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MECHANISM OF DETERMINING THE KINETICS OF MOISTURE CONTENT AND TEMPERATURE IN MEAT DURING CONDUCTIVE DRYING

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Abstract

Aim. Establishing the rational thickness of meat during conductive drying based on the obtained kinetics of moisture content and temperature, specific energy consumption and organoleptic evaluation of the quality of dried products. Methods. An experimental stand has been developed for conducting research. Standard methods of analysis were used for the research – duration of the process, output of the finished product, moisture content, etc. Statistical processing of experimental research results was carried out using standard Microsoft Office and Mathcad software packages. Results. The work developed an experimental stand and proposed methods for studying the kinetics of moisture content and temperature in experimental samples of pork meat. The kinetics of moisture content and temperature in pork meat of different thicknesses were determined experimentally. It was established that the determined kinetic dependencies during conductive drying have a common feature with other drying methods, however they are compressed in time. Theoretical models of the kinetics of moisture content in meat and the kinetics of temperature in the surface layers of meat are offered in the form of modified exponents which describe the real kinetics with a reliability up to 95 %. The quality of the finished product was evaluated by the organoleptic method, according to which the dried meat with an initial thickness of 0.003 m was the best. The specific electricity consumption for the process of drying test sample of meat of different thicknesses was studied. Conclusions. A feature of conductive drying of food products is small heat loss and speed of the process. The kinetics of the moisture content of meat during conductive drying were studied. It was established that the highest quality of finished products and the lowest specific electricity consumption can be achieved with the initial thickness of the samples of 0.003 m. It is offered to remove layers of dried meat during drying using physical and electrophysical methods in order to intensify the process of conductive drying.

Key words: conductive drying; kinetics; temperature; moisture content; meat.

МЕХАНІЗМ ВИЗНАЧЕННЯ КІНЕТИКИ ВОЛОГОВМІСТУ І ТЕМПЕРАТУРИ В М’ЯСІ ПІД ЧАС КОНДУКТИВНОГО СУШІННЯ

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Анотація

Мета. Встановлення раціональної товщини м’яса у кондуктивному сушінні за отриманими показниками кінетики вологовмісту та температури, питомих витрат електроенергії та органолептичної оцінки якості сушеного м'яса. Методи. Для проведення досліджень було розроблено експериментальний стенд. Стандартними методами аналізу визначено параметри – тривалість процесу, вихід готового продукту, вологовміст тощо. Статистичну обробку результатів експериментальних досліджень проводили за допомогою стандартних пакетів програм Microsoft Office та Mathcad. Результати. У роботі розроблено експериментальний стенд та запропоновано методику дослідження кінетики вологовмісту та температури дослідних зразків м’яса свинини. Експериментально визначено кінетику вологовмісту та температури в м’ясі свинини різної товщини. Встановлено, що визначені кінетичні залежності під час кондуктивного сушіння мають спільний характер з іншими методами сушіння, однак є стислими в часі. Запропоновано теоретичні моделі кінетики вологовмісту в м’ясі та кінетики температури в поверхневих шарах м’яса у вигляді модифікованих експонент, які описують реальну кінетику з достовірністю до 95 %. Якість готового продукту оцінювали органолептичним методом, за яким найкращим визнано сушене м’ясо з початковою товщиною 0.003 м. Досліджено питомі витрати електроенергії на процес сушіння дослідних зразків м’яса різної товщини. Висновки. Особливістю кондуктивного сушіння харчових продуктів є невеликі втрати теплоти та швидкість процесу. Досліджено кінетику вологовмісту в м'ясі під час кондуктивного сушіння. Встановлено, що найвищої якості готового продукту та найменшої питомої витрати електроенергії можна досягти при початковій товщині зразків 0.003 м. Для інтенсифікації процесу кондуктивного сушіння пропонується видаляти шари висушеного м’яса під час сушіння за допомогою фізичних і електрофізичних методів.

Ключові слова: кондуктивне сушіння; кінетика; температура; вологовміст; м'ясо.

