The study of heat and mass transfer during dehydration of gelatin from waste products of hydrobionts

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Abstract. Fish processing waste is rich in collagen and promising as a source of raw materials for the production of gelatin. Gelatin today remains one of the most popular collagens in various industries, while the main share in the Russian gelatin market is occupied by imported products. Given there are structural, mechanical and foam structural characteristics of gelatin extract, including from fish processing waste, one of the ways to increase the effectiveness of dried gelatin technology will be its radiation dehydration in foamy form. The formation of a stable foam structure leads to a significant intensification of the moisture removal operation due to the growth of the phase contact surface during transfer and exchange of thermal energy and substance, a decrease in adhesion between the drying object and the working surface of the unit and, as a result, to simplification of the separation of the dehydrated material from it and the elimination of the energy-intensive crushing operation finished products. The purpose of this research was to develop rational drying regimes of gelatin extract based on the study of kinetic laws of choosing ways to intensify the process of moisture removal. Foamed gelatin extract was dried in the form of round rods with volumetric convective and convective-radiation energy supply. Based on the results of experimental and analytical studies of convective and convective-radiation foam drying of gelatin, practical recommendations are given on the hardware design of the drying process, including the design of a complex convective-radiation drying installation, which is applicable both to the production of dry gelatin and similar complex properties thermolabile elastic-viscous, gel-like and paste-like materials.

1. Introduction

Recycling of waste products from animal products against the background of increasing production volumes remains one of the important tasks of the food industry, the actual direction of which is the use of waste as secondary material resources. In particular, fish processing waste is rich in collagen and promising as a source of raw materials for the production of gelatin.

The most energy-consuming final step in gelatin technology, which determines its quality parameters and specific productivity when it is received, is moisture removal from the gelatin extract, which is traditionally air-dried in a gelled state in the form of strands, plates, layer, granules. Moreover, the drying time can reach several days [1]. As a result of a study of the kinetics and intensity of convective-radiation drying of the gelatin extract from fish processing waste in the foamed and gelled state, it was found that preliminary foaming of the gelatin extract and the introduction of
infrared energy supply to the convective drying process can significantly increase the speed of gelatin drying without affecting the quality of the native product [2].

Given there are structural-mechanical and foam-structural characteristics of the gelatin extract, including from fish processing waste [1, 2, 3, 4, 5], one of the ways to increase the efficiency of the dried gelatin technology will be its radiation-based dehydration in foam form [6]. The formation of a stable foam structure leads to a significant intensification of the moisture removal operation, due to the growth of the phase contact surface during transfer and exchange of thermal energy and substance, a decrease in adhesion between the drying object and the working surface of the unit and, as a result, to simplification of the separation of the dehydrated material from it and the elimination of the energy-intensive crushing operation finished products [6, 7]. Compared to traditional methods, volumetric radiation energy supply also has a number of advantages [8, 9], which contribute to energy and resource saving, simplification of the hardware design of the process.

The form of the material supplied for drying is established by the technology of its production, is determined by the drying method and has a significant effect on the process of moisture removal. Thus, dispersion (granulation, spraying, grinding, foaming, etc.) of the raw material significantly accelerates the drying process by increasing the heat and mass transfer surface. Moreover, the use of infrared energy supply for drying a dispersion medium in an optically thin layer helps to achieve a high process intensity [2, 8]. However, in the case of infrared drying of thermolabile raw materials in an optically thin layer (as a rule, not exceeding a few millimeters), one of the main scientific and technical tasks in designing the design of infrared drying equipment is to exclude uncontrolled overheating of the material and the maximum possible loading of the apparatus working volume with the product.

2. Materials and methods

Gelatin obtained from fish scales of the Volga-Caspian basin and commercial aquaculture facilities using an innovative technology developed by scientists of FSBEI HE "ASTU" was used as an object of study. To conduct studies of thermoradiation characteristics and optical characteristics, gelatin extract samples were prepared according to the procedure [1]. The optical characteristics were determined by calculation on the basis of information on the spectral reflective \(R_\lambda\), transmittance \(T_\lambda\) and absorbance \(A_\lambda\) of the product. The dependences of \(R_\lambda\) and \(T_\lambda\) on the infrared wavelength \(\lambda\), \(\mu\text{m}\) were obtained using a PHOTON RT multifunctional two-beam scanning spectrophotometer and published data [5, 8] for various moisture values \(w\), \(\text{kg} / \text{kg}\) and foam layer thickness \(h_\text{f}\), \(\text{mm}\), in the infrared range spectral region \(1 \leq \lambda \leq 2 \mu\text{m}\).

