Interaction analysis of the electrotechnological system "emitter-material" in the process of heating and drying of food plant raw materials

V D Ochirov, I V Altukhov, S M Bykova and M A Blokhnin

Irkutsk State Agrarian University named after A.A. Ezhevsky, Molodezhny settlement, Irkutsk district, Irkutsk region, 664038, Russia

E-mail: ochirov@igsha.ru

Abstract. The article considers the heat treating process of edible vegetable raw materials in the system "emitter - material" as the simplest case of heating and drying a homogeneous and isotropic body. It is accepted that the cooling conditions, the ambient temperature and the heat transfer coefficient in time remain constant, and there are no internal heat sources. Based on the study of the fundamental works of famous scientists in the field of food drying, the problem of determining the time constant of raw material heat treatment is solved. This parameter during heat treatment directly depends only on the physical properties of the material, the cooling process on its surface, geometric shape and body size. Knowing the values of the heating time constant, it is possible to determine the time and speed of heating the material to a given temperature.

Currently, the prospects for the development of electrical technology in the food industry and agriculture show the widespread use of drying plants operating on the principle of using electric energy converted into thermal radiation energy for processing edible vegetable raw materials.

A great contribution to this field of research was made by A.S. Ginzburg, S.I. Ilyasov, V.V. Krasnikov, P.D. Lebedev, A.V. Lykov, Yu.M. Plaksin, I.A. Rogov et al. [1-5]. Their systematic studies made it possible to solve a number of general problems of theory, technique, and drying technology and are the basis for finding the most rational methods and modes of infrared (IR) heating in food drying technologies. Work on the effective use of infrared heating in the processing and drying of edible vegetable raw materials shows that active research is currently underway in this direction [6-18].

When heating and drying wet materials with IR rays, radiant energy is converted into heat, and the phenomena of heat and mass transfer develop both outside the material - in the working chamber of the drying unit and inside the material [1, 3, 4].

The "emitter - material" system is regarded as the simplest case of heating a homogeneous and isotropic body. The analysis of the interaction of the "emitter - material" system is based on the joint solution of the equations of heat balance and heat transfer taking into account the dynamics of heating. Calculations in radiant heat transfer between bodies must be carried out, assuming that the radiating surfaces are gray and their radiation is diffuse with a constant density on isothermal parts of the surface.

The effect of IR heating on the irradiated materials is manifested in a number of effects - in heating the material, in removing moisture from the material and in the loss of heat into the environment due to
convective and radiant heat transfer. Based on the energy conservation law, the heat balance equation for the time interval $dt$ has the form:

$$dQ_{sup} = dQ_{heat} + dQ_{vp} + dQ_{conv} + dQ_{rad},$$  \hspace{1cm} (1)$$

where $dQ_{sup}$ – the amount of heat supplied to the material, J; $dQ_{heat}$ – the amount of heat spent on heating the material, J; $dQ_{vp}$ – the amount of heat spent on phase transformations, J; $dQ_{conv}$ – heat loss resulting from convective heat transfer between the material and the environment, J; $dQ_{rad}$ – heat loss resulting from radiant heat transfer between the material and surrounding surfaces, J.

The determination of the components of the heat balance is presented below [1, 3, 19].

The amount of heat supplied to the material:

$$dQ_{sup} = AEF,dt,$$  \hspace{1cm} (2)$$

where $A$ – the radiation absorption coefficient of the material; $E$ – the surface density of the radiation flux, W/m$^2$; $F_{o}$ – the area of the irradiated surface of the material, m$^2$.

The ability of a material to absorb infrared rays depends on its optical properties and the radiation wavelength, and the surface flux density from the emitters depends on the temperature of the emitters $T_{emit}$, the distance between the emitters $S$ and the distance between the emitters and the object $h_{o}$.

The amount of heat spent on heating the material:

$$dQ_{heat} = Cdt = Mcdt,$$  \hspace{1cm} (3)$$

where $C$ – the heat capacity of the material, J/°C; $M$ = $(M_{m} + M_{dm})$ – mass of material, kg; $M_{m}$ – moisture mass, kg; $M_{dm}$ – dry matter mass, kg; $c$ – the specific heat of the material, J/(kg•°C); $dt$ – the change in temperature of the material, °C.

