# COMPARATIVE ANALYSIS OF METHODS SUPPLIES THERMAL ENERGY IN HIGH-WATER BIOLOGICAL OBJECTS DURING DRYING

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ABSTRACT

**Object of research:** the process of heating a biological object with various methods of supplying thermal energy, in particular, convective, direct electric and combined methods.
**Solved problem:** intensification of heating of high-moisture biological objects during the drying process.
**Main scientific results.** The expediency of using a combined (direct electric and convective) supply of thermal energy for intensifying heating of raw materials in the drying process has been established. In terms of the duration of the heating process, combined heating is much more effective than using purely convective or direct electric heating. Comparison of the values of the duration of the heating process for a body weighing 0.0028 kg shows that the combined heating occurs 1.5–2.5 times faster. At the same time, the consumption of electrical energy for the selected processing modes is 279–254 J, which is 80–87 % of the total required energy. It has been found that the main control factor in the combined heat supply is the applied voltage of direct electric heating.
**The area of practical application of the research results:** enterprises of the processing industry, specializing in the production of dried products.
**Innovative technological product:** a combined method of heating high-moisture objects during the drying process, which will provide intensive and energy-efficient processing modes while maintaining the established quality of the finished product.
**Scope of application of the innovative technological product:** production of finished food products and semi-finished products.

## 1. Introduction

### 1. 1. The object of research

The object of research is the process of heating a high-moisture biological object with various methods of supplying thermal energy, in particular, convective, direct electric and combined methods.

### 1. 2. Problem description

Drying is the simplest, cheapest and least labor-intensive process of preserving biological objects, in particular, vegetables and fruits. Dried foods store well, require no special storage space and take up little space. Recently, in the development of technologies and equipment for thermal dehydration of food products, attention is mainly paid to improving their consumer properties due to the complication of production, and a high level of profitability is supported by marketing moves.

Drying plants differ in the ways of supplying heat to the objects of dehydration: convective, conductive, with the help of infrared rays, currents of high, ultrahigh frequency and ultrasound [1–4]. A more innovative way of drying fruits and vegetables is the freeze-drying method [5]. All of these drying methods are based on the use of a clean type of energy – electric. However, most of the proposed methods cannot provide an acceptable drying time for the specified quality of the finished product. In addition, the specific energy costs for the implementation of the dehydration process are several times higher than the theoretical values of energy costs for the evaporation of one kilogram of water [1].

The main approach to solving the problem of increasing the utilization rate of high-potential electricity and production efficiency is the intensification of the drying process. The greatest effect is achieved when using combined drying methods [6, 7].

### 1. 3. Proposed solution to the problem

In the proposed drying method [8], the acceleration of the moisture removal process consists in the introduction of the required amount of electrical energy for subsequent conversion into heat energy throughout the entire volume of a wet body with a minimum number of conversions. The desired result is achieved by using direct electric heating in the process of convective drying of high-moisture raw materials.

**The aim of research** is to determine the duration and efficiency of heating the temporal object with various methods of supplying thermal energy to substantiate the most effective method of processing.

## 2. Materials and methods

When using convective and direct electric heating, the following combinations of their use are possible:

– purely convective heating (when the temperature of the coolant is higher than the temperature of the heated body)

– purely direct electrical heating at ambient temperature (when body temperature is higher than air temperature);

– combined heating.

**Fig.1, 2** show a diagram of options for supplying thermal energy to an object and the course of an increase in its temperature during heating.