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Introduction

Current realities of life in Ukraine in the conditions of war contribute to an increased demand for long shelf-life food products. The problem of providing the population with food, especially in the areas of hostilities must be solved at the expense of long-term storage products. Among such products dried foods and particularly meat are included as not require demanding storage conditions. While in peacetime consumers of dried products were mainly tourists, athletes, journalists etc., currently these products are most relevant for the military and civilians in combat zones.

In Ukraine and throughout the world, the demand for dried food products (meat is included) is constantly increasing. The drying of moist food raw materials is a simultaneous thermal-physical and technological process which includes mass and heat transfer [1–5]. Conductive drying is one of used methods. In conductive drying the heat (which is required to heat the raw material and evaporate the moisture) transfers from the heated surface, while the moisture removes in the form of vapour into the surrounding environment [6–8].

Each of the traditional drying method has its advantages and disadvantages. The efficiency of drying methods can be chosen by the features of the food raw material and equipment quality of the final product and energy consumption during the drying process [9; 10]. For convective drying, the specific energy consumption ranges from 6.0 to 12.5 MJ/kg for a process duration of 1200 seconds [11–14]. For sublimation drying, it ranges from 10.0 to 14.0 MJ/kg for a process duration of $36 \cdot 10^3$ to $254 \cdot 10^3$ seconds [15; 16]. Radiative drying requires 3.0 to 4.5 MJ/kg for a process duration of up to 900 seconds [10; 17]. Microwave drying ranges from 8.0 to 13.0 MJ/kg [18–21], while vacuum drying requires 3.0 to 4.0 MJ/kg for a process duration of up to 5100 seconds. On the other hand, conductive drying consumes 5.0 to 7.0 MJ/kg for a process duration of up to 3600 seconds [6–8]. The heat and mass transfer phenomena during conductive drying of capillary-porous colloidal bodies, (meat is included) were investigated by Krasnikov [22]. He found that after a short heating period further reduction of moisture content to equilibrium moisture content occurs in two stages: initially, the temperature of the surface layer of the raw material rapidly increases, and then it remains almost unchanged for a certain period, and subsequently slightly decreases before rising again [22]. Currently there is no available information specifically regarding conductive drying of meat. The optimal mode of conducting conductive drying capillary-porous colloidal bodies including meat is developed based on the laws of heat and mass transfer, which are influenced by various factors such as heating surface temperature, process duration, raw material thickness and compression of the raw material on the heating surface [23; 24]. Use of conductive drying technologies allows a tight contact between a product and a heating surface which results in a high heat transfer coefficient during the heating period reaching $k = 3800\ \mathrm{W/(m^2 \cdot K)}$ [25; 26] for the experimental sample, and during the stationary drying period it can reach $k = 170...180\ \mathrm{W/(m^2 \cdot K)}$ [22]. This method also facilitates mass transfer significantly reducing the drying process duration and producing high-quality dried meat. The relevance of this issue lies in the significant demand for meat including dried meat.

Aim of this study is to determine the optimal thickness of meat during conductive drying based on the obtained kinetics of moisture content, temperature, specific energy consumption and organoleptic evaluation of the quality of dried products.

Materials and Methods

Carbonate was purchased from the «Meat Processing Plant» chain of stores (Poltava, Ukraine) for the investigation of moisture content and temperature kinetics in meat. From the raw material (pork longest muscle), films and fat were removed, and then experimental samples were cut: sample No. 1 with dimensions of 0.07×0.04×0.003 m and a mass of 0.0082 kg; sample No. 2 with dimensions of 0.07×0.04×0.005 m and a mass of 0.0137 kg; sample No. 3 with dimensions of 0.07×0.04×0.007 m and a mass of 0.0192 kg, after removing the films and fat from the meat.

For the research, an experimental setup was used, the diagram of which is shown in Figure 1.

The experimental setup utilized a conductive drying apparatus based on the contact grill FROSTY SP-1A3 (Italy), consisting of an upper heating surface and a lower heating surface connected by a hinge. The power of the heating element for each surface was 1 kW.