Specific heat of wet materials:

$$c_{m} = \frac{c_{dm}(100 - \omega) + c_{w}\omega}{100} = \frac{c_{dm}100 + c_{m}\omega}{100 + \omega},$$  \hspace{1cm} (4)$$

where $c_{dm}$ – the specific heat of the dry matter of the material (for most plant materials is 0.733-1.55 kJ/kg•°C); $c_{w}$ – specific heat of water ($c_{w} = 4.1868 \times 10^3$ J/kg•°C), J/kg•°C; $\omega = (M_{m}/M) \cdot 100\%$ – material humidity, %; $u = (M_{m}/M_{dm}) \cdot 100\%$ – the moisture content of the material, % [20].

Equation (4) indicates the linear nature of the dependence of the specific heat on the humidity or moisture content of the material.

The amount of heat spent on the evaporation of moisture:

$$dQ_{evap} = q_{m}rF_{mat}dt,$$  \hspace{1cm} (5)$$

where $q_{m}$ – initial intensity or rate of evaporation of the substance, kg/(m$^2$•s); $r$ – the specific heat of evaporation (vaporization), J/kg; $F_{mat}$ – the total surface area of the material, m$^2$.

Heat losses resulting from convective heat transfer between the material and the environment:

$$dQ_{conv} = a_{conv}(t - t_{e})F_{mat}dt,$$  \hspace{1cm} (6)$$

where $a_{conv}$ – average convective heat transfer coefficient, W/(m$^2$•K); $t$ and $t_{e}$ – temperature of the material and the environment (air), °C.

Decisions to determine the heat transfer coefficient $a_{conv}$ in convective heat transfer, described by a system of differential equations and uniqueness conditions with a large number of variables, run up against serious difficulties. These difficulties can be solved by the theory of similarity [21, 22].

Using the theory of similarity prof. P.D. Lebedev [3] proposed an equation for determining the heat transfer coefficient during heat transfer, suitable for any method of supplying heat to a material that covers the entire drying process:
\[ \text{Nu} = A \text{Re}^{\alpha} \text{K}^{\beta} \left( \frac{\omega}{\omega_s} \right)^{\gamma} \left( \frac{p}{B} \right) \gamma. \]  

(7)

where \( \text{Nu} = a / \lambda \) – the Nusselt number (dimensionless heat transfer coefficient) characterizing the intensity of the convective heat transfer process; \( \alpha \) – \( c \) the average heat transfer coefficient, W/(m²*K); \( l \) – the characteristic linear size of the evaporation surface, m; \( \lambda \) – the coefficient of thermal conductivity, W/(m*K); \( A \) and \( n \) – constants depending on the number \( \text{Re} \); \( \text{Re} = w l / \nu \) – the Reynolds number (criterion of the heat carrier motion mode), characterizing the hydrodynamic conditions of the process; \( w \) – the heat carrier velocity, m/s; \( \nu \) – the kinematic viscosity coefficient, m²/s; \( K = t_e / t_w \) – the modified Guchman criterion, determines the increase in the heat transfer coefficient due to turbulization of the air flow by the vapors formed at the surface of the material; \( t_e \) – the temperature of the wet thermometer, °C; \( \theta = t_{em} / t_c \) – a parametric criterion that determines an increase in the heat transfer coefficient by reducing the thickness of the boundary layer with increasing temperature of the emitter surface during infrared heating; \( t_{em} \) – emitter temperature, °C; \( \omega / \omega_c \) – a parametric criterion that takes into account a decrease in the heat transfer coefficient with a decrease in the moisture content of the material during the falling drying speed; \( \omega \) – the moisture content of the material during the falling drying rate; \( \omega_c \) – critical humidity of the material; \( p / B \) – a criterion that takes into account the conditions of complex heat and mass transfer during vacuum drying of materials; \( p \) – the pressure of the medium in the working chamber, Pa; \( B \) – barometric pressure, Pa.

