying can lead to material supercooling, decrease in current, and reduction in the intensity of moisture evaporation. This must be taken into account when developing energy-efficient drying modes for capillary-porous materials using combined energy supply.

Author contributions

Conceptualization, O.Sav.; methodology, O.Sav. and V.S.; validation, O.S., O.Sol. and V.K.; formal analysis, O.T. and V.K.; investigation, O.Sav. and V.S.; data curation, O.Sav.; writing – original draft preparation, O.Sav. and O.T.; writing – review and editing O.Sol. and V.K.; visualization, O.Sav. and O.T.; project administration, O.Sav.; funding acquisition, O.Sav. All authors have read and agreed to the published version of the manuscript.

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