Experimental studies into the kinetics of the process of vacuum drying of carrot chips

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Abstract. The need to develop a technology for the production of a new healthy food product from vegetable raw materials has been substantiated in the paper. The choice of carrots of the cultivar Chantenay royal, Champion, Dordogne for use as the feedstock is justified. The design and principle of operation of the installation for conducting experimental studies are described. Experimental studies and a comparative analysis of their results in the production of carrot chips by drying at atmospheric pressure, vacuum drying at a pressure of 10 kPa and using preliminary pore formation followed by vacuum drying at a pressure of 10 kPa has been carried out. By the method of selection of objects according to their belonging to one of the structural elements (product, pores) by analyzing photographs of slices of chips, the dependence of the surface area of moisture evaporation on drying methods has been determined. It was found that the use of preliminary pore formation between the periods of heating the material and a constant drying rate significantly increased the energy efficiency of the process.

1. Introduction
In accordance with the Strategy for improving the quality of food products in the Russian Federation until 2030 (approved by order of the Government of the Russian Federation dated 06/29/16 No. 1364-p.), the priority areas comprise creating conditions for the production of new-generation food products with specified quality characteristics, promoting healthy food principles, etc.

Leading scientific organizations have begun the development of new food products, being in demand among the population. It has become advisable to combine healthy ingredients with popular foods. Analysis of social marketing research showed that adolescents and people under the age of 40 would like to see various snacks or chips as a healthy food product. In turn, the currently used technologies for their manufacture by frying in vegetable oil categorize these products as “not healthy” or even “harmful”.

It is also known that fruit and vegetables are the richest in vitamins and minerals. For Russia, providing the population with agricultural products is especially important, because most of its territory does not have favorable climatic conditions for growing vegetables and fruit. The production of fruit and vegetables is traditionally concentrated in the southern and some central regions of the European part of the country. The transportation of fresh fruit and vegetables to remote regions is complicated by long distances, as well as large losses of products. In this regard, there is a constant
demand of the population for long-term storage products, including dried fruit and vegetables. For the Southern Federal District of Russia, carrot is one of the most suitable for the production of fruit and vegetable snack products.

Thus, the aim of the research was to develop a technology for the production of a new food product, i.e. carrot chips.

According to the results of preliminary studies, the hypothesis was put forward that in order to preserve the useful vitamins of the feedstock, it is necessary to reduce the temperature of heat treatment to 55-60 ° C.

As an innovative technology for the production of carrot chips, it was proposed to replace frying with vacuum drying with preliminary pore formation in the feedstock to intensify the process and reduce energy consumption.

2. Materials, methods and equipment

2.1 Selection of carrot varieties for research

The studies were carried out using standard methods of experiment planning. Previously, the carrot varieties suitable for drying by priority indicators (table 1) were identified. They were as follows: Chantenay royal, Champion, Dordogne.

| Name of the carrot cultivar | Content |
|-----------------------------|---------|
|                             | Dry matter, % | Total sugar, % | Carotene, mg/% | Vitamin C, mg/% | Pectin, % |
| Chantenay royal             | 10.9     | 6.5            | Up to 15.0     | 3.95            | 0.6       |
| Champion                    | 13.3     | 6.9            | Up to 17.2     | 4.05            | 0.6       |
| Dordogne                    | 12.2     | 7.4            | Up to 12.1     | 4.00            | 0.6       |

2.2 Design and principle of operation of the installation for experimental research

To carry out the major part of laboratory research, a new design of the experimental installation was proposed (Figure 1).

