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Physical and mathematical modelling of the massing process of marinated pork and beef preparation technology

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ABSTRACT

The main process in the technology of natural marinated semi-finished meat products is the marinating process, which depends on the marinating method, temperature conditions, and composition of the marinade mixture. To enhance the distribution of marinades within the meat, mechanical processing of the raw material is necessary, specifically using the massaging process, to achieve uniform distribution of curing agents, changes in structure, and increased activity of enzymatic systems utilized in marinades. The main goal of this study is to model the massaging process, which allows the processing of the obtained experimental data in the form of a criterion equation. For the research, 8 samples were used, including 3 experimental pork samples and 1 control, as well as 3 experimental beef samples and 1 control. The main components of the samples include pork meat, beef meat, canola oil, sunflower oil, olive oil, curing ingredients, spices and seasonings, bromelain enzyme, and yeast extract. To carry out the massaging process in the investigated procedure, a massager of the model MAL 50-1500 was employed. The research results indicate that the determined mass transfer equation demonstrates a predominant influence in the investigated massaging process, involving changes in the concentration of sunflower, canola, and olive oil in the product, affecting the diffusion coefficient, size of dispersed phase particles, and mass transfer coefficient within the load.

Keywords: marinating, massaging, beef, pork, mass exchange

INTRODUCTION

One of the most important issues in ensuring the quality of marinated pork and beef preparation is effectively structuring necessary components and mixing their ingredients, creating a consistency that meets the required standards **[1]**. The main process in the mentioned technology is the marination process, which depends on the marinating method, temperature conditions, and the composition of the marinade mixture itself **[2]**. To intensify brine distribution, mechanical treatment of raw materials is applied, namely tenderization, tumbling, or massaging of meat to distribute curing agents, change the structure, and increase the activity of enzymatic systems. As a result of this technological action, accelerated salting and meat ageing are expected, improvement of its organoleptic and physicomechanical indicators, particularly plasticity and shear strength. The projected technology involves a massaging operation, the essence of which lies in utilizing the energy from the fall of meat pieces from a certain height, impact, and friction of these pieces against each other and the inner surface of the rotating drum **[3]**.

The main factors of this process are the product density ρ, shear yield stress τ_r, variation in the concentration of sunflower, rapeseed, or olive oil in the product ΔC, the diffusion coefficient D, and the mass transfer coefficient in the technological mass β, processing time t the average size of meat pieces, and the rate of their advancement in the massage drum υ **[4]**. Considering a significant number of factors in the investigated process, it is advisable to model it using the Buckingham π theorem, which allows processing the obtained experimental data in the form of a dimensionless equation **[5]**.

Considering the peculiarities of the studied massaging process, characterized by the action of centrifugal forces and fluid flows, which requires using Euler's number Eu to measure the ratio of pressure forces to velocity thrust in the model. The presence of the convective flow of technological media, leading to diffusion at the interface of interacting phases, necessitates applying Sherwood's number Sh. Local pulsations in non-stationary flows reveal the relevance of representing the heat and mass exchange in the sought equation by diffusion Fourier's number Fo_d **[6]**.

Scientific Hypothesis

The development of physical-mathematical modelling of the technological process (massaging or mixing) allows the processing of experimental data in the form of a criteria equation. Additionally, modelling the massaging process in the technology of natural marinated meat semi-finished products enables preliminary determination of the required equipment characteristics for this process, namely, the massager.

MATERIAL AND METHODOLOGY

Samples

In this article, 8 samples were examined: 4 samples using pork and 4 samples from beef.

- Sample 1 – pork without marinade.
- Sample 2 – pork with marinade based on rapeseed oil.
- Sample 3 – pork with marinade based on a blend of oils (sunflower: rapeseed = 70:30).
- Sample 4 – pork with marinade based on a blend of oils (sunflower: olive = 80:20).
- Sample 5 – beef without marinade.
- Sample 6 – beef with marinade based on rapeseed oil.
- Sample 7 – beef with marinade based on a blend of oils (sunflower: rapeseed = 70:30).
- Sample 8 – beef with marinade based on a blend of oils (sunflower: olive = 80:20).

Chemicals

Inorganic sulfuric acid salt ($C_6H_7NaO_6$, producer «Inter-Synthesis» Limited Liability Company, Ukraine, chemically pure for analysis).

Animals, Plants, and Biological Materials

For the researcher, we used beef grade II and pork grade II, with a high connective tissue content. Pork and beef meat were purchased from a retail network.

