High–speed infrared photography in the study of thermophysical processes in the manufacture of jelly products

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Abstract. The article considers the possibilities of using infrared (IR) photography to control thermophysical processes in the production of jelly products in order to preserve their antioxidant properties. Jelly products were made on the basis of extracts of squeezed wild berries with the addition of gelatin and sugar. The prepared mixture was heated under various conditions (convective and microwave heating), controlling thermophysical processes using pyrometric sensors and a contact thermometer. Pyrometric sensors of two types were used: field measuring devices (IR camera) and point measurements (IR pyrometer), which minimize the measurement time. The use of the microwave field evenly heated the prepared mixture and stopped heating after the cessation of microwave energy. Convective heating due to thermal inertia exceeded the temperature regime for the manufacture of jelly products, which destroys antioxidants. IR photography, used for test determination of the temperature of the mixture, allows you to instantly determine not only the temperature range, but also record the distribution of thermal energy in the test medium.

1. Introduction

Digital methods for controlling technological processes and food quality are rapidly developing in modern society [1–3]. One of the control methods is the use of photography in the visible, infrared and ultraviolet regions of the spectrum. Their advantage over other control methods is non–contact, speed, automatic detection of all image attributes. Digital processing allows you to quickly and objectively evaluate two and three–dimensional (2–D and 3–D) image, both with visual characteristics of the object, and its structural and texture properties [4, 5]. Computer vision systems, as a control method, are used in the production of beverages, assessing the quality of grains, fruits and vegetables, nuts, bread and meat [6, 7]. The combination of photography with other precise control methods allows you to explore complex phenomena that cannot be described using traditional control methods [8, 9]. At the same time, the study of the technological process of production can be carried out by multiple photographs and sequential processing of the obtained images.

IR photography, as one of the methods of computer vision systems, allows you to study the thermophysical characteristics of technological processes, based on the visualization (conditional coloring) of the image of the object in accordance with the temperature scale of the measuring system. Multiple infrared photography allows you to visualize the stability or a temporary change in the...
temperature of the object, which determines the stability or dynamic characteristics of the process [10, 11].

The production of jelly products is based on the thermal effect exerted on the system from plant extracts, a structure stabilizer (gelatin, agar) and sugar (if necessary). Plant extracts in this system are sources of biologically active substances, the preservation of which in a jelly product will allow them to be positioned as food products useful for health [12–14]. In this regard, an important technological factor is the selection of the temperature regime ensuring the preservation of antioxidants and their activity in vitro and in vivo systems [15–17]. Long-term high-temperature heating destroys antioxidants [18, 19]. However, volumetric heating of plant objects with microwave energy can ensure their preservation even when exposed for 5 minutes [20, 21].

The aim of the work was to study the possibility of using IR photography to control thermophysical processes in the production of jelly products with maximum preservation of their antioxidant properties.

2. Methods
In this work, we studied the production process of jelly products based on extracts from squeezed wild berries of cranberries and lingonberries in two ways—convective heating and heating in a microwave oven and their influence on the preservation of antioxidant properties in finished products. To study the possibility of using electrophysical methods in assessing the quality of vegetable oil, model experiments were carried out, and then quality control at different stages of production.

2.1. Manufacturing of jelly products
Water extracts from squeezed wild berries of cranberries and lingonberries, 3% gelatin, 2.5% sugar for the production of jelly products were used. After swelling the gelatin for 40 minutes, the solution was stirred. Thermal heating to a temperature of 72°C was carried out in two ways: convective on a gas burner; 820 W microwave heating for 1 minute. The hot solution was poured into molds, cooled and kept until the formation of the structure of jelly products.

2.2. Determination of antioxidant activity of jelly products
Antioxidant activity was determined in the finished jelly products by DPPH (2, 2-diphenyl-1 picryl hydrazyl) and FRAP (ferric reducing antioxidant power) methods.