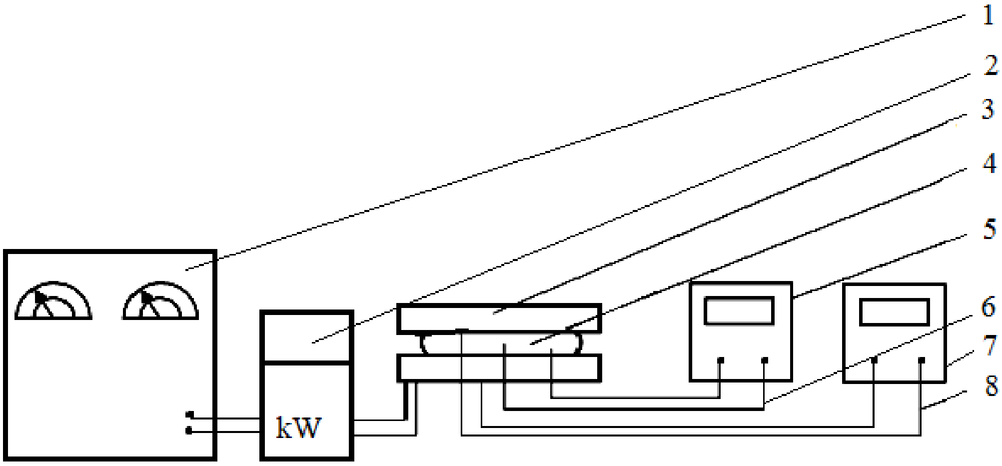

Fig. 1. Diagram of the experimental setup for studying the kinetics of moisture content and temperature in meat during conductive drying: 1 – Laboratory power transformer for supplying heating elements with a set of measuring instruments (voltmeter, ammeter); 2 – Electricity meter; 3 – Apparatus for conductive drying of the experimental sample; 4 – Experimental sample; 5 – Digital temperature device TRC 02, used to measure the temperature of the experimental sample; 6 – Thermocouple HK-0.5 inserted into the center of the experimental sample; 7 – Digital temperature device TRC 02, used to maintain the temperature of the lower and upper heating plates; 8 – Thermocouples HK-0.5 connected to the upper and lower surfaces of the apparatus.

The temperature of the surfaces was set and maintained at a specified level using an electronic temperature controller – TRC 02, and two HK-0.5 thermocouples were soldered into the upper and lower heating surfaces.

The duration of the conductive drying process was recorded using a stopwatch. The initial and final mass of the sample were determined using analytical scales «AXIS AD-600» with an accuracy of 10^{-5} kg. The energy consumption was measured by the difference in the readings of the electricity meter «Energy-9». The moisture content in the experimental samples was determined using a drying cabinet at a temperature of 103 °C according to ISO 1442:2005 [27]. The quality of the finished product was evaluated using an organoleptic method based on a 5-point scale [28]. The experiments were conducted with each sample in triplicate.

In the conductive drying apparatus, the sample No. 1 was placed on the lower surface heated to a temperature of 130 °C, with thermocouples placed in the center and the surface layer of the sample. Then, it was covered with the upper surface (top plate) heated to 130 °C. The mass of the upper surface was 1.26 kg, which provided an excess axial pressure on the experimental samples of 4.4 kPa. The temperature of the heating surfaces was selected to prevent any negative changes in the meat associated with the formation of carcinogenic substances [29], such as heterocyclic aromatic amines [30; 31]. After 60 seconds, the sample was taken out, weighed on analytical scales, and then dried to equilibrium moisture content W_p according to ISO 1442:2005 [27], in a drying cabinet. The dried sample was weighed on analytical scales. The moisture content value was calculated using the formula (excluding the mass of the dish, sand, and glass rod):

$$W = \frac{m_1 - m_2}{m_1} \cdot 100\%;$$

where m_1 is the mass of the tester before drying; m_2 is the mass of the tester after drying.