Instruments

The following tool was used to determine the moisture content in the prepared samples:

Analytical balance (Radwag AS 220/C, producer «Inter-Synthesis» Limited Liability Company, Ukraine).

Boxes (aluminium laboratory, producer «Inter-Synthesis» Limited Liability Company, Ukraine).

Ulab 3-31 M penetrometer (producer «Inter-Synthesis» Limited Liability Company, Ukraine).

pH meter (HI8314 HANNA, producer (Spectro lab) Limited Liability Company, Ukraine).

Thermometer (digital laboratory thermometer TH310 Milwaukee, producer (Spectro lab) Limited Liability Company, Ukraine).

Laboratory scales (AXIS BDM 3, (Spectro lab) Limited Liability Company, Ukraine).

Laboratory Methods

The authors used the following laboratory research methods:

The penetration degree was determined using the Ulab 3-31 M penetrometer (producer «Inter-Synthesis» Limited Liability Company, Ukraine). The sample's temperature was brought to 20 ±0.5 °C by placing it in an air bath at a constant temperature of 20 °C. The investigated sample was positioned steadily on the penetrometer table under the horizontal indenter. Penetration of natural marinated meat semi-finished products was determined using a needle indenter. Three measurements were taken on the open surface of the sample. Measurements were conducted at a distance of not less than 10 mm from the edge of the sample and at the maximum distance from the points of other measurements to avoid the deformed part of the surface entering the measurement zone. Air inclusions and other visible surface defects should be avoided. The penetration results are calculated as the arithmetic mean of the results of three parallel measurements, rounded according to standard СТ СЄВ 543. To convert the penetration value of elastic products (ready-to-eat food products, smoked products, carbonate, neck, bacon, and other whole-piece products) measured over 180 s into penetration stress θ, in Pa, with the indication of the used indenter, the following formula is applied:

$$\theta = Ph^{-2} = mgh^{-2}$$

Where:
P is the applied force in Newtons (N); h is the depth of penetration of the needle indenter in meters (m); g is the acceleration due to gravity (9.8 m/s²); m is the mass of the needle, rod, and additional load in kilograms (kg).

m rod = 47.3 g
m load = 50.0 g
m needle = 2.7 g.

The determination of product yield was carried out by weighing before and after thermal treatment, expressed as a percentage using the formula:

$$\text{Yield} = \frac{\text{A}}{\text{C}} \times 100$$

Where:
A is the mass of the product after thermal treatment in grams (g); C is the mass of the raw material for making the mince in grams (g).

Determining the water-holding capacity of natural marinated meat semi-finished products was carried out using the "Press Method," developed by Grau and Hamm in the modification of Volovinska and Kelman **[7]**. This method is based on pressing the test sample with a mass of 0.3 g under a load of 1 kg, sorption of the released moisture under pressure by filter paper, and determination of the amount of released moisture by the wet spot area on the filter paper using the method.

The determination of plasticity was carried out using the data obtained during the determination of water-holding capacity. The calculation was based on the wet spot area formed after pressing the filter paper and determining water-holding capacity **[7]**.

The water-retaining capacity was determined by the quantitative content of water retained by the test sample after thermal treatment **[7]**.

The fat-retaining capacity was determined as the difference between the fat content in the product and the amount of fat released during thermal processing **[7]**.

The pH was determined by the potentiometric method, based on measuring the electromotive force of an element consisting of a reference electrode with a known potential and an indicator (glass) electrode, the potential of which is determined by the concentration of hydrogen ions in the test solution **[8]**.

Description of the Experiment

Sample preparation: The preparation of samples for the mentioned experiments was carried out by DSTU 7963:2015 **[9]**. Sample collection was performed by DSTU 7992:2015 **[10]** and DSTU 8051:2015 **[11]**.

Number of samples analyzed: 8 samples were examined: 4 samples using pork and 4 from beef.

Number of repeated analyses: The study was repeated 5 times, with the experimental data processed using mathematical statistics.

Number of experiment replications: Each study was carried out five times, and the number of samples was three, resulting in fifteen repeated analyses.

Design of the experiment: Experimental studies were conducted to obtain values that would serve as input data for the physical-mathematical modelling of the massaging process. Researchers determined penetration, product yield, water-holding capacity, plasticity, moisture-binding capacity, and pH. The results of these investigations clearly describe the meat's firmness and enable the conduct of physical-mathematical modelling of the process.