The experimental installation consists of a processing chamber, a receiver, and a vacuum pump, a control unit, locking and measuring equipment. The principle of operation of the installation is as follows: in the processing chamber 1 on the thermo balance 2 with the perforated plate 3 located on them, the samples of the product under research were placed; heating the processing chamber to a preset temperature was carried out by convective method using a water bath 4 at atmospheric pressure; at the same time, vacuum pump 5 in the receiver 6 created a vacuum to a preset absolute pressure, while the pipeline between the processing chamber and the receiver is closed; Further, the processing chamber and the receiver were connected to each other, the pressure in them was equalized, due to the fact that the processing chamber was 6 times smaller than the receiver in absolute volume, the absolute pressure indicators remained much lower than atmospheric pressure, at this time inside the feedstock due to heating and the established reduced pressure, “microexplosion” occurred with the formation of pores due to boiling of moisture; in addition, the installation is equipped with a switch 7, a control lamp 8, a temperature controller 9, a screen of a thermal balance 10, a screen for indicating the temperature in the processing chamber 11, a temperature measuring sensor 12, and a needle valve 13 [1].
Figure 1. The exterior and the scheme of the pilot experimental installation

The temperature and pressure in the processing chamber were taken as variable parameters, and the drying process to a moisture content of 12% was taken as the output parameter. By analogy with potato chips, we selected the following size of the samples under research (carrot snacks): snack diameter was 30 mm, snack height was 2 mm. We considered snacks produced by chopping carrots into pieces of 0.2 ... 0.5 mm. In the process of research, we changed the operating temperature and vacuum drying pressure from 50 to 60 °C and from 0.1 to 0.2 atm. respectively.

2.3 Methodology for calculating changes in the surface area of the moisture evaporation during the drying process

To analyze the structure of porous and dried carrots, a commercial computer software developed by the Berlin Technical University and adapted to solve the tasks was used. In accordance with the classification adopted in the analysis of images, microphotographs of porous and dried carrots refer to systems with a contour image, where the boundaries of the force image are displayed in the form of a closed disjoint line with points of the same brightness, color and intensity of staining.

An analysis of photographs of the microstructure of the analyzed carrot samples was as follows. We used the selection of objects by belonging to one of the structural elements. They were product and pores [2]. Application of appropriate color filters allowed us to separate the analyzed samples with a high degree of reliability.

The spatial area was calculated by the following formula:

$$S = \sum_{i=1}^{N} i_i,$$

where $N$ – the number of unit areas; $i$ – the serial number of a unit area.

The spatial perimeter was determined by the following formula:

$$P = \sum_{i=1}^{M} z_i,$$

where $M$ – the number of unit lengths around the perimeter; $z$ – the serial number of the length unit around the perimeter.
The Feret diameter, or equivalent particle diameter, by which we mean the diameter of a conventional spherical particle that has the same volume as a particle of complex shape, was calculated by the following formula:

\[ D_p = \sqrt{\frac{4 \cdot S}{\pi}}, \]

where \( S \) – the projection area of particles within the field of view of the microscope.

Samples immediately after pore formation and drying were taken as objects of study. In order to increase the reliability of the results obtained for the analysis of the microstructure of samples, micrographs of 3 fields of each of the analyzed samples were summarized and then subjected to processing and analysis.

The average relative number of pores (\( \delta \)) in the internal volume of the product was determined by the following formula:

\[ \delta = \frac{V_1}{V_2}, \]

where \( V_1 \) – the pore volume per a unit of the product, m\(^3\); \( V_2 \) – the volume of the unit of the product, m\(^3\).

3. Discussion of the results

In the course of a series of experimental studies, drying curves and drying speed curves were produced for various combinations of variable parameters.

Figures 2 and 3 show examples of the drying curve and drying speed obtained with the following parameters: heating of the raw material was carried out at a temperature of 60 °C and atmospheric pressure; pore formation with subsequent vacuum drying - at a temperature of 55 °C and a pressure of 0.15 atm. The results were compared with the results of changes in humidity and drying speed for vacuum drying at similar parameters.

![Figure 2. The example of the curve of the carrot snacks drying: 1 – vacuum drying; 2 – vacuum drying after pore formation](image)

![Figure 3. The example of the speed curve of the carrot snacks drying: 1 – vacuum drying; 2 – vacuum drying after pore formation](image)

On the curves presented, the segment AB corresponds to the period of heating of the sample; BC segment is the pore formation period for a method using pore formation; segments BD’ and CD are the periods of constant drying speed, segments D’E and DE are the periods of falling drying speed.
Analysis of the curves showed that the use of pore formation could increase the rate of evaporation of moisture during the period of constant drying speed by 10%, and reduce the drying time to a moisture content of 12 ... 15% by 11%.

