Theoretical justification of film electric heater parameters as a source of infrared radiation in the technology of drying green crops

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Abstract. Storage of green crops for a long time, possibly at a moisture content of no higher than 15%. Therefore, drying plays a decisive role in this technological process. The rationality of the choice of drying technology is judged by two criteria: high energy efficiency and the degree of mitigation of the thermal effect on the product structure. The use of IR radiation in the process of drying green crops is one of the promising directions. A film electric heater is one of the sources of infrared radiation, which is able to provide high-quality low-temperature drying. Investigating the drying of green crops using electric film heaters, we substantiated the necessary parameters of the radiation source based on the optical characteristics of the drying object. The study was carried out with the financial support of the Russian Foundation for Basic Research and the Chelyabinsk Region within the framework of the scientific project No. 20-416-740001. The article describes the design of an electric film heater. Based on the optical characteristics of the absorption spectrum of dill and parsley, as well as the laws of thermal radiation, the necessary temperature regime for the operation of the heater as a source of infrared radiation is substantiated. Based on this, the choice of the power density and design parameters of the film electric heater is made. An analysis of the absorption spectrum led to the conclusion that all the main maxima are in the wavelength range from 4 μm to 11 μm. Calculations have shown that the maximum integral radiation flux in this range is provided at an average temperature of the emitter surface of about 500°C. Moreover, to cover the two largest maxima, the temperature of various points of the heater should be in the range from 460°C to 900°C. This is achievable at a power density of an electric film heater of about 260 W/m² and a distance between current-carrying elements of 4.5 cm. The analysis of the results obtained, and the technical features of the electric film heater indicates the possibility of its application to create effective modes of drying green crops. The upper end of the temperature range during the drying process is the limit for polyethylene terephthalate. Therefore, the goal of further research is to find solutions to increase the reliability of the film electric heater.

1. Introduction
Today, the issues of energy saving in various sectors of the national economy remain relevant and problematic for solution. The share of energy costs in the cost of production often becomes the main one. When solving the problems of energy conservation, it is important to determine not only the strategy, but also the methods of rational use of energy resources, taking into account the peculiarities of the industries and agriculture. For example, the use of resource-saving technologies in energy technology facilities, in the design and reconstruction of technological lines, can serve as a solution to this kind of problems [1]. The above is also true for drying technology. This process is an
indispensable link in the technology for the production of various agricultural products, therefore, the requirements for it are constantly increasing, and the production of high-quality products is not possible without improving the equipment and the technological process as a whole. Storage of green crops for a long time, possibly at a moisture content of no higher than 15%. Therefore, drying plays a decisive role in this technological process. The rationality of the choice of drying technology is judged by two criteria: high energy efficiency and the degree of mitigation of the thermal effect on the product structure. The high productivity of this kind of technology is achieved using conveyor-cascade drying plants in a continuous technological cycle. The use of IR radiation in the process of drying green crops is one of the promising directions. In this case, it makes no sense to increase the temperature of the product, and evaporation will proceed intensively at a temperature of 40-60 °C [2-6]. A film electric heater is one of the sources of infrared radiation, which is capable of providing high-quality low-temperature drying [3]. Investigating the drying of green crops using electric film heaters, we substantiated the necessary parameters of the radiation source based on the optical characteristics of the drying object.

2. Materials and methods
Drying by infrared radiation has a wave electromagnetic nature, and, therefore, is subject to the basic laws of optics [7-9]. The structural evolution and state of raw materials at each stage of the drying kinetics are accompanied by dissipation and energy accumulation. This process requires a special approach and labor-intensive research, since biological raw materials are often thermo labile and, ideally, monitoring of its living components, the preservation of which is regulated by the development of technologies for their processing, in real time. In addition, it is important to note that a change in the structural and optical properties of raw materials significantly affects the processes of concentration and dissipation of energy, which makes it possible to associate it with a change in the spectral properties of the source and product and to propose methods for monitoring the main modes of drying in the real course of the process.

The optical sensitivity of raw materials plays a decisive role in the development of energy-saving technologies for its processing. Theoretical methods for its assessment are currently little used by technologists. We propose to evaluate the spectral susceptibility of raw materials in the infrared range using the theory of synthesis and analysis of amplitude-frequency logarithmic characteristics (LAVC), which is based on an assessment of the attenuation of the IR radiation flux in amplitude.

In connection with the constant improvement of methods and means of influencing biological raw materials, aimed at studying the processes of destruction and preservation of biological value in them, this method will allow you to look deep into the process and consider it not only from the point of view of the known optical properties of radiation sources, but also considering poorly studied properties of raw materials processing objects. The LAVC, obtained by plotting with the minimum wavelength step, will allow you to determine those wavelength ranges and peaks at which a given product has the highest absorbing and transmitting capacity.