Statistical Analysis

Considering the peculiarities of the studied massaging process, characterized by the action of centrifugal forces and fluid flows, which requires using Euler's number *Eu* to measure the ratio of pressure forces to velocity thrust in the model. The presence of the convective flow of technological media, leading to diffusion at the interface of interacting phases, necessitates applying Sherwood's number *Sh*. Local pulsations in non-stationary flows reveal the relevance of representing the heat and mass exchange in the sought equation by diffusion Fourier's number Fo_d **[6]**. Statistical processing was performed in Microsoft Excel 2016. Values were estimated using mean and standard deviations and evaluated in the XL Stat statistical program.

RESULTS AND DISCUSSION

According to the classical technique, the marinade typically includes the following components **[12]**: table salt, ground black pepper, and bay leaf **[13]**. However, in the scientific study, it is suggested to add sunflower **[14]**, rapeseed **[15]**, or olive oil **[16]** to the marinade **[17]**, as presented in Table 1 and patented Patent no. 134474 **[18]**, Patent no. 134475 **[19]**, Patent no. 134476 **[20]**.

Table 1 Functional and technological indicators of control and experimental samples of natural marinated meat semi-finished products.

Sample	Content of rapeseed oil in the marinade	Content of sunflower (70%) + rapeseed (30%) oil in the marinade	Content of sunflower (80%) + olive (20%) oil in the marinade	Plasticity, cm²/g	Penetration, Pa
Pork semi-finished products					
1	6.64	-	-	9.45	5035.9
2	-	6.64	-	9.06	4355.5
3	-	-	6.64	7.74	1885.2
Control	-	-	-	6.75	1935.8
Beef semi-finished products					
1	6.64	-	-	6.88	8804.8
2	-	6.64	-	7.15	7038.2
3	-	-	6.64	6.72	4661.1
Control	-	-	-	7.17	4535.1

By employing the dimensional analysis theory as a mathematical method, the factors of the studied process **[21]** were initially represented in Table 2.

Table 2 Main calculated parameters of the massaging process.

No.	Process parameter	Dimension
1	Product density ρ, kg/m³	$kg.m^{-3}$
2	Processing time per load t, s	s
3	Shear yield stress τ_r, N/m² (Pa)	$kg.s^{-2}.m^{-1}$
4	Diffusion coefficient D, m^2/s	$m^2.s^{-1}$
5	The average size of meat pieces ℓ, m	m
6	Meat piece advancement speed in the massager drum υ, m/s	$m.s^{-1}$
7	Mass transfer coefficient in technological mass load β, m/s	$m.s^{-1}$

The above similarity criteria were presented through the indicated physicomechanical and rheological factors of the studied massaging process **[22]** as follows:

Euler's criterion was represented as:

$$Eu = \frac{P}{\rho \cdot S \cdot \upsilon^2} = \frac{\tau}{\rho \cdot \upsilon^2} \quad (1)$$

Where:

P – is the resistance of the medium, which is equal to the load acting on the product during processing, *H*; *S* – is the area of force contact within the working volume, m²; $\tau = \frac{P}{s}$ - is the shear yield stress, Pa; υ – is the speed of meat piece movement in the massager drum: $\upsilon = \omega R_б = \frac{\pi \cdot n_б \cdot R_б}{30}$ $R_б$ – is the radius of the drum; $n_б$, ω – are the rotation frequency and angular velocity of the massager drum respectively. $n_б = \varphi \cdot n_{кр}$

Where:

φ – is the coefficient of the technological mass load inside the drum, which was taken within the range of φ = 0.8-0.85: was adopted as φ=0,82; $n_{кр}$ – is the critical drum rotation frequency, rev/min; which was adopted from the dependence $n_{кр} = \frac{12,3}{\sqrt{2R_б}}$

The Sherwood's criterion Sh is classically calculated as:

$$Sh = \beta \cdot \ell / D \tag{2}$$

Where:
ℓ – s is the characteristic size under the conditions of the investigated mass transfer, which can be identified with the average size of the dispersed phase particles, which for the investigated massaging process corresponds to the average size of meat pieces; D – is the diffusion coefficient **[23]**.

The mass transfer coefficient for the investigated process can be determined using the following relationship:

$$\beta = \frac{\Pi_V}{\Delta C \cdot S} \tag{3}$$

Where:
P_V – volumetric productivity of the process.

The Fourier's number for diffusion was determined using the formula:

$$\mathrm{Fo}_\partial = \frac{D \cdot t}{\ell^2} \tag{4}$$

Using the experimental research data (Table 3) **[1]**, the main parameters of the massaging process were determined using the following methodology **[24]**.