In drying plants for edible vegetable raw materials, the drying process occurs at atmospheric pressure, then \( p = B \) and the criterion \( p / B = 1 \).

Heat losses resulting from radiant heat transfer between the irradiated material and the surrounding surfaces

\[ dQ_{\text{rad}} = c_{\text{red}} \left[ \left( \frac{T}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right] F_{\text{mat}} d\tau \varphi_{12}, \]

(8)

where \( T \) – material temperature, K; \( T_s \) – temperature of surrounding surfaces, K; \( c_{\text{red}} = c_{\text{red}} c_0 \) – the reduced emissivity of the two-body system, W/(m²*K); \( c_{\text{red}} \) – reduced coefficient of thermal radiation of a system of two bodies; \( c_0 \) – the emissivity of a completely black body, W/(m²*K); \( \varphi_{12} = d Q_{\text{rad}} / d Q_{\text{em,mat}} \) – the average angular coefficient of radiation of the material; \( d Q_{\text{em,mat}} \) – the amount of heat emitted by the material, J.

For the general case, when two bodies are arbitrarily located in space, the reduced coefficient of thermal radiation \( e_{\text{red}} \) is determined using the coefficient of thermal radiation \( e_{\text{mat}} \) of the material and \( e_s \) of the surrounding surfaces:

\[ e_{\text{red}} \approx \left[ \frac{1}{e_{\text{mat}}} - 1 \right] \phi_{12} + \left[ \frac{1}{e_s} - 1 \right] \phi_{21} + 1 \right]^{-1}, \]

(9)

where \( \phi_{21} \) – average angular emissivity of surrounding surfaces.

Since the irradiated material is inside the drying chamber, for this case (\( \phi_{12} = 1 \) and \( \phi_{21} < 1 \) ), taking into account the reciprocity of the angular coefficients \( \phi_{12} F_{\text{mat}} = \phi_{21} F_s \), where \( F_s \) – the surface area of the surrounding surfaces, formula (9) takes the form:

\[ e_{\text{red}} = \left[ \frac{1}{e_{\text{mat}}} + F_{\text{mat}} / \left( \frac{F_s}{e_s} - 1 \right) \right]^{-1} \]

(10)

At \( F_s > F_{\text{mat}} \), \( F_{\text{mat}} / F_{\text{non}} \to 0 \), then \( e_{\text{red}} = e_{\text{mat}} \).
Total heat loss by the heated material to the environment:

\[
dQ_l = dQ_{\text{conv}} + dQ_{\text{rad}} = \alpha_{\text{conv}}(t - t_e)F \tau d\tau + c_{\text{red}} \left[ \left( \frac{T}{100} \right)^4 - \left( \frac{T_s}{100} \right)^4 \right] F_{\text{mat}} \tau \varphi_{12},
\]  

(11)

Formula (11) can be represented as follows:

\[
dQ_l = dQ_{\text{conv}} + dQ_{\text{rad}} = (\alpha_{\text{conv}} + \alpha_{\text{em}})(t - t_e)F \tau d\tau = \alpha(t - t_e)F \tau d\tau,
\]  

(12)

where \( \alpha_{\text{rad}} = \frac{e_{\text{red}} \cdot c_0 \cdot T^4_{\text{mat}} - T^4_s}{(T^4_{\text{mat}} - T^4_s)F_{\text{mat}}} \) – conventional heat transfer coefficient by radiation, W/(m\(^2\)•K);

\( \alpha \) – total coefficient of radiant convective heat transfer.

For practical conditions prof. P.D. Lebedev recommends taking the value of the total heat transfer coefficient \( \alpha \) in the range from 18.6 to 23.2 W/(m\(^2\)•K) [3].

