Chapter 3
Influence of the Direction of Air Movement in the Microwave-Convection Drier on the Energy Intensity of the Process

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3.1 Introduction

The use of electrotechnologies in grain drying allows to reduce energy consumption of the process and to increase the productivity of equipment. In FSAC VIM, studies are carried out on microwave-convective grain drying [1–3], and as a result of these studies, a system of algebraic equations and transfer functions describing heat and moisture exchange in the grain layer is obtained [4, 5].

With the use of this system of algebraic equations and transfer functions, a computer model of heat and moisture exchange in the grain layer has been developed, and the model considers the influence of a microwave field and a drying agent on the grain. To develop the model, Simulink was used [6].

3.2 Principles of the Computer Model Design

Usage of the staircase calculation method [7] has allowed to develop a drying model for a dense layer of grain based on the computer model of an elementary layer [8].

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Table 3.1 Experimental data on the influence of grain moisture content and the distance to the magnetron on the energy absorbed by a unit of grain volume

Grain moisture content, W (%)	Distance to the magnetron along the axis, L (cm)	Energy per volume absorbed by grain at the control point, Qv (kJ/m^3)
21.3	3	3180.3
17.8	6	1646.2
16.9	9	913.9
15.9	3	3090.4
15	6	1632.5
13.9	9	911.4
12	3	3235.4

When constructing a computer model for microwave-convective drying of a grain layer, the results of investigations on the distribution of the microwave field in the microwave core were taken into account. Since the energy absorbed by a unit of grain varies depending on the moisture content of the grain and the distance to the magnetron, a two-factor experiment was conducted to determine this relation [9]. The results of the experiment are partially shown in Table 3.1.

Using the experimental data obtained, regression analysis was performed and the following regression model was obtained:

$$Qv = 5778 - 14{,}92\mathrm{W} - 846{,}2\mathrm{L} + 0{,}2332\mathrm{W}^2 - 3{,}727\mathrm{W}\cdot\mathrm{L} + 42{,}74\mathrm{L}^2. \quad (3.1)$$

The regression analysis was performed using MATLAB. Coefficients of the model are significant by the Student's criterion. The adequacy of the model was tested by the Fisher criterion. Indicators evaluating accuracy of the model are the following: SSE, 1.409×10^6; R-squared, 0.9731; adjusted R-squared, 0.9698; and RMSE, 185.4, which shows a good level of reliability of the model.

The regression Eq. (3.1) is used in the computer model, which allows to simulate the change in the energy density of the microwave field in the grain layer during the process of drying.

The thickness of the grain layer, which undergoes microwave-convective processing, was taken equal to 15 cm. Such thickness is comparable to the depth of penetration of the microwave field into the wheat grain layer of the normal moisture content (14%). It was assumed that the grain layer can be divided into sections of 5 cm thick, within which the microwave field is evenly distributed. Simulink model of the 15-cm-thick grain layer, divided into three layers of 5 cm, is shown in Fig. 3.1.

In the model, the grain layer is represented by three blocks "Grain layer," in each of which the microwave field has a different intensity, by analogy with the real grain layer. The drying agent successively passes through all the layers. Input parameters of the drying agent are set with the help of the blocks Tvh and Fvh.

With the help of the Relay block, switching on and switching off of the magnetrons are controlled. The magnetrons are switched off when the temperature of the grain reaches 55 °C at the point of maximum power of the microwave field. The