Table 3 Functional and technological indicators of natural marinated meat semi-finished products.

Sample No.	pH	Moisture content, % of meat weight	Moisture content, % of total moisture	Plasticity, $10^6 \times cm^2/g$	Water holding capacity, %	Yield, %
Pork semi-finished products						
1	5.67	58.150	91.515	9.45	63.45	80.5
2	6.4	60.095	81.23	9.06	73.87	102.4
3	6.18	59.345	83.235	7.74	71.17	74.6
Control	6.15	58.515	81.475	6.75	71.77	62.6
Beef semi-finished products						
1	6.57	63.565	90.39	6.88	70.24	66.3
2	5.75	61.995	87.93	7.15	70.43	68.6
3	5.87	63.090	88.845	6.72	70.76	66.3
Control	6.04	63.755	85.65	7.17	74.39	65.8

Then, the speed of meat piece movement inside the massager drum is determined as follows:

$$\upsilon = \frac{\pi \cdot \varphi \cdot n_{кр} \cdot R_б}{30} = \frac{12.3 \cdot \pi \cdot \varphi \cdot \sqrt{R_б}}{30 \cdot \sqrt{2}} = \frac{12.3 \cdot 3.14 \cdot 0.82 \cdot \sqrt{0.6}}{30 \cdot \sqrt{2}} = 0.578 м/с$$

The investigated massaging process's characteristic size corresponds to the meat pieces' average size: *ℓ = 0,04 m.*

The mass transfer coefficient for the investigated process can be determined using the following relationship:

$$\beta = \frac{\Pi_v}{\Delta C \cdot S} = \frac{m}{t \cdot S \cdot \Delta C \cdot \rho} \tag{5}$$

Where:
t – is the processing time per product load **[25]**.

The massaging cycle in the developed marinating technology proceeds as follows. The rotary motion of the massager's executive elements for pork semi-finished products takes place for t = 30 minutes, while for beef semi-finished products, it's – t = 40 minutes. These cycles are repeated throughout 24 to 36 hours. The raw material and room temperature range from 4 to 6 °C **[26]**.

The change in the concentration of sunflower, rapeseed, or olive oil in the product is taken as ΔC = 0.664 (Table 1) **[27]**.

The product's density is assumed as follows: for pork semi-finished products, it is ρ = 1030 kg/m³; for beef semi-finished products of grade II, it is ρ = 1087 kg/m³ **[28]**.

Thus, the mass transfer coefficient β can be expressed as:

$$\beta = \frac{m \cdot (g + \frac{\nu^2}{R_б})}{t \cdot S \cdot \Delta C \cdot (g + \frac{\nu^2}{R_б}) \cdot \rho} = \frac{\tau}{t \cdot \Delta C \cdot (g + \frac{\nu^2}{R_б}) \cdot \rho} = \frac{\tau}{t \cdot \rho \cdot 0.664(9.81 + \frac{0.578^2}{0.6})}$$

Where g = 9,81 m/s² is the acceleration due to gravity, and the shear stress $\tau = \frac{P}{S} = \frac{m \cdot (g + \frac{\nu^2}{R_б})}{S}$; is represented by the magnitude P = m $(g + \frac{\nu^2}{R_б})$ which is the load in the investigated process resulting from the action of the force of gravity on the product mass and the centrifugal forces during its rotation in the working drum **[29]**.

The expression was then transformed

$$\beta = \frac{\tau}{t \cdot \rho \cdot 6.81} \quad (6)$$

The shear yield stress τ can be determined using the plasticity values X and the penetration number Q, obtained from the investigations of corresponding samples (Table 3).

Using the fact that the penetration index is proportional to the shear stress of the minced mass τ, the penetration coefficient Q was determined from the relationship:

$$Q = \frac{P}{h^2} = \tau \cdot k_{np} \quad (7)$$

where k_{np} – is the proportionality coefficient; h – is the depth of the indenter penetration into the minced mass under a certain load P, determined from experimental studies **[30]**.