The results of the analysis of the spectral thermoradiation characteristics make it possible to preselect the IR emitters, however, in this case it is necessary to take into account that during the drying process the IR energy supply occurs in the form of an integral heat flux. In this case, the integrated thermoradiation characteristics are determined by the type and intensity of the IR emitters, as well as the irradiation conditions, which is caused by a wide range of spectral and emission characteristics of the IR emitters.

Figures 1 and 2 show examples of directional hemispherical thermoradiation characteristics \(R_\lambda\) and \(T_\lambda\), obtained using a PHOTON RT spectrophotometer for a gelatin foam layer of various thicknesses \(h\), \(\text{m}\) and humidity \(w\), \(\text{kg} / \text{kg}\).

As a result of the processing of empirical data and calculations for the process of foaming the gelatin in the gelled state with a bilateral IR energy supply with an initial moisture content of \(w = 0.85 \text{ kg} / \text{kg}\) and a foam layer thickness \(h = 0.004 \text{ m}\) corresponding to the maximum specific productivity of the process [2], experimental-analytical dependencies of the following optical characteristics:

- reflective integrated ability of the optically semi-infinite layer \(R_\infty\) on the moisture content of the product \(w\), \(\text{kg} / \text{kg}\):

\[
R_\infty(w) = 0.2628 \cdot w + 0.0511
\]
the dependence of $L$ on the moisture content of the material $w$, kg / kg and the coordinates of the layer thickness $x = 0 \ldots 0.004$ m:

$$L(w,x) = (-7.1707 \cdot 10^4 \cdot w - 8.5285 \cdot 10^4) \cdot x + 546.7213 \cdot w + 1.1411 \cdot 10^3.$$  (2)

Figure 1. Reflective $R$ and transmittance $T$ of the ability of a layer of a foamed gelatin solution at a product moisture content of $w = 0.85$ kg / kg and a foam layer thickness: a) $h = 4$ mm and b) $h = 2$ mm

Using the obtained equations (1) and (2) using the formula proposed in [5], we obtained the dependence $W = f(x,w)$, W / m² for an optically thin layer of gelatin foam with its thickness $x = 0 \ldots 0.004$ m and $w = 0.14 \ldots 0.85$ kg / kg with bilateral IR irradiation of the foam layer:

$$W(x,w) = L(x,w) \cdot E_{in1} \cdot \frac{1 - R_x(w)}{1 - \psi^2(w,x)} \left[ \exp \left( -L(w,x) \cdot x \right) - \frac{\psi^2(w,x) \cdot \exp \left( L(w,x) \cdot x \right)}{R_x(w)} \right] +$$

$$+ L(h-x,w) \cdot E_{in2} \cdot \frac{1 - R_x(w)}{1 - \psi^2(w,h-x)} \left[ \exp \left( -L(w,h-x) \cdot (h-x) \right) - \frac{\psi^2(w,h-x) \cdot \exp \left( L(w,h-x) \cdot (h-x) \right)}{R_x(w)} \right]$$

where $E_{in1}=E_{in2}$ is the density of the incident heat flux from one side of the foam layer, W / m², determined as a result of experimental studies [4, 5, 6, 8]; $\psi = R_x(w) \cdot \exp(-L(w,x) \cdot x)$.

Figure 2 shows the value field $W$ obtained using the Mathcad software for the ranges $x = 0 \ldots 0.004$ m and $w = 0.14 \ldots 0.85$ kg / kg.
Figure 2. The distribution of $W$ over the depth of the foam layer of the gelatin extract with moisture content $w = 0.14 ... 0.85$ kg/kg in the range of the coordinate of the layer thickness $x = 0 ... 0.004$ m with two-sided IR energysupply.

Thus, based on spectral analysis, as a result of an experimental-analytical study of the thermal radiation characteristics and optical characteristics of the gelatin foam layer, taking into account $W$, as well as previously obtained experimental and published data [4, 5, 6, 8], we can recommend:

- the supply of radiant energy lamps KGT (KI, KG) -220-1000;
- the optimal wavelength range of infrared emitters is $\lambda = 1.01 ... 1.11$ µm, which determines the highest radiant heat flux and the difference in electric potentials on the lamps [2], which correspond to the highest transmittance of the material. Due to the small range of variation of the wavelength in a rational mode, it is impractical to include it as an independent factor in further research;
- optically thin layer for effective dehydration $h \leq 0.004$ m.