The basis for constructing this characteristic is the dependence of the main parameters of optical susceptibility. Y-axis is the amplitude of the infrared radiation flux, expressed in decibels. The abscissa is the decimal logarithm of the wavelengths (figures 1 and 2). The radiation amplitude, being the power value, is expressed as follows [6]:

\[ L_d = 10 \log \frac{A}{A_0} \]  

(1)

Where \( L_d \) is the amplitude in decibels; \( A \) is the radiation flux received by the biological raw material; \( A_0 \) is the value of the radiation flux falling on the surface of biological raw materials.
Having the data of the wave characteristics of the drying object, it is possible to detect the radiation wavelength range at which the process is guaranteed to take place with the maximum energy concentration in the volume of the raw material, since the wavelength of the IR radiation generator will be in the region corresponding to the maximum absorption capacity of the raw material. Note also that the absorption will decrease with increasing intensity of the electromagnetic wave, while the width of the LAVC peak increases, which is important when creating low-inertial sources of infrared radiation, as well as for developing adaptive systems for automatic control and regulation of processes using them. A number of experimental studies have revealed the need to take into account the influence of the processes of accumulation and dissipation of infrared radiation energy in the development of theoretical laws and transfer functions describing the process of dehydration of biological raw materials and the destruction of target components in it, which will form the basis for the design of drying equipment and the development of technological drying procedures.

The wave characteristics of parsley and dill (figure 1 and figure 2) allow us to draw the main practical conclusions:

- The maximum extinction coefficient, and, consequently, the degree of absorption of infrared radiation is located at three averaged points of the wave characteristic at around -23.9 decibels and log λ equal to 1.1; -23.82 decibels and log λ equal to 0.9 and 23.78 and log λ equal to 0.8;
- The wavelengths of infrared radiation corresponding to the main peaks characterizing the maximum absorption of infrared radiation by greens are 11 μm, 9 μm, 8 μm and 4.5 μm;
- The wavelength of 11 microns is the range of another type of drying - sublimation, since it corresponds to the level of negative temperatures. Dehydration by negative temperatures is not inferior to infrared radiation in terms of preserving nutritional value, but is not suitable for green crops processed for spices, dyes and long-term storage without special equipment.

\[ \log \lambda = \text{some values} \]

\[ L_d, \text{ db} \]

**Figure 1.** Amplitude-wave characteristic of dill greens in logarithmic expression.

**Figure 2.** Amplitude-wave characteristic of parsley in logarithmic expression.
• 9 microns and 8 microns are peaks corresponding to the required temperature range for obtaining spices from high quality dill and parsley.

Summarizing the above, we can conclude that today the radiation source capable of having a radiation density sufficient for the technologies of dehydration of plant raw materials in the far and middle infrared ranges are low-temperature flexible film electric heaters (NEP) [3]. On the basis of NEP, one can develop energy-saving technologies and design dryers with optimized parameters for selective drying of raw materials of various origins.

Based on the foregoing, it becomes necessary to create a source of IR radiation emitting the maximum flux in the wavelength range from 4 to 11 microns.

Radiation of a black body is described by the laws of Planck and Stefan-Boltzmann [5]. Applying these laws, we have formulated the dependence of the ratio of the radiation flux density, located in the wavelength range from 4 μm to 11 μm, to the total radiation flux density. This ratio was called "efficiency" (COP) (2).

Figure 3 shows the dependence of the efficiency of the radiation process depending on the surface temperature of the radiation generator, obtained using the mathematical package Mathcad.

\[
\eta(T) = \frac{100}{\sigma \cdot T^4} \cdot \int_{\lambda_2}^{\lambda_1} \frac{2 \cdot h \cdot c^2}{\lambda^5} \cdot \frac{1}{\exp \left( \frac{h \cdot c}{\lambda \cdot k \cdot T} \right) - 1} \cdot d
\]

Where \( \lambda_1 = 11 \) μm, \( \lambda_2 = 4 \) μm, \( \lambda \) - is the wavelength, \( T \) - is the absolute temperature of the emitting surface, \( c = 3 \cdot 10^8 \) m / s, \( k = 1.38 \cdot 10^{-23} \), \( h = 6.62 \cdot 10^{-34} \) J · s, \( \sigma = 5.67 \cdot 10^{-8} \) W / (m\(^2\) · K\(^4\)) - Stefan-Boltzmann constant.