After substituting the individual components in equation (1), obtain:

\[
AEF_0 d\tau dt = Mc dt + q_m r F d\tau + \alpha(t - t_e)F_d d\tau,
\]  

(13)

Divide each term of the obtained equation (13) by \( \alpha F d\tau \) and obtain:

\[
\frac{AEF_0}{\alpha F} = \frac{M c dt}{\alpha F d\tau} + \frac{q_m r}{\alpha} + (t - t_e),
\]  

(14)

or

\[
\frac{M c}{\alpha F} \cdot \frac{dt}{d\tau} + t = \left( t_e + \frac{AEF_0}{\alpha F} - \frac{q_m r}{\alpha} \right) = 0,
\]  

(15)

Denote [3, 19]:

\[
T_h = \frac{Mc}{\alpha F},
\]  

(16)

\[
\overline{F} = \frac{F}{F_m},
\]  

(17)

\[
t_{ss} = t_e + \frac{AE}{\alpha F} - \frac{q_m r}{\alpha} = t_e + \frac{AE - q_m r \overline{F}}{\alpha F},
\]  

(18)

where \( T_h \) – the heating time constant, s; \( \overline{F} \) – the ratio of the total surface area and its irradiated part; \( t_{ss} \) – the steady-state temperature of the material (at \( dt / d\tau = 0 \)).

Then equation (15) can be written as:

\[
T_h \frac{dt}{d\tau} + t - t_{ss} = 0,
\]  

(19)

After solving the equation:

\[
t = t_{\text{init}} e^{-\tau / T_h} + t_{ss} \left( 1 - e^{-\tau / T_h} \right),
\]  

(20)

where \( t_{\text{init}} \) – material temperature at the initial time at \( \tau = 0, \text{°C} \).
Dependence (20) shows that at $\tau \to \infty$ or practically (with an error of no more than 5%) for $\tau \geq (3÷4)T_h$ a balance is established between the amount of heat absorbed by the material and the heat loss to the environment. This moment corresponds to the steady temperature of the heated material, with $t = (0.95÷0.98)t_{ss}$.

The expression obtained from equation (20) for determining the time of heating the body to any temperature $t$ in the interval from $t_{\text{init}}$ to $t_{ss}$ is as follows:

$$\tau = T_h \ln \frac{t_{ss} - t_{\text{init}}}{t_{ss} - t}.$$  \hspace{1cm} (21)

The heating rate in the process of supplying heat to the material is determined by the expression:

$$\frac{d\tau}{dt} = \frac{t_{ss} - t_h}{T_h} e^{-t/T_h}.$$  \hspace{1cm} (22)

During the heat treatment of edible vegetable raw materials, the heating rate must be limited in order to avoid damage to the heated materials.

An analysis of the interaction of the electrotechnological system "emitter - material" in the process of heating and drying food vegetable raw materials [1, 3, 19] showed that the heating time constant $T_h$, which determines the value of the time and heating rate, is among the most important parameters in heat treatment.

If one takes $M = V \rho$ ($V$ is the volume of the material, $m^3$, $\rho$ is its density, $kg/m^3$), then expression (16) can be written:

$$T_h = \frac{Mc}{\alpha F} = \frac{c \rho V}{\alpha F}.$$  \hspace{1cm} (23)

As can be seen from expression (23), the heating time constant $T_h$ is completely determined only by the cooling conditions at the interface between the material and the medium, the physical properties of the material and its geometric shape and dimensions. The heating time constants for carrots [23], Jerusalem artichoke [24], beets [25], apples [26], lingonberry, black currants and sea buckthorn [27] were determined using the above method.

In conclusion, it should be noted that theoretical calculations for the current state of the theory, technique and technology of infrared heating would not be convincing enough, nevertheless, there are some difficulties consisting in insufficiently accurate data on the parameters included in the calculation formulas. Therefore, there is a need for experimental studies of the heating process.

References

[1] Ginzburg A S 1973 Fundamentals of the theory and technique of food drying (Moscow: Food industry) p 527
[2] Ilyasov S G and Krasnikov V V 1978 Physical basis of infrared irradiation of food products (Moscow: Food industry) p 359
[3] Lebedev P D 1962 Calculation and design of drying plants (Moscow-Leningrad: Gosenergoizdat) p 320
[4] Lykov A V 1968 Theory of drying (Moscow: Energy) p 472
[5] Rogov I V and Gorbatov A V 1974 Physical methods of food processing (Moscow: Food industry) p 582
[6] Altukhov I V, Tuglenok N V and Ochirov V D 2015 Influence of pulsed infrared drying on the safety of active substances Vestnik APK Stavropol'skaya 17-10
[7] Andreeva A A and Kirdyashkin V V 2017 Application of infrared processing in the production of grain bread Bread Products 7 54-6
[8] Aleksanyan I Yu, Maksimenko Yu A, Feklunova Yu S and Pshenichnaya N E 2015 Convective-radiation spray dryer for liquid and paste materials Technologies of food and processing industry of the agro – industrial complex-healthy food products 3 57-61