2.2.1. DPPH radical–scavenging activity
The determination was carried out using the 2, 2-diphenyl-1 picryl hydrazyl stable free radical (DPPH), which was reduced in the reaction with the antioxidants of the product for 30 minutes in the dark at room temperature. Light absorption of the original DPPH solution—0.5 srvc. units Jelly products were crushed and extracted with 50% ethanol. 0.2 ml of the extract was added to 2 ml of DPPH solution and kept in the dark for 5 minutes. The optical density was measured at a wavelength of 517 nm on a SHIMADZU 1240 spectrophotometer (SHIMADZU, Japan) of an experimental sample against the control (0.2 ml of the extract without the addition of DPPH) [21]. Antioxidant activity was determined according to the calibration curve and expressed in terms of ascorbic acid (AA).

2.2.2. Ferric–Reducing antioxidant power (FRAP) assay
The method is based on the ability of ferric chloride (III) to oxidize antioxidants, while reducing to iron (II) chloride [22]. By changing the color intensity after adding o–phenanthroline, antioxidant activity is determined.

The starting extract from jelly products with FRAP reagent (2, 4, 6–tripyridyl–5–triazine) was kept at 37°C for 10 minutes in a dark place. To the extract was added 0.2 ml of a 25 mM solution of o–phenanthroline, 2.4 ml of 96% ethanol and dropwise 0.2 ml of a 12.3 mM FeCl₃ solution. After stirring, kept in the dark for 10 minutes. The reaction was stopped with 1 ml of a 0.4 M HCl solution.
The control is a sample to which 0.2 ml of a 25 mM solution of o-phenanthroline, 2.6 ml of 96% ethanol, 0.2 ml of a 12.3 mM FeCl₃ solution, and 1 ml of a 0.4 M HCl solution were added. The light absorption of the extract against a solution of 96% ethanol were measured at a wavelength of 505 nm using a SHIMADZU 1240 spectrophotometer (SHIMADZU, Japan). The light absorption value of the extract was subtracted from the light absorption value of the control sample. Antioxidant activity was determined according to the calibration curve and expressed in terms of ascorbic acid (AA).

2.3 The study of thermophysical processes

For research, a setup was created that consisted of a JENS model No. JM 002 Sr. magnetron No J82–0221 with a capacity of 820 W and a resonator (microwave), in which a prepared mixture of extract, gelatin and sugar was placed, and a pyrometric measuring complex, consisting of two types of receivers: 1—personnel recording of the temperature field of the heated object; 2—point measuring instrument of the temperature of the heated object, (the point is in the temperature field of the image formed during the frame recording by the receiver). The scheme of the measuring complex is shown in Figure 1.

![Figure 1. Comprehensive analysis system of electrophysical indicators of vegetable oils.](image)

The industrial infrared pyrometer (temperature meter from the radiation of a heated body), recording the temperature in the range + (32–280)°С with a resolution of ± 0.1°C, was used as a test temperature meter. The measurement time was 500 ms. The range of measurements was 8–14 µm. The angle of the field of view of the sensor horizontally and vertically was less than 1°C.
Test measurements of the temperature of the mixture after heating were carried out after opening the door of the magnetron resonator (microwave) with an IR camera in the visible, IR and combined (visible+IR) ranges of the IR pyrometer through the vessel walls and were stored in the memory of computers with Android 8.1 OS for subsequent processing and analysis. Then, the studied object was removed from the microwave oven and repeated test measurements of temperature were carried out through the open surface of the heated medium using a pyrometer and control measurements with a contact (mercury) thermometer.

The uniformity of heating was estimated from the image, the temperature range selected by the system was checked with an industrial IR pyrometer, and its uniformity was evaluated.

3. Results and Discussion

The method for producing jelly products using convective heating or microwave heating did not affect the quality of the finished products. The structure of the jelly product was formed during its further cooling at the same temperature—from +15.5°C and below. There were no differences in sensory evaluation. There was no syneresis in jelly products. However, the experimental jelly products were characterized by antioxidant activity, in products obtained by heating in a microwave oven, antioxidant activity prevailed (table 1).

| Table 1. Antioxidant activity, µg AC g⁻¹, depending on the method of production of jelly products |
|---------------------------------------------------------------|
| Research method | Type of heating | Jelly products based on extracts from marc | |
| | | cranberries | lingonberries |
| DPPH | microwave | 9.10±0.25 | 9.35±0.28 |
| FRAP | microwave | 11.82±0.28 | 13.40±0.30 |
| DPPH | convective | 7.92±0.28 | 8.10±0.32 |
| FRAP | convective | 10.1±0.30 | 11.45±0.30 |

So, DPPH of jelly products based on cranberry extract when using microwave heating was higher by 14.9%, and lingonberry extract—by 15.4% compared with convective heating at the same heating temperature. The same tendency was also characteristic of the FRAP values—17.0% higher, irrespective of the type of extract used.