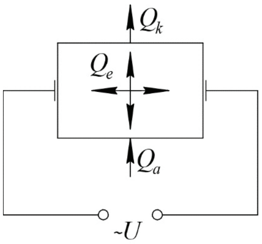


**Fig. 1.** Scheme of energy supply to the dried object: $Q_a$ – heat flow from heated air; $Q_k$ – heat loss from the body surface due to convective heat transfer; $Q_e$ – heat flux from direct electrical heating

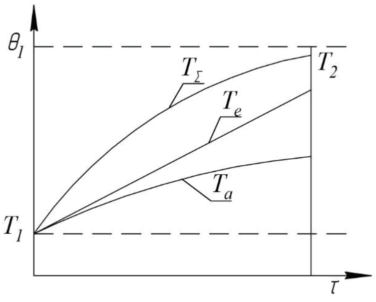


**Fig. 2.** The course of the increase in the temperature of the object during heating: $T_a$, $T_e$, $T_\Sigma$ – the course of the body temperature from convective, direct electric and combined heating, respectively

With purely convective heating, an increase in the object's temperature $T_a$ occurs due to heat transfer from the heated air $Q_a$.

If an electric current passes through an object whose temperature is equal to the ambient temperature, then the body temperature $T_e$ gradually rises, since all the energy losses during the passage of the current pass into heat $Q_e$. Part of the released heat is spent on heating the body and increasing its temperature, while the other part $Q_k$ is given from the body surface to the environment due to heat transfer.

With combined heating, a body heated by electric current is placed in atmospheric air with a temperature above the final value of the body heating temperature. In this case, an increase in the temperature of the object $T_\Sigma$ occurs due to heat from convective $Q_a$ and direct electric heating $Q_e$, and in the waste of heat into the environment $Q_k$ are excluded.

### 2. 1. Convective heating

The amount of heat energy required to heat a body to an equilibrium temperature

$$Q_s = C_s m(T_2 - T_1), \tag{1}$$

where $Q_s$ – the amount of thermal energy required to heat the body, J; $C_s$ – heat capacity of the sample, J/kg·°C; $m$ – mass of the sample, kg; $T_1$, $T_2$ – respectively initial and final body temperature, °C.

The amount of thermal energy coming from the heated coolant

$$Q_a = KC_a(\theta_1 - \theta_2), \tag{2}$$

where $Q_a$ – amount of thermal energy with a heated coolant, J; $K$ – amount of air consumed for heating the body, kg; $C_a$ – heat capacity of air, J/kg·°C; $\theta_1$, $\theta_2$ – respectively, the initial and final temperature of the coolant, °C.

Equation (2) shows that the main parameter of the heating process, time is a function of the final air temperature $\tau_a = f(\theta_2)$.

The amount of air for heating the body during time $\tau_a$

$$K = G \cdot \tau_a, \tag{3}$$

where $G$ – air flow required to heat the body, kg/s; $\tau_a$ – duration of convective heating, s.

Air consumption required to heat the sample [9]

$$G = \frac{\alpha F}{C_a \ln B}, \tag{4}$$

where α – heat transfer coefficient, W/(m$^2$·°C); $F$ – surface area of the body heat exchange, m$^2$; $B$ – constant.

Body heat transfer surface area

$$F = 2\frac{\pi D^2}{4} + \pi D l = \pi D\left(\frac{D}{2} + l\right), \tag{5}$$

where $D$, $l$ – respectively the diameter and thickness of the object, m.

Determine the constant for the entire heating process

$$B = \frac{T_2 - \theta_1}{T_2 - \theta_2}. \tag{6}$$

The duration of heating the sample with air of variable temperature [10]

$$\tau_a = -\frac{m \cdot C_s}{C_a G} \cdot \ln\frac{T_2 - \theta_1}{T_1 - \theta_1} \cdot \frac{B}{B - 1}. \tag{7}$$

Efficiency of the convective heating process

$$\eta_a = \frac{Q_s}{Q_a}. \tag{8}$$

### 2. 2. Direct electric heating

Heat balance equation for direct electric heating

$$dQ_e = dQ_s + dQ_k, \tag{9}$$

where $Q_e$ – thermal energy released in the object when an electric current passes through it, J; $Q_k$ – thermal energy lost from the body surface due to convective heat transfer, J.

The amount of heat generated during the passage of an electric current over a period of time

$$dQ_e = \frac{U^2}{R} d\tau_e, \tag{10}$$

where $U$ – voltage of direct electric heating, in; $R$ – active electrical resistance of the sample, Ohm; $\tau_e$ – duration of direct electric heating, sec.