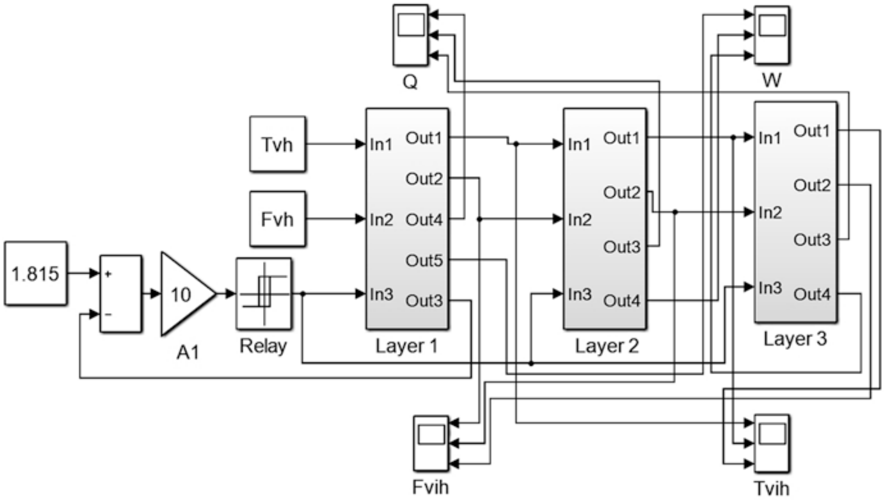

Fig. 3.1 Computer model of heat and moisture exchange in the grain layer under microwave-convective processing

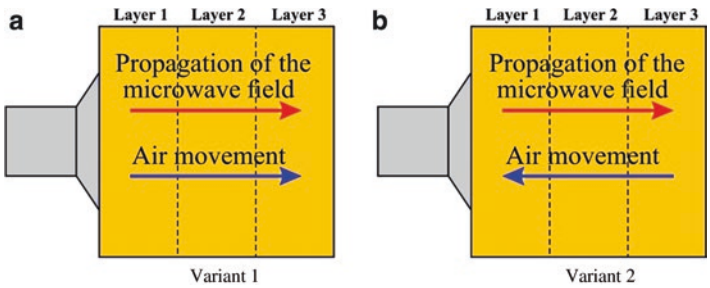

Fig. 3.2 Layout of the grain layers and distribution of the microwave field and drying agent in them. (**a**) Variant 1. (**b**) Variant 2

oscillograms display graphs of grain temperature change in each layer (block Q), grain moisture in the layers (block W), relative humidity of air going out of each grain layer (Fvih), and temperature of the drying agent going out of each grain layer (Tvih) [10].

When developing the design of microwave-convective zones, the direction of movement of the drying agent, its temperature, and uniformity of distribution in the grain layer are of great importance. Proceeding from this, modeling of the microwave-convective grain drying process was carried out. Figure 3.2 shows the schematic diagram of positions of the grain layers, propagation of the microwave field, and movement of the drying agent.

In the first variant of movement of the drying agent, it first passes through the grain Layer 1. Since this layer is closest to the source of the microwave field, it must have higher temperature than Layers 2 and 3. Therefore, when air passes successively through Layer 1 → Layer 2 → Layer 3, it must be heated from the grain in Layer 1. Then, air temperature might both decrease or be maintained at a constant level—it all depends on the specific modes of grain drying.

In the second variant of air distribution, it moves from Layer 3, in which the microwave field has the smallest power. Therefore, the change in the grain temperature and humidity of the drying agent depends on the initial parameters of the air supplied to Layer 3.

3.3 Results of Modeling

Figure 3.3 presents the results of modeling the change in grain temperature in the layers. The simulation was carried out with the following initial parameters: $W_0 = 22\%$, $F_0 = 65\%$, $T_0 = 20$ °C, and $V = 0.5\frac{m}{s}$.

With the relative air humidity of 65%, the equilibrium moisture content of the grain is 14%. This value of the relative air humidity is taken in order to estimate how drying of grain in the layers distant from the magnetron will change. It can be seen from the graphs that the air distribution scheme significantly affects the change of the grain temperature in the microwave-convective zone. With the first variant of air distribution, there is a significant difference in heating of the grain along the layers in the beginning of the drying process. Then, the difference in heating of the grain decreases and stays within 3 °C until the grain dries out. The maximum temperature does not exceed 55 °C. This allows to say that the microwave-convective drying process is sufficiently controlled in order to ensure the preservation of the technological qualities of the grain.

With the second variant of air distribution, the difference in heating of the grain zones is even higher than with the first variant. Moreover, the difference in heating of the grain between Layer 1 and Layers 2 and 3 changes insignificantly during the drying process. Layer 3 is less affected by the microwave field, so grain temperature there does not increase significantly. Besides, it is constantly affected by the drying agent having the temperature of 20 °C. Therefore, temperature of Layer 3 does not exceed 35 °C.