The antioxidant activity of jelly products also depended on the type of extract used from marc. In jelly products based on extracts from cranberries, it was higher than from cranberries, regardless of the method of determination.

Preservation of antioxidants could be related both to the heating rate and the uniform distribution of heat throughout the mixture. The heating in the microwave oven occurred uniformly throughout the volume, as evidenced by the image in the IR range in the form of red coloring of the mixture solution and yellow—the walls of the glass vessel (figure 2). Analysis of the color zone by means of computer technology showed a slight heterogeneity of the coloring of the object in the zone of the mixture solution of less than 1%.
Figure 2. Visualization of heating of the extract with a stabilizer of structure in a microwave field

A feature of heating the test mixture, placed in the magnetron resonator (microwave) to the required temperature, is the predominance of water in its composition, which acts as a conductor and heat carrier. Instantaneous heating of water occurs, which transfers thermal energy to the components of the mixture included in the solution. When removing radiation, heating of water and substances dissolved in it, stops instantly. There is no heating of the glass measuring vessel, as can be seen in the image in the IR range, as yellow staining.

Image formation of the object in the visible range was carried out in order to fix its spatial position and eliminate interference arising in the IR range, and the combination of visible and IR images confirmed the reliability of the results obtained on the thermal field of the object.

IR photography made it possible to minimize the time for determining the heating temperature of the test mixture, which occurred immediately after the magnetron cavity door was opened. A test measurement of the temperature of the mixture by an IR pyrometer through the walls of the vessel did not establish differences in temperature compared to IR photography.

Next, the heated object was removed from the cavity of the furnace, and repeated test measurements of the temperature of the mixture were carried out through the open surface of the heated medium using an IR pyrometer and control measurements with a mercury thermometer. The measurement results showed a decrease in the temperature of the mixture from 1–2°C to 4–5°C depending on the measurement time after removing the vessel with the mixture from the resonator, respectively 1 and 3 minutes. The later the temperature was measured after removing the glass vessel with the mixture, the greater the difference at different points of its measurement with a decrease from the central layers of the mixture to the layers in contact with the walls of the glass vessel. This difference could be 5°C. Measurement with a mercury thermometer showed similar results as with an IR pyrometer.

When using convective heating, the mixture reached the required temperature over a different period of time, depending on the intensity of the heat flow of the gas burner. However, the distribution of heat was different. Visualization of the IR image (figure 3) showed that the heat flux in the form of a red coloration was concentrated in the field of a gas burner, gradually heating a glass vessel, and then heat spread through the mixture.
When the mixture reached the required temperature, which was recorded by the IR camera and the IR pyrometer, the mixture was removed from the gas burner. Test measurements showed an excess of the heating temperature of the mixture by 4–5°C when measured with an IR pyrometer and a mercury thermometer through the open surface of the heated medium. This is due to the additional overheating of the glass vessel and the unevenness of the thermal processes.

4. Conclusions
Jelly products based on extracts from squeezed berries have antioxidant properties, the formation of which is associated with the features of the selected production method—maintaining the heating conditions of the mixture and the absence of temperature rise in accordance with the technological map.

The use of heating the prepared mixture for the manufacture of jelly products in a microwave oven allows uniform heating to a predetermined temperature, instantly stopping the supply of thermal energy to the medium due to the absence of thermal inertia, which preserves the antioxidant properties of the finished product. Convective heating of the prepared mixture has greater thermal inertia, leading to a temperature increase of 4–5°C, determined by the technological map, which increases the destruction of antioxidants.

An IR photograph used for test determinations of the temperature of the mixture allows you to instantly determine not only the temperature range, but also record the distribution of thermal energy in the medium under study.

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Figure 3. Visualization of control heating of the extract with a stabilizer convective method implemented on a gas burner
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