3. Discussion of the results

The purpose of this research was to develop rational drying regimes of gelatin extract based on the study of kinetic laws of choosing ways to intensify the process of moisture removal. Taking into account the literature data [1, 3, 4, 5, 8, 9, 10], as well as preliminary experimental data for studying the convective-radiation drying of the foamed gelatin extract in the gelled state, the following process options were selected from fish processing waste:

- in the form of circular rods with a convective volumetric energy supply;
- in the form of circular rods with a volumetric convective-radiation energy supply.

The foam of the gelatin extract at the beginning of the drying process remains stable exclusively in the gelled state (in the state of jelly). In this case, the use of only the radiation supply of radiant energy without combination with convection in the process of foam drying can lead to a spontaneous increase in temperature, which causes the destruction of the foam structure and glass transition. The use of an air cooling coolant, the temperature of which does not exceed the gelatinization temperature ($T = 292$-$295$ K), as well as maintaining the heat flux density of infrared radiation incident on one side of the rod in the range $E = 0.95$-$2.45$ kW/m², make it possible to stabilize the temperature of the dried foam layer at a level not exceeding its melting point. At $E<0.95$ kW/m², it is not rational due to a sharp drop in the removal rate of the dried material, and at $E> 2.45$ it leads to local melting and destruction of the foam layer. To ensure maximum efficiency of energy use of emitters (infrared generators), the radiation wavelength should correspond to the maximum emissivity of radiation emitters [8].
The range of variation of the air flow rate \( v = 4-5 \, \text{m/s} \) is limited by the technical capabilities of the process. Exceeding \( v = 5 \, \text{m/s} \) is impractical due to mechanical failure (rupture of the foam rod) and product entrainment. A decrease in \( v < 4 \, \text{m/s} \) contributes to an increase in the temperature of the foam layer in the process of convective-radiation drying of more than 333 K, which leads to a deterioration in its quality characteristics, local melting and destruction.

As a result, the evolution of the current sample moisture \( w, \, \text{kg/kg} \) during drying time \( \tau \) was obtained. Examples of drying curves of gelatin extract foam with the studied energy supply methods are shown in Fig. 3. The obtained curves were subsequently used to construct drying speed curves in order to analyze the heat and mass transfer mechanism and determine the specific productivity of the process.

\[ G = M_{cn} / (F \cdot \tau), \]

where \( M_{cn} \) is the mass of the dehydrated sample at humidity \( w_k < 0.1 \, \text{kg/kg} \), which is due to the results of the thermodynamics of the drying process; \( F \) is the surface area under the sample, \( \text{m}^2 \); \( \tau \) is the duration of dehumidification, including the values of the objective function \( G, \, \text{kg/(m}^2\cdot\text{h)} \) obtained at various initial foam rod diameters \( d_n, \, \text{mm} \) and the initial humidity of the expandable extract \( w_n (1-C), \, \text{kg/kg} \). The relative error in determining the objective function did not exceed 12%. As a result of computer processing of the experimental data, adequate approximating dependences of the removal of dry material, related to the area of the used surface and the duration of the operation, on varied factors were obtained, while the approximation error \( R^2 \) of the obtained dependence \( G = f(w_n, d_n) \) was not less than 0.997:

\[ G (w_n, d_n) = \left( a_1 \cdot d_n^2 + b_1 \cdot d_n + c_1 \right) \cdot w_n^2 + \left( a_2 \cdot d_n^2 + b_2 \cdot d_n + c_2 \right) \cdot w_n + \left( a_3 \cdot d_n^2 + b_3 \cdot d_n + c_3 \right), \]

where \( a_1, b_1, c_1, a_2, b_2, c_2, a_3, b_3, c_3 \) are parametric coefficients, the values of which are summarized in table 1.

| Table 1. The values of the empirical coefficients of the objective function |
Figure 4 shows the evolution of the $G$ values calculated by expression (2) for various energy supply methods. The dependences of the objective functions of convective (Figure 4a) and convective-radiation (Figure 4b) drying of gelatin extract foam from influencing factors $d_n$ and $w_n$ are generally similar. For the considered options for the implementation of the process, an increase in the objective function is observed both with an increase in the diameter of the rod, and with an increase in the concentration of dry substances in the product and is limited by the upper limit values of these factors.

![Figure 4](image.png)

**Figure 4.** Evolution of $G$ values depending on variable factors, for different values of the initial diameter of the rod $d_n$ and the initial humidity $w_n$ of the foamed gelatin extract with convective (a) and convective-radiation (b) energy supply methods.