A new sample No. 1 was dried for 120 seconds, repeating the moisture content determination algorithm. The new sample No. 1 was dried for 180 seconds, and so on until reaching the equilibrium moisture content. Drying of sample No. 2 and No. 3 was conducted with the determination of the equilibrium moisture content using a similar methodology. The experiment was conducted in triplicate for each experimental sample.

Results

As a result of the experimental part, the moisture content and temperature values were determined both in the center and surface layer during the drying of the experimental samples to equilibrium moisture content every 60 seconds.

The results of the experimental determination of moisture content during conductive drying are presented in Table 1.

Table 1

Moisture content of the experimental samples during conductive drying

τ, c	Sample No. 1 *W*, ±0.05 %	Sample No. 2 *W*, ±0.05 %	Sample No. 3 *W*, ±0,05 %
0	0.725	0.725	0.725
60	0.450	0.570	0.630
120	0.220	0.400	0.520
180	0.090	0.260	0.420
240	0.025	0.150	0.330
300	0.005	0.080	0.250
360	0.000	0.040	0.190
420	-	0.020	0.140
480	-	0.010	0.100
540	-	0.005	0.075
580	-	0.000	0.055
600	-	-	0.050
660	-	-	0.035
720	-	-	0.025
780	-	-	0.015
840	-	-	0.010
900	-	-	0.005
940	-	-	0.000

The results of experimental studies on moisture content determination during conductive drying allow us to establish the actual moisture content kinetics during conductive drying of meat with different thicknesses. The actual moisture content kinetics are presented graphically in Figure 2.

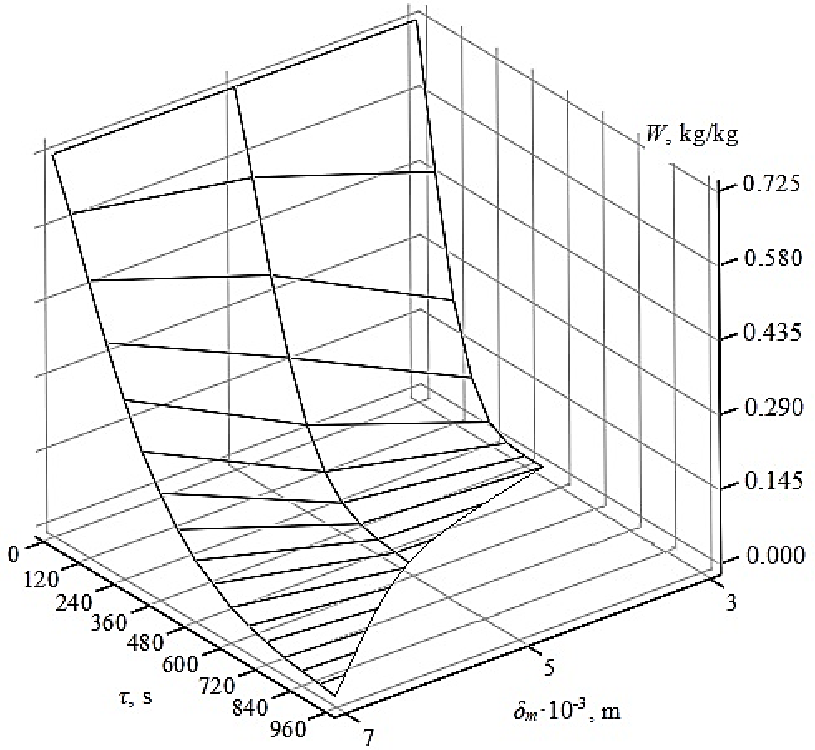

Fig. 2. Actual moisture content kinetics during conductive drying of experimental samples with thickness ranging from 3×10^{-3} m to 7×10^{-3} m

The results of temperature determination in the center and surface layer of the experimental samples during conductive drying every 60 seconds are presented in Table 2.

The results of experimental studies on temperature determination in the surface layers and center of the sample during conductive drying allow us to establish the actual temperature kinetics during conductive drying of meat with different thicknesses. The temperature kinetics in the surface layers and center of the experimental sample, as a function of duration, are graphically presented in Figure 3 and Figure 4.