To evaluate the change in the surface area of moisture evaporation, we studied slices of carrot snacks using a BresserLCDMicro digital microscope with a four-fold increase. Photographs of slices of snacks for drying at atmospheric pressure (Figure 4, a), drying of snacks under vacuum (Figure 4, b), pore formation and drying of snacks under vacuum (Figure 4, c) revealed that the product after pore formation had significantly more pores filled with air, that is, we could see the difference between the porous product and the dried one.

![Figure 4](image)

**Figure 4.** Slices of dried snacks (fourfold increase): (a) - drying at atmospheric pressure; (b) - vacuum drying at a pressure of 10 kPa; (c) - pore formation and drying at a pressure of 10 kPa

The study of the structure of snacks produced by various methods allowed us to determine the average relative number of pores in the internal volume of the finished product (Figure 5). As shown in the graph, during the production of snacks by the method of pore formation and drying at a pressure of 10 kPa, pores occupied 35 ... 38% of the internal volume of the product, while during drying at a pressure of 10 kPa - 18 ... 21%, and subject to drying under atmospheric pressure - only 11 ... 13%.

![Figure 5](image)

**Figure 5.** The dependence of the average relative number of pores in the internal volume of the finished product upon the method of producing dried products
During drying, in case of pores, the surface area of moisture evaporation increased. Based on the data obtained during experimental studies, an additional area of moisture evaporation was calculated from the size of the formed pores. The research results are shown in Figure 6.

![Figure 6. Dependence of an average relative number of pores in the internal volume of the finished product upon the method of producing dried products.](image)

Analysis of the research results (Figures 5 and 6) demonstrated that an increase in the surface of moisture evaporation occurred gradually both during pore formation and during drying. Pore formation before the drying process allows one to increase the area of moisture evaporation and, as a result, reduce energy consumption by cutting short the duration of the process.

4. Conclusion

The experimental studies allow us to conclude that the use of preliminary pore formation between the periods of heating of the raw material and a constant drying rate made it possible to reduce the duration of the vacuum drying process, all other things being equal, by increasing the surface area of moisture evaporation.

Further research will be aimed at determining the thermophysical parameters of carrot raw materials, rational parameters of the process of pore formation and drying of carrot snacks, evaluating the effect of heat treatment temperature on the preservation of vitamins of the feedstock.

References

[1] Poymanov V V, Grishanova D S and Antipov S T 2018 Investigation of the processes of freezing and freeze-drying of bacterial concentrates for the dairy industry Proceedings of Voronezh State University of Engineering Technologies 80 (4) 19-24 (In Russ.) https://doi.org/10.20914/2310-1202-2018-4-19-24

[2] Sokolov S A, Afenchenko D S, Malich A A, Yashonkov A A and Yakovlev O V 2019 Influence of high pressure treatment on the rheological characteristics of fish paste IOP Conference
Series: Earth And Environmental Science 403 012233 https://doi.org/10.1088/1755-1315/403/1/012233

[3] Sharikov A Y, Stepanov V I, Ivanov V V, Polivanovskaya D V and Amelyakina M A 2018 Extrusion cooking of wet mixtures of wheat flour with carrot bagasse in technology of ready-to-eat products Proceedings of Voronezh State University of Engineering Technologies 80 (3) 43-49 (In Russ.) https://doi.org/10.20914/2310-1202-2018-3-43-49

[4]Perfilova O V 2019 The using of microwave, infrared heating in technology of carrot powder from refuse Proceedings of Voronezh State University of Engineering Technologies 81 (1) 144-148 (In Russ.) https://doi.org/10.20914/2310-1202-2019-1-144-148

[5] Yashonkov A A and Kurdoglo M E 2018 Research of the influence of pre-pore formation on the kinetics of the drying process while producing snacks of carrots Polzunovskiy vestnik № 464-67 (In Russ.) https://doi.org/10.25712/ASTU.2072-8921.2018.04.013

[6] Furman YA A, Yur’ev A N and Yashin V V 1992 Digital methods for processing and recognizing binary images (Krasnoyarsk: publishing house of Krasnoyarsk University)