The results of a study of convective and infrared foam drying of a gelatin extract in the form of circular cross-sections (in an optically thin layer) [2, 8, 11] made it possible to develop a drying method and recommend the design of an integrated convective-radiation drying apparatus (Fig. 5) for gelatin and similar ones the complex of properties of thermolabile elastic-viscous, gel-like and pasty materials (for example, collagens, meat and vegetable mixtures, concentrated extracts, vegetable and fruit concentrates and other similar materials). The main requirements for dehydrated material are suitability for molding by extrusion, the ability to maintain a given geometric shape (granules).

|       | Convection foam dryer | Convective radiation foam dryer at $E = 0.95$ kW/m$^2$ | Convective radiation foam dryer at $E = 2.45$ kW/m$^2$ |
|-------|-----------------------|------------------------------------------------------|------------------------------------------------------|
| $a_1$ | 0.7                   | 10.8                                                 | 31.3                                                 |
| $b_1$ | -7.7                  | -85.6                                                | -250.5                                               |
| $c_1$ | 22                    | 164                                                  | 460.2                                                |
| $a_2$ | -0.945                | -16.39                                               | -48.045                                              |
| $b_2$ | 10.995                | 129.85                                               | 384.465                                              |
| $c_2$ | -33.82                | -251                                                 | -709.81                                              |
| $a_3$ | 0.267                 | 6.086                                                | 18.1765                                               |
| $b_3$ | -3.547                | -48.176                                               | -145.4185                                             |
| $c_3$ | 12.615                | 94.422                                                | 270.413                                               |

The diagrams show the evolution of $G$ values depending on variable factors, for different values of the initial diameter of the rod $d_n$ and the initial humidity $w_n$ of the foamed gelatin extract with convective (a) and convective-radiation (b) energy supply methods.
The proposed design of a complex convection-radiation drying plant allows you to implement the main stages of the technological process of obtaining a dry product (Fig. 5): molding and applying native material to the working surface of the installation, drying, removal and removal of the dry product from the drying chamber. The basis of the installation is the frame 1. As a loading device for molding and applying the product to the working surface, it is proposed to use a screw extruder 2 with an end grill 3 with holes in which pipelines 4 with dies 5 are rigidly fixed at the ends of the pipelines 4. The drying chamber 6 of the installation is horizontal, due to the location of the granular material to be dried. In addition, the installation includes: a brush of cylindrical shape 7, designed to remove material; infrared emitters 8; partitions 9 dividing the drying chamber 6 into four sections 10; the carrier of the dehydrated material (working surface of the installation), made in the form of a horizontal belt conveyor 11 with tape 12; granulator 13, the output conveyor 14.

Traditionally, the gelatin extract is dried in a gelled (gel) state in the form of a layer, plates, strands, granules on the working surface of the dryer with convective energy supply, including using combined drying modes, as well as by spraying. It should be noted that the introduction of radiation energy supply into the process of convective foam drying of gelatin extract under rational conditions almost three times increases the specific productivity of the process [2].

Figure 5. Integrated convection-radiation drying plant: a – sectional front view; b is a top view in section; 1 – frame; 2 – screw extruder; 3 – end grille;
4 – pipelines; 5 – die; 6 – drying chamber; 7 – a brush of cylindrical shape;
8 – infrared emitters; 9 – partitions; 10 – section of the drying chamber;
11 – horizontal belt conveyor; 12 – tape; 13 – granulator; 14 – output conveyor
4. Conclusion
As a result of the study of the kinetics of convective and convective-radiation drying, the functional
dependences of the drying speed of the extruded foam gelatin extract on the concentration of dry
substances in the product $C$, kg / kg for the considered modes of the process are obtained. Using
the velocity curves, the analysis of heat and mass transfer during convective radiation foam drying of the
gelled extract was established, as a result of which it was established that the nature of the change in
the drying rate of the product is typical for most biopolymers, the velocity curves are characterized by
two distinct moisture removal zones, delimited by the extrema of the functions.

Based on the results of experimental and analytical studies of convective and convective-radiation
foam drying of gelatin, practical recommendations are given on the hardware design of the drying
process, including the design of a complex convective-radiation drying installation, which is
applicable both to the production of dry gelatin and similar complex properties thermolabile elastic-
viscous, gel-like and paste-like materials. The proposed technical solutions can be used to implement
promising pulsed and combined methods of energy supply (pulsed infrared and combined, convective-
radiation) in the drying process, they can intensify the process and improve the quality of the obtained
dry products in comparison with traditional methods.

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