Herewith, air heated by the grain in Layer 3 enters Layer 2. Density of the microwave field in Layer 2 is also higher than in Layer 3. Therefore, temperature of the grain in the layer already reaches 37–39 °C. In Layer 1 of the grain, the maximum power of the microwave field is emitted, so the magnetron is switched off when the grain temperature reaches 55 °C. And air in Layer 1 is already heated from Layer 2, so the fluctuations in the temperature of grain heating in Layer 1 are minimal.

The increase in temperature of the air, when it passes through the grain layer, affects its moisture-absorbing capacity. This can significantly affect the speed of grain drying in the layers. To discover the dependency, modeling of moisture content dynamics was carried out. The simulation results are shown in Fig. 3.4.

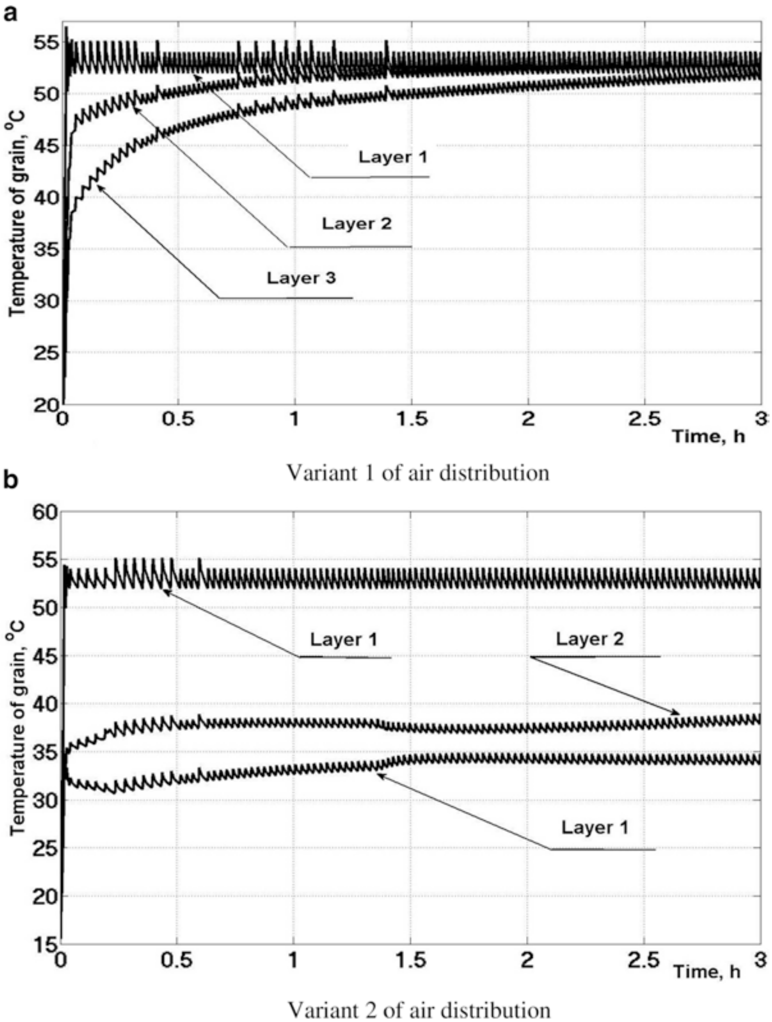

Fig. 3.3 Change in the temperature of grain layers during the process of microwave-convective processing. (**a**) Variant 1 of air distribution. (**b**) Variant 2 of air distribution

Results of the simulation show that the change of the air distribution scheme in the grain layer significantly affects the change of moisture content across the grain layers. With the first variant of air distribution, uniform decrease in humidity across all layers is observed. The drying speed is significantly different in the grain layers, and the maximum power density of the microwave field, absorbed by specific grain layer, does not ensure the maximum drying speed at all. The first layer does not dry up to the normal moisture content of 14% even during 4 hours, while the second layer reaches that moisture content in 1.5 h and the third in 1.3 h. Herewith, the average moisture content of all layers reaches 14% in 1.7 h. Unevenness of moisture content in the layers is 3%.