Table 2

Temperature in the surface layer and center of the experimental samples during conductive drying

τ, *c*	Sample No. 1		Sample No. 2		Sample No. 3	
	t_c, ±0.05, °C	t_s, ±0.05, °C	t_c, ±0.05, °C	t_p, ±0.05, °C	t_c, ±0.05, °C	t_p, ±0.05, °C
0	8	8	8	8	8	8
60	94	104	80	102	45	102
120	100	110	96	106	72	104
180	100	112	100	108	87	105
240	92	114	100	110	96	106
300	98	118	100	110	100	108
360	101	120	94	112	100	109
420	-	-	91	114	100	110
480	-	-	97	116	100	111
540	-	-	101	120	100	112
580	-	-	-	-	99	112
600	-	-	-	-	97	113
660	-	-	-	-	90	114
720	-	-	-	-	88	115
780	-	-	-	-	90	116
840	-	-	-	-	98	117
900	-	-	-	-	100	118
940	-	-	-	-	101	120

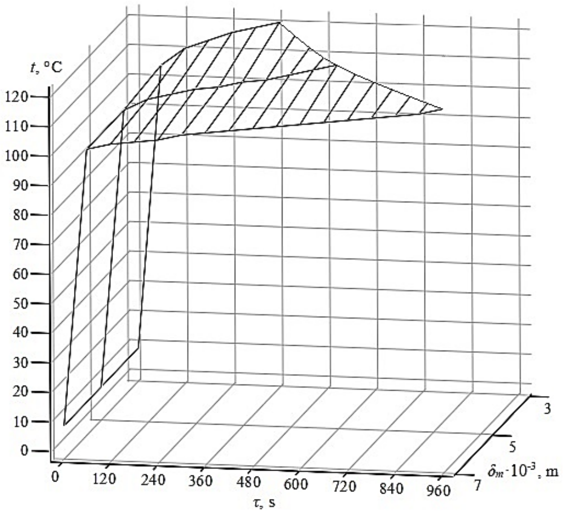

Fig. 3. Actual temperature kinetics in the surface layers of the experimental meat samples with thickness ranging from 3×10^{-3} m to 7×10^{-3} m during conductive drying

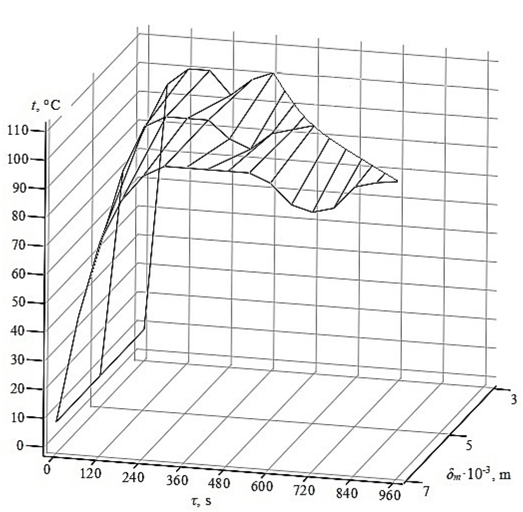

Fig. 4. Actual temperature kinetics in the center of the experimental meat samples with thickness ranging from 3×10^{-3} m to 7×10^{-3} m during conductive drying

During the experiment, the weights of the experimental samples before and after drying were determined, as well as the energy consumption for the drying process. The results are presented in Table 3.

Table 3

Results of determining the weights of experimental samples before and after conductive drying, specific energy consumption, and heat for the drying process

Indicator Name	Sample No. 1	Sample No. 2	Sample No. 3
Initial sample weight, kg	0.00820	0.01370	0.01920
Weight of dried sample, kg	0.00226	0.00377	0.00528
Finished product yield, %	27.56	27.52	27.50
Amount of evaporated moisture, kg	0.00594	0.00993	0.01392
Energy consumption, kWh/kg of evaporated moisture	1.15	1.17	1.21
Heat consumption, MJ/kg of evaporated moisture	4.14	4.21	4.36

Thus, drying pork meat to equilibrium moisture content ensures the yield of the finished product of 27.53±0.03 %. If necessary, the drying process can be stopped at the desired value of moisture content in the finished product (Table 1, Fig. 2) and thus ensure the desired yield of the finished product.