[9] Antipov S T, Zhuravlev A V, Sukharev I N, Marukhin A S and Kirnosov A V 2017 Apparatus for drying dispersed materials in a swirling flow of heat carrier with IR power supply Technologies of food and processing industry of agro – industrial complex-healthy food products 5 94-9

[10] Demidov S F, Voronenko B A, Pelenko V V, Demidov A S and Elovik D K 2014 Oscillating mode of drying shredded carrots by infrared radiation The scientific journal ITMO 4 49-54

[11] Zavalyi A A, Lago L A and Rybalko A S 2017 Device for infrared drying of agricultural raw materials at low pressure Agrarian Bull. of the Urals 6 42-9

[12] Zuev N A, Rudobasha S P, Zueva G A and Zotova E Ya 2013 The combined process of drying and stimulation of seeds with a pulsed infrared radiation Bull. of the Moscow State Agroengineering University 3 7-9

[13] Ostrikov A N and Zheltouhova E Y 2012 Radiative-convective drying pear chips under pulsed energopodachi News of higher educational institutions Food technology 1 83-6

[14] Ochirov V D, Fedotov V A and Altukhov I V 2017 Experimental IR unit for drying fruits and vegetables Vestnik IrGSKHA 81-2 90-6

[15] Popov V M, Afonkina V A and Baranova A I 2017 Theoretical substantiation of the design parameters of an infrared plant for drying vegetable seeds in order to save energy Agro-industrial complex of Russia 2 503-07

[16] Semenov G V and Belyaeva M A 2009 Development of rational modes of thermal IR processing of meat products based on information technologies FES: Finance Economics 10 14a-7

[17] Filatov V V, Plaksin Yu M, Kirdyashkin V V, Azizov R R and Elkin N V 2008 Infrared technologies in the processing of grain raw materials Storage and processing of agricultural raw materials 8 76-8

[18] Khudonogova E G, Khudonogov I A and Khudonogov A M 2012 Influence of infrared-convective-vacuum drying method on the content of biologically active substances in medicinal plant raw materials Bull.of KrasSAU 5 343-6

[19] Kudryavtsev I F and Karasenko V A 1975 Electric heating and electrical technology (Moscow: Energoizdat) p 349

[20] Filonenko G K, Grishin M A, Goldenberg Ya M and Kossek V K 1971 Drying of food plant materials (Moscow: Food industry) p 439

[21] Isachenko V P, Ospova V A and Sukomel A S 1981 Heat transfer (Moscow: Energoizdat) p 416

[22] Mikhailov M A and Mikhailova 1977 I M Basics of heat transfer (Moscow: Energy) p 344

[23] Altukhov I V and Ochirov V D 2010 Thermophysical characteristics as the basis for calculating the heating time constant of sugar-containing root crops in heat treatment processes KrasSAU Bull.4 134-9

[24] Altukhov I V, Ochirov V D and Fedotov V A 2013 Determination of the heating rate of Jerusalem artichoke during drying by infrared radiation Mechanization and electrification of agriculture 1 14-5

[25] Altukhov I V and Ochirov V D 2014 Speed of beet heating with IR power supply Bull. of the Altai State Agrarian University 4 138-42

[26] Ochirov V D and Fedotov V A 2018 Determination of the time and speed of heating of crushed Apple fruits during thermo radiation drying Bull. of KrasSAU 1 89-95

[27] Blokhin M A and Ochirov V D 2019 Determining the constant time of heating berries Mat. of the Int. Scien. and Prac. Conf. of Young Scientists Research and development for implementation in the agro-industrial complex (Irkutsk: ISAU) pp 117-23