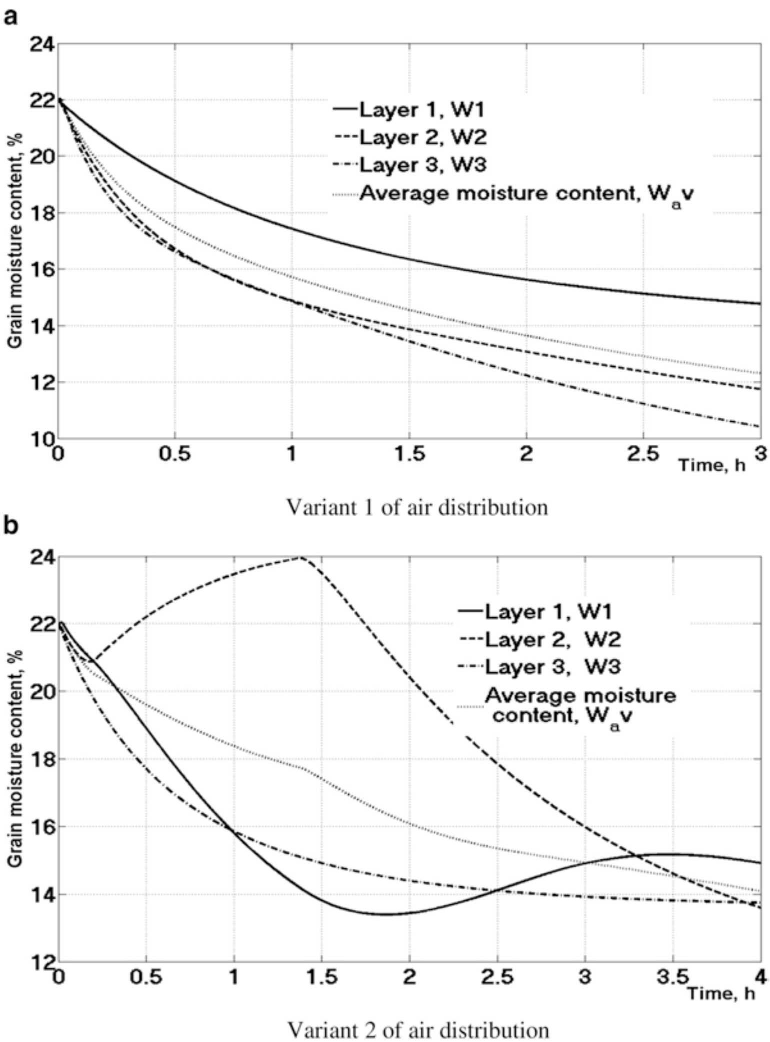

Fig. 3.4 Graphs of drying for the layers. (**a**) Variant 1 of air distribution. (**b**) Variant 2 of air distribution

With the second variant of air distribution, Layer 1 dries to the moisture content of 14% in 1.4 h. For the other 0.3 h, it continues to dry and then starts to moisten. Layer 3 dries to the normal moisture content in 2.5 h. In Layer 2, the first stage is the moistening of the grain and then drying to the normal moisture content in 4 h. Such scheme of air distribution provides rather largely uneven drying of the grain over for different layers and increases durations of the process. Thus, the average moisture content of the grain in the layer will reach 14% in only 4 h, which is more than twice as much as in the first variant of air distribution.

3.4 Conclusions

Developed computer model of heat and moisture exchange in a grain layer under microwave-convective impact makes it possible to study the drying process with changing parameters of the drying agent and the grain layer and also with a change in the direction of air movement.

Simulation results show that the rate of grain drying varies for different parts of grain layer. What is more, for maximum speed of drying, it is not necessary to provide the maximum power density of the microwave field.

The best variant of drying in terms of speed and energy intensity of the process is the air distribution scheme in which air moves sequentially from the grain layers with higher power density of the microwave field to the layers of grain that are less heated by the field.

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