The quality of dried meat products is evaluated according to physic-chemical and organoleptic parameters. We stopped at this stage of research on the organoleptic evaluation of quality. The study of the quality of ready-made dried meat products according to organoleptic indicators was subject to meat products dried to equilibrium moisture content (W_{p} = 0 %). Organoleptic evaluation of the quality of dried meat products was conducted immediately after cooling the dried products using a 5-point scale. The results of the evaluation are as follows: sample No. 1 – 4.3 points, sample No. 2 – 4.0 points, sample No. 3 – 3.5 points.

Discussion

Analysis of the actual moisture content kinetics allows us to conclude the following. The actual drying kinetics (Figure 2) has a similar shape to the overall drying kinetics [7; 19; 32]. The difference lies only in the reduced drying time. With an increase in the thickness of the meat sample from 0.003 m to 0.007 m, the duration of the moisture removal process nonlinearly increases from 360 s to 940 s.

As seen from Figure 2, in the initial period of the conductive drying process of meat samples with different thicknesses, moisture removal occurs linearly (proportionally) up to 40...45% of the drying time, after which the shape of the moisture content curve changes to non-linear. Overall, such dependencies can be described by a modified exponential function

$$y = k + a \cdot b^{x} \tag{1}$$

where k is the horizontal asymptote, in this case k = 0;
a and *b* are the parameters of the function [33].

A nonlinear least squares method was used to model the moisture content function during conductive drying. Subsequently, trends in the change of moisture content during conductive drying were constructed, and their approximation with a 95% confidence level yielded the solution of the function (1) in the following form (Table 4, Figure 5)

$$W = W_{in.} \cdot (0.989 + \sigma_m)^{\tau};$$

where $W_{in.}$ – initial is the initial moisture content, kg/kg;
σ_m is the initial thickness of the experimental sample, m;
τ is the duration of the drying process, s;
0.989 is the kinetic coefficient.

Table 4

Determination of the function W(τ) – trend of the moisture content change during conductive drying

τ, c	$\sigma_m = 0.003$ m	$\sigma_m = 0.005$ m	$\sigma_m = 0.007$ m
0	0.7250000	0.7250000	0.7250000
60	0.4477528	0.5052672	0.5700308
120	0.2765277	0.3521309	0.4481863
180	0.1707808	0.2454071	0.3523862
240	0.1054725	0.1710292	0.2770634
300	0.0651388	0.1191937	0.2178410
360	0.0402291	0.0830685	0.1712773
420	-	0.0578921	0.1346667

Continuation of the table 4

480	-	0.0403462	0.1058816
540	-	0.0281181	0.0832493
580	-	0.0221025	0.0709176
600	-	-	0.0654547
660	-	-	0.0514637
720	-	-	0.0404633
780	-	-	0.0318143
840	-	-	0.0250140
900	-	-	0.0196672
940	-	-	0.0167539