Energy lost from the body surface due to convective heat transfer

$$dQ_k = \alpha F(T - \theta_0) d\tau_e, \tag{11}$$

where $T$ – current body temperature; $\theta_0$ – ambient air temperature, °C.

Taking $\theta_0=T_1$, taking into account (1), (10) and (11), the heat balance equation (9) with direct electric heating will look like

$$\begin{gathered}\frac{U^2}{R} d\tau_e = C_s m \cdot d(T - T_1) + \\ +\alpha F(T - T_1) d\tau_e.\end{gathered} \tag{12}$$

Having solved equation (12) with respect to $\tau_e$, let's obtain an expression for determining the duration of heating the body to the final temperature $T_2$ with direct electric heating

$$\tau_e = \frac{C_s m \cdot \ln\left(1 - \frac{(T_2 - T_1)\alpha F R}{U^2}\right)}{\alpha F}. \tag{13}$$

Efficiency of the heating process by direct electric heating

$$\eta_e = \frac{Q_s}{Q_e}. \tag{14}$$

### 2. 3. Combined heating

Heat balance equation for combined heat supply

$$Q_\Sigma = Q_a + Q_e. \tag{15}$$

The amount of heat energy, will be able to give a coolant with a constant temperature

$$Q_a = \alpha F \Delta \tau_\Sigma, \tag{16}$$

where $\Delta$ – average logarithmic difference between air and body temperatures

$$\Delta = \frac{(\theta_1 - T_1) - (\theta_1 - T_2)}{\ln \frac{\theta_1 - T_1}{\theta_1 - T_2}}. \tag{17}$$

Taking into account (17), expression (16) has the form

$$Q_a = \frac{\alpha F\left((\theta_1 - T_1) - (\theta_1 - T_2)\right)}{\ln\left(\dfrac{\theta_1 - T_1}{\theta_1 - T_2}\right)} \tau_\Sigma. \tag{18}$$

Taking into account expressions (10) and (18), the heat balance equation (15) with combined heating takes the following form

$$Q_\Sigma = \frac{\alpha F\left((\theta_1 - T_1) - (\theta_1 - T_2)\right)}{\ln\left(\dfrac{\theta_1 - T_1}{\theta_1 - T_2}\right)} \tau_\Sigma + \frac{U^2}{R}\tau_\Sigma. \tag{19}$$

On the other hand, the total heat is spent on heating the body to an equilibrium temperature. Therefore, equating (1) and (19) and after the appropriate transformations, there is the final expression for the duration of the combined heating of the body

$$\tau_\Sigma = \frac{mC_s\left(T_2 - T_1\right)}{\dfrac{\alpha F\left((\theta_1 - T_1) - (\theta_1 - T_2)\right)}{\ln\left(\dfrac{\theta_1 - T_1}{\theta_1 - T_2}\right)} + \dfrac{U^2}{R}}. \tag{20}$$

## 3. Results and discussion

To unify and compare the results, the calculation of heating parameters for different methods of energy supply was carried out with the following initial data: $m$=0.0028 kg; $C_s$=3800 J/kg·°C; $T_1$=20 °C; $T_2$=50 °C; $D$=0.028 m; $l$=0.005 m; $F$=0.00167 m$^2$; $R$=225 ohms; $C_a$=1030 J/kg·°C; $\alpha$ = 10 W/(m$^2$·°C).

**Fig. 3** shows the results of calculations of the efficiency $\eta_a$ and the duration $\tau_a$ of heating the body to $T_2$ with convective heat supply, depending on the final air temperature $\theta_2$ at different initial temperatures of the coolant $\theta_1$.

Data analysis **Fig. 3** shows the opposite trends of the presented dependencies when the final temperature of the heated coolant changes. When the value of the final air temperature is closest to the final body temperature (**Fig. 3, *a***), there is the highest degree of use of the thermal potential (efficiency) – 40–60 %. But at the same time, the highest duration of the process is observed, it is 20–30 minutes (**Fig. 3, *b***).