Then, when using equation (7):

$$\tau = \frac{Q}{k_{np}} \quad (8)$$

When determining the plasticity, the following mathematical transformation method was used **[31]**.

$$X = \frac{S}{m} = \frac{S \cdot (g + \frac{\nu^2}{R_б})}{m \cdot (g + \frac{\nu^2}{R_б})} = \frac{S \cdot (g + \frac{\nu^2}{R_б})}{P} = \frac{(g + \frac{\nu^2}{R_б})}{\tau} \quad (9)$$

The magnitude P = m$(g + \frac{\nu^2}{R_б})$ represents the load in the investigated process due to the force of gravity acting on the product mass and the centrifugal forces during its rotation in the working drum **[32]**. Thus, when using equation (9), the sought shear stress takes the form:

$$\tau = \frac{(g + \frac{\nu^2}{R_б})}{X} = \frac{(9.81 + \frac{0.578^2}{0.6})}{X} = \frac{10.26}{X} \quad (10)$$

According to the research results, the diffusion coefficient of the marinade for the experimental sample of grade II beef is D = 12.5 $\cdot 10^{-8}$ m²/s, and for semi-fatty pork D = 10.6$\cdot 10^{-8}$ m²/s.

Considering the substantial number of factors determining the process, we will replace the relationships between them with dependencies between the presented similarity criteria. To do this, we use a dimensional matrix **[33]**, which is formed using Table 4.

Table 4 Dimensional matrix of the investigated massaging process.

Parameters	ρ, kg/m³	υ, m/s	τ, H/m².kg/(m.s²)	t, s	ℓ, m	D, m²/s	β, m/s
M, kg	1		1				
L, m	-3	1	-1		1	2	1
T, s		-1	-2	1		-1	-1
Exponential coefficients	ε	δ	m	α	Θ	λ	

In the general form, the relationship between the presented parameters can be expressed as a function:

$$\beta = f(\rho, \upsilon, \tau, \ell, t, D) \quad (11)$$

Based on the dimensional matrix compiled in Table 4, the function takes the form of a power series:

$$\beta = K \cdot \tau^m \cdot \rho^\varepsilon \cdot \upsilon^\delta \cdot t^\alpha \cdot D^\lambda \cdot \ell^\Theta \quad (12)$$

Where:

K – is a constant coefficient.

The presented factor space with 6 variables and the number of dimensionless components determined by the π-theorem as 6 - 3 = 3 corresponds to the chosen similarity criteria, specifically the Sherwood, Fourier, and Euler numbers **[34]**.

We reproduce the dimensional matrix compiled in Table 3 in the following system of equations for the exponential coefficients of the mass transfer equation (12) **[35]**:

$$\begin{cases} m + \varepsilon = 0 & (13) \\ \delta - m - 3\varepsilon + \Theta + 2\lambda = 1 & (14) \\ -\delta - 2m + \alpha - \lambda = -1 & (15) \end{cases}$$

From equation (13), we obtain:

$$\varepsilon = -m \quad (16)$$

Substituting equation (16) into equation (14):

$$\delta + 2m + \Theta + 2\lambda = 1 \quad (17)$$

From the sum of equations (17) and (15):

$$\Theta + \alpha + \lambda = 0 \quad (18)$$

From equation (18):

$$\lambda = -\Theta - \alpha \quad (19)$$

Considering equations (12, 16, 19):

$$\beta = \rho^{-m} \cdot \upsilon^{\delta} \cdot t^{\alpha} \cdot \tau^{m} \cdot D^{(-\Theta-\alpha)} \cdot \ell^{\Theta} \quad (20)$$

Considering equation (20):

$$\frac{\beta \cdot \ell}{D} = \frac{\ell}{D} \cdot \left[\frac{\tau}{\rho \cdot \upsilon^2} \right]^m \cdot t^{\alpha} \cdot \upsilon^{(2m+\delta)} \cdot D^{(-\Theta-\alpha)} \cdot \ell^{\Theta} \quad (21)$$

Considering equations (21, 2):

$$Sh = Eu^m \cdot \left[\frac{\ell^2}{D \cdot t} \right]^{\Theta} \cdot \ell^{(1-\Theta)} \cdot D^{(-\alpha-1)} \cdot \upsilon^{(2m+\delta)} \cdot t^{(\alpha+\Theta)} \quad (22)$$

Considering equations (1, 22):

$$Sh = Eu^m \cdot Fo_{\partial}^{-\Theta} \cdot \left[\frac{\ell^2}{D \cdot t} \right]^{\alpha} \frac{\ell^{(1+\lambda-\alpha)}}{D} \cdot \upsilon^{(2m+\delta)} \cdot t^{\Theta)} \quad (23)$$

Considering equations (1, 23):

$$Sh = Eu^m \cdot Fo_{\partial}^{-\Theta} \cdot Fo_{\partial}^{\alpha} \cdot K \quad (24)$$

Then, the general expression for the mass transfer equation of the investigated process takes the form:

$$Sh = Eu^m \cdot \mathrm{Fo}_{\partial}^{(\alpha-\Theta)} \cdot K \quad (25)$$

$$f(K) = \frac{\ell^{(1+\lambda-\alpha)}}{D} \cdot \upsilon^{(2m+\delta)} \cdot t^{\Theta} \quad (26)$$

To obtain the initial data during the graphoanalytical analysis of the investigated process, we determined the values of the Fourier, Sherwood, and Euler numbers, and mass transfer coefficient using formulas (1, 2, 4) respectively, and experimental data obtained from the conducted research (Table 1, 3) **[36]**.