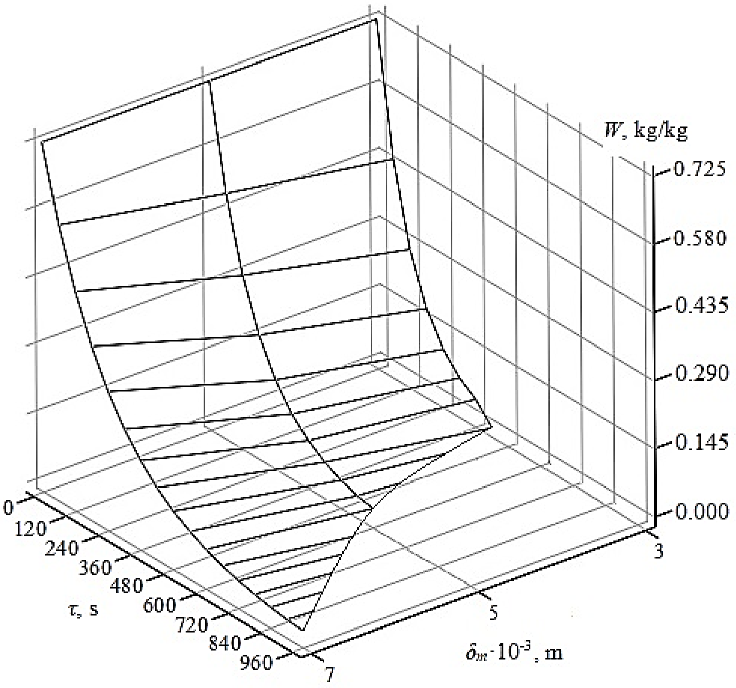

Fig. 5. Moisture content kinetics during conductive drying of meat with a thickness ranging from 3×10^{-3} m to 7×10^{-3} m according to the proposed model (1)

Analysis of the actual temperature kinetics in the surface layers and the center of the meat during conductive drying reveals the following findings. The actual temperature kinetics (Figure 3) exhibits a similar pattern to the overall temperature kinetics during drying [6]. As seen in Figure 3, the surface layers of the experimental samples quickly heated up to the evaporation temperature (100 °C), followed by a nearly linear increase in the temperature of these layers from 100 °C to 130 °C towards the end of the drying process. Such relationships can be described by a modified exponential function

$$y = k\text{-}a \cdot b^{x}; \qquad (2)$$

where *k* represents the horizontal asymptote, in this case *k*=130 °C – the temperature of the heating surfaces;
a and *b* are the parameters of the function [33].

A nonlinear least squares method was used to model the temperature change function of the surface layers of the experimental samples during conductive drying. Subsequently, trends in the temperature change process of the surface layers during conductive drying were constructed, and their approximation with a 95 % confidence level yielded the solution of the function (2) in the following form (Table 5, Figure 6).

$$t = t_p - \left(t_p - \Delta\bar{t}\right) \cdot 0.98^{\tau}, \mathrm{c};$$

where t_p represents the heating surface temperature, in °C;

$\Delta\bar{t}$ is the average temperature difference between the heating surface and the surface of the experimental sample, in °C;
τ is the duration of the drying process, in seconds;
0.98 is the kinetic coefficient.

The center of the experimental samples heats up to the evaporation temperature (100 °C) not as quickly as the surface layers, which can be attributed to the low thermal conductivity coefficient of the meat [34].

Table 5

Definition of the function t(τ) – trend of the temperature change process in the surface layers of meat during conductive drying

τ, c	$\sigma_m = 0.003$ m	$\sigma_m = 0.005$ m	$\sigma_m = 0.007$ m
0	8	8	8
60	93.69852	88.97495	83.64829
120	119.19838	116.20447	112.3895
180	126.78594	125.36097	123.3092
240	129.04365	128.44003	127.45800
300	129.71543	129.47543	129.03420
360	129.91533	129.82360	129.63310
420	-	129.94068	129.86060
480	-	129.98005	129.94700
540	-	129.99329	129.97990
580	-	129.99676	129.98940
600	-	-	129.99240
660	-	-	129.99710
720	-	-	129.99890
780	-	-	129.99960
840	-	-	129.99980
900	-	-	129.99990
940	-	-	130.00000