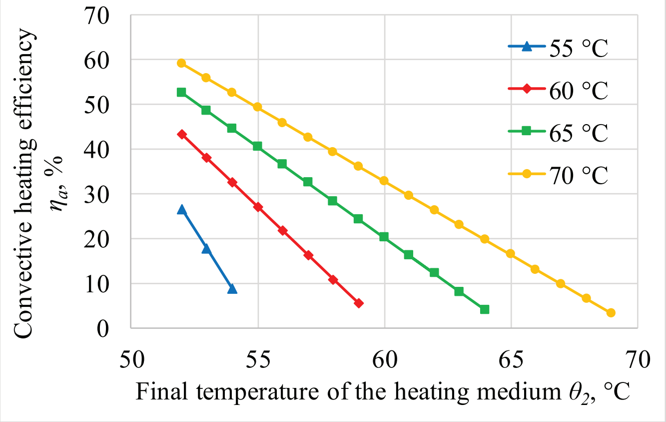
The initial temperature of the coolant has the same effect. With an increase in its value, the quality indicators of the use of thermal energy improve and at the same time the time of heat treatment decreases. When supplying thermal energy, in the process of convective drying, the final selection of temperature parameters is carried out according to the technological conditions.

When heating electrically conductive materials, in particular high-moisture fruit raw materials, by passing an electric current, the control factor is the magnitude of the electric field strength. The studies carried out [11] show that to ensure the required quality of the finished product, the electric field strength should be in the range of 20–40 V/cm. Accordingly, with a sample thickness of 5 mm, the voltage on the electrodes is 10–20 V.

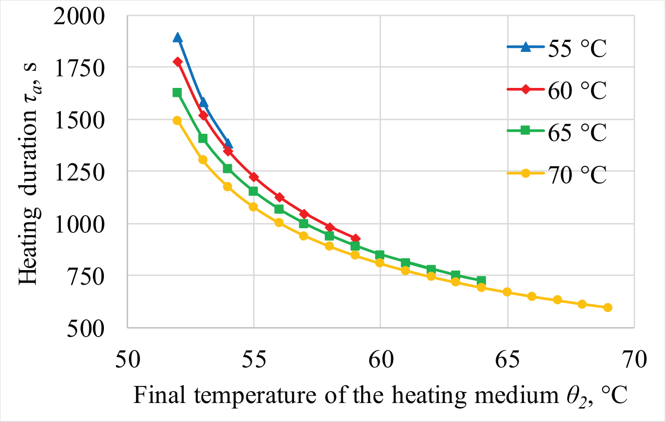
An increase in the voltage applied to the object sharply reduces the heating time in both cases from 1710 to 210 s with direct electric heating (**Fig. 4**) and from 400 to 150 s with combined energy supply (**Fig. 5**). This indicates that it is the voltage across the electrodes that is the main controlling factor in the combined heating of the body.

At the selected constant temperature of the coolant $\theta_1$=55 °C, the processing time is 150–250 s with a voltage on the electrodes of 15–20 V. The energy consumption for heating the body for these modes is 254–279 J, which is 80–87 % of the total necessary energy. At the same time, the energy consumption for purely direct electric heating is 375–443 J.

Comparison of the values of the duration of the heating process shows that the combined heating is much faster (1.5–2.5 times). Moreover, with purely direct electrical heating, a part of the released thermal energy is transferred to the external atmospheric air, as evidenced by the value of the efficiency, lies in the range of 35–85 %. If the object is located in an atmosphere with a temperature higher than the final body temperature, then heat loss to the environment is excluded. In addition, the body can receive energy from the heated coolant, especially during the warming up period.



*a*



*b*

**Fig. 3.** Dependences of the parameters of the body heating process to $T_2$=50 °C with convective heat supply, depending on the final air temperature $\theta_2$ at different initial temperatures of the coolant $\theta_1$: *a* – efficiency $\eta_a$; *b* – heating duration $\tau_a$

**Fig. 4, 5** show graphical dependences of the heating duration for direct electric $\tau_e$ and combined $\tau_\Sigma$ heating at different values of the voltage on the electrodes *U*.