According to this ratio, the maximum efficiency falls on the operating temperature range of 320-323 K, which corresponds to the heating temperature of the NEP surface 47-50°C.

For a more detailed understanding of the design features of the heater, it is necessary, using Wien’s displacement law (3), to calculate which temperatures correspond to the absorption spectrum maxima at wavelengths of 8 and 9 μm:

\[
\lambda_{max} = \frac{2896}{T} \ \mu m
\]
Where T is the surface temperature of the infrared radiation generator.

The calculated data are shown in the (table 1):

| T=30°C/303K | T=50°C/323K | T=70°C/343K | T=90°C/363K |
|-------------|-------------|-------------|-------------|
| λ; μm       | M_{IR}; W/ m²μm | λ; μm       | M_{IR}; W/ m²μm | λ; μm       | M_{IR}; W/ m²μm | λ; μm       | M_{IR}; W/ m²μm |
| 5           | 5           | 17.086      | 5           | 18.635      | 5           | 45.339      |
| 7           | 7           | 39.94       | 7           | 57.798      | 7           | 80.328      |
| 8           | 8           | 45.262      | 8           | 62.593      | 7.97        | 83.573      |
| 9.55        | 8.96        | 46.617      | 8.44        | 62.951      | 9           | 80.574      |
| 10          | 10          | 45.223      | 10          | 58.752      | 10          | 74.225      |
| 12          | 12          | 38.52       | 12          | 48.061      | 12          | 58.595      |
| 14          | 14          | 30.735      | 14          | 37.293      | 14          | 44.336      |

Based on the analysis of the graphical dependence and tabular data, it is possible to draw conclusions about the requirements for the design of an infrared radiation source made on the basis of an electric film heater.

A radiant film electric heater is widely used in the processes of drying agricultural products and thermolabile biological raw materials [10-14], technologies for heating greenhouse plants [8]; heating industrial and residential premises [10]. It is a flexible resistive element enclosed between layers of polyethylene terephthalate film [11] (figure 4).

![Figure 4. General view of a low-temperature film IR-radiation generator: 1 - multilayer polyethylene terephthalate fabric; 2 - resistive material with emissivity factor not less than 0.8; 3 - conductive wires; а is the distance between the branches of the resistive material; b is the width of the tape of the resistive element.](image)

The selection of the required temperature range of the surface of the heater, as well as its average temperature, is carried out using a correctly calculated power density and the distance between live elements.

The method for calculating these parameters is given in [12]. According to this technique, the temperature on the surface of the electric film heater is distributed according to the law:

\[ T_n(x) = A_1e^{\sqrt{\beta_2}x} + A_2e^{-\sqrt{\beta_2}x} + B_0 \]  

(4)
Where $A_1$ and $A_2$ are some constants that depend on the power density of the electric heater, the wire diameter of the resistive element, the thermal conductivity and heat transfer coefficients of the material from which the heater is made, and the ambient temperature.

$\beta_1$ and $\beta_2$ are coefficients that depend on the coefficients of thermal conductivity and heat transfer, as well as on the thickness of the heater.

$B_0$ is a constant coefficient which is the root of the polynomial:

$$\beta_1 \cdot B_0^4 + \beta_2 \cdot B_0 - \beta_2 \cdot T_0 = 0 \quad (5)$$

Where $T_0$ is the ambient temperature.

3. Results and discussion

Analysis of the graphical dependence shown in figure 3, as well as the data in the table, allow us to conclude the need to develop and create an infrared radiation source based on a film heater with an average surface temperature of 47 °C to 50 °C. At the same time, areas with a temperature of 46 °C and 90 °C should be present on the surface. This is possible with a very small thickness of resistive current-carrying elements and a significant distance between them. A wire-based film heater [4] ideally suits these features. In this case, a temperature of 90 °C is observed on the surface of the wire-wound resistive element, and the lowest temperature is 46 °C at an equal distance between adjacent conductive elements. Calculation according to formulas (4) and (5) indicates that such temperature conditions are satisfied by a film heater with a power density of 260 W/m² with a distance between adjacent conductive parts of 4.5 cm.

4. Conclusion

Of all the known designs of a film heater [3; 11], a wire-based film heater [11] is able to most fully satisfy the requirements for the temperature distribution and its average value. However, the upper end of the optimum temperature range is the limit for polyethylene terephthalate. Therefore, the goal of further research is to search for solutions that allow increasing the reliability and durability of the film electric heater, as well as, within the framework of this study, experimental studies devoted to the processes of accumulation and dissipation of infrared radiation energy in plant raw materials with a different set and complex hierarchy of target components and the effect of these processes on preservation these components.

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