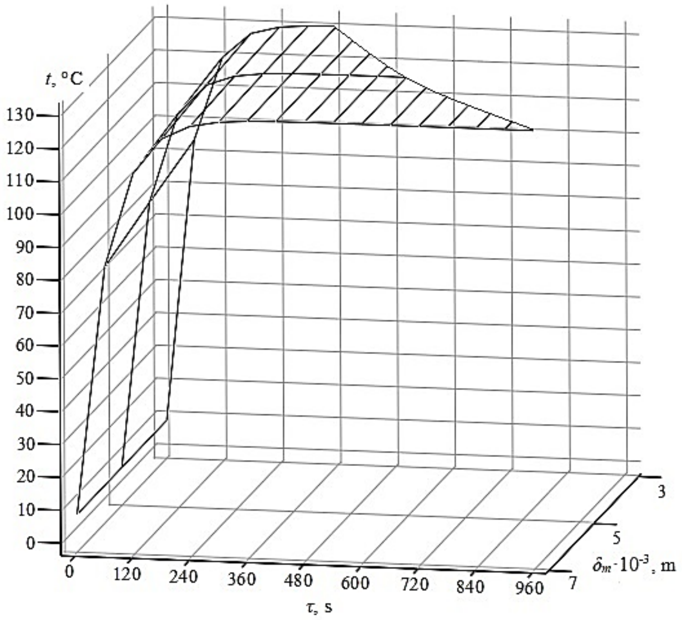

Fig. 6. Kinetics of temperature in the surface layers of the experimental samples of meat with a thickness ranging from 3x10^{-3} m to 7x10^{-3} m during conductive drying according to the proposed model (2)

Then comes the phase of moisture removal from the samples at a constant temperature in the center (100 °C), after which the temperature in the center begins to decrease to 92 °C in sample No. 1, 91 °C in sample No. 2, and 88 °C in sample No. 3. The decrease in temperature in the center of the experimental samples after the phase of moisture removal at a constant temperature can be explained by reaching the so-called first critical moisture content W_{kr1} [6]. Additionally, the meat sample acquires solid-like properties due to irreversible changes caused by thermal denaturation of proteins [35]. Under these conditions, the fronts of vapor formation [22; 36] penetrate deeper into the experimental sample, leading to a significant increase in heat transfer resistance from the heating surfaces into the depth of the sample. Describing the dependence of such a nature is challenging.

Compensating for the movement of vapor fronts into the depth of the dried product to reduce thermal resistance can be achieved through mechanical removal of the dried meat layers. Additionally, preventing the migration of vapor fronts deeper into the meat can be achieved through the use of various physical and electrophysical methods [37].

As seen in Figure 2 and Figure 3, during the first phase of the process (40...45 % of the total duration), which is the phase of linear moisture removal, up to 80 % of the moisture is removed from the samples: the moisture content W decreases from 72.5 to 14.0...14.5 %. Then, the rate of moisture removal significantly decreases, leading to overheating of the surface layer up to 120 °C and the development of a light brown color on the surface due to melanoidin formation.

The energy (heat) consumption per 1 kg of evaporated moisture depends on the thickness of the experimental sample. In sample No. 1, it amounts to 1.15 kWh/kg (4.14 MJ/kg); in sample No. 2, it is 1.17 kWh/kg (4.21 MJ/kg), and in sample No. 3, it is 1.21 kWh/kg (4.36 MJ/kg). This can be attributed to the higher heat transfer resistance from the heating surfaces into the depth of thicker samples [5].

The best organoleptic indicators were observed in sample No. 1. The sample had a good chewability, a taste of roasted meat during chewing, and a thinner dehydrated meat crust with signs of melanoidin formation upon fracture. Sample No. 3 had a longer and more difficult chewing process, although it had a taste of roasted meat, it had the thickest crust with signs of melanoidin formation upon fracture.

Conclusions

Based on the conducted research and analysis of the obtained results following has been established:

(a) general form of the actual moisture content kinetics during conductive drying of meat with a 95.5 % confidence level can be approximated by a modified exponential function

(b) general form of the actual temperature kinetics in the surface layers and center of meat during conductive drying can be approximated by a modified exponential function with a 95.5 % confidence level

(c) it is advisable to remove the layers of dried meat during drying using physical and electrophysical methods in order to intensify the process of conductive drying

(d) among three thicknesses investigated (0.003 m, 0.005 m, and 0.007 m) the most rational thickness was 0.003 m which results in the shortest duration of the drying process to equilibrium moisture content (finished product yield ≈27.5 %), and the lowest specific energy (heat) consumption per 1 kg of evaporated moisture, while providing better organoleptic quality indicators.

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