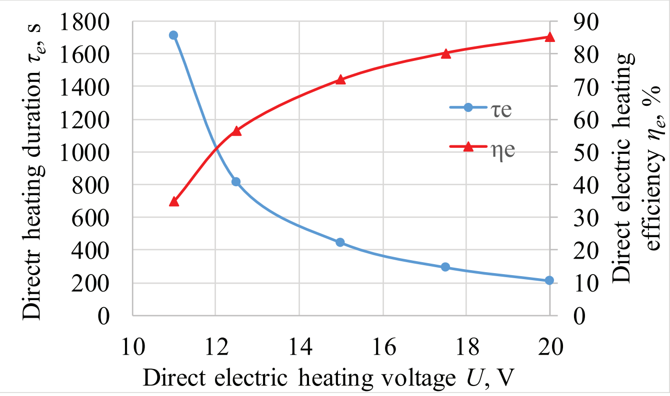


**Fig. 4.** Dependences of the heating duration $\tau_e$ and the efficiency $\eta_e$ with direct electric power supply on the applied voltage *U* at ambient air temperature $\theta_0$=20 °C

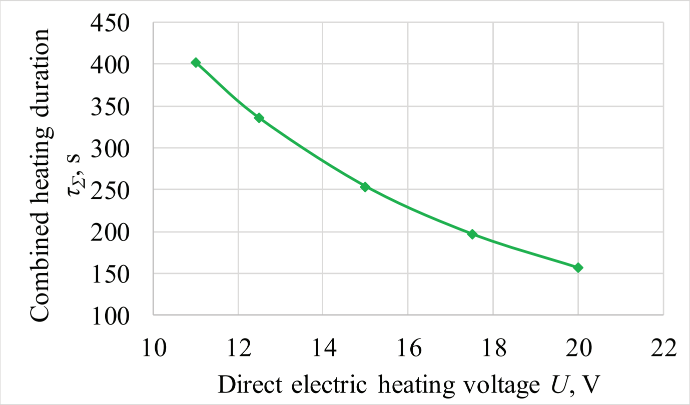


**Fig. 5.** Dependence of the heating duration $\tau_\Sigma$ with a combined energy supply on the applied voltage *U* at an air temperature of the coolant $\theta_1$=55 °C

One of the main parameters that determines the intensity of heat release when using direct electric heating is the electrical resistance of the material. The value of this parameter in the conditions of this study was limited to a constant value of 225 ohms. The experiments carried out show [11] that this parameter changes during heating and depends on the temperature and moisture content of the sample. Due to the complexity of the electrophysical phenomena occurring in an object when heated by a combined method, it is practically impossible to obtain a theoretical dependence of the change in electrical resistance. However, this problem can be solved by carrying out a series of experimental studies and obtaining on their basis empirical dependences of changes in this parameter.

The disadvantages of the study can be attributed to the fact that the proposed mathematical model of the heating process does not take into account the speed of the coolant in the drying oven, which can change during the drying process.

The next stage of the research is the development, based on the data obtained, of the technology and electrical means for the combined drying of biological objects.

## 4. Conclusions

1. The results confirm the expediency of using a combined (direct electric and convective) supply of thermal energy to intensify the heating of raw materials during the drying process. Comparison of the values of the duration of the heating process shows that the combined heating occurs 1.5–2.5 times faster.

2. It has been established that an increase in the voltage of direct electric heating significantly reduces the heating time of the object, both with purely electric heating and with combined energy supply. An increase in the voltage on the electrodes from 11 to 20 V reduces the duration of the process from 1710 to 210 s with purely electric heating and from 400 to 150 s with combined heating. This means that the main control factor for combined heat supply is the applied voltage of direct electric heating, which can be easily adjusted either manually or automatically.

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