Using the data from Table 5.

Table 5 Similarity criteria values for the investigated massaging process.

Process parameter	Control	Experimental Sample No.1	Experimental Sample No.2	Experimental Sample No.3
Pork semi-finished products				
Plasticity X, cm²/g	6.75	9.45	9.06	7.74
Oil Content in the marinade, ΔC	0.664	0.664	0.664	0.664
Shear stress τ=10.26/X, MPa	1.52	1.08	1.132	1.326
Product density ρ, kg/m³	1030			
Particle size ℓ, m	0.04			
Processing time t, s	1800			
Flow velocity in the cutter bowl υ, m/s	0.578			
Diffusion coefficient D, $\times 10^{-8} m^2/s$	10.8	11.2	11.8	12.5
The mass transfer coefficient in the loading mass $\beta = \frac{\tau}{t \cdot \rho \cdot 6,81}$, m/s	0.12	0.0855	0.0897	0.105
Pork semi-finished products				
Sherwood's number is $Sh \times 10^4$	4.45	3.05	3.04	3.36
Euler's number, Eu	0.00422	0.00314	0.00329	0.00385
Fourier's number, Fo_d	0.122	0.126	0.133	0.141
Beef semi-finished products				
Plasticity X, cm²/g	6.88	7.15	6.72	7.17
Oil content in the marinade, ΔC	0.664	0.664	0.664	0.664
Shear stress τ=10.26/X, MPa	1.49	1.445	1.527	1.431
Product density ρ, kg/m³	1087			
Particle size ℓ, m	0.04			
Processing time t, s	2400			
Flow velocity in the cutter bowl υ, m/s	0.578			
Diffusion coefficient D, $\times 10^{-8} m^2/s$	8.9	9.3	9.8	10.6
The mass transfer coefficient in the loading mass $\beta = \frac{\tau}{t \cdot \rho \cdot 6,81}$, m/s	0.0838	0.0816	0.0859	0.0805
Sherwood's number Sh, $\times 10^4$	3.77	3.51	3.51	3.04
Euler's number, Eu	0.0041	0.00398	0.0042	0.00394
Fourier's number, Fo_d	0.1335	0.1395	0.147	0.159

Additionally, a method for graph-analytical assessment of power functions was applied, and a graph of the function $Sh = f(Eu)$ was constructed. This function is linear, with its graph forming an angle φ with the abscissa axis in Figures 1 and 2 **[37]**.

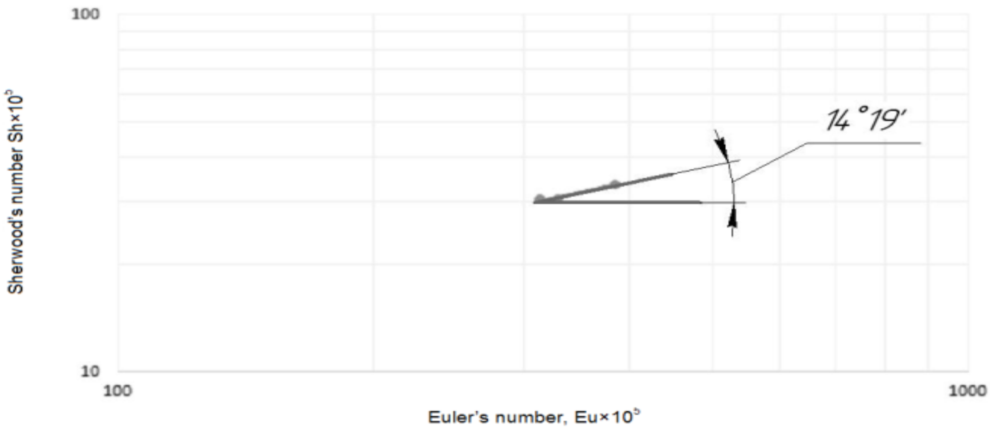

Figure 1 Graph of the function $Sh = f(Eu)$ for semi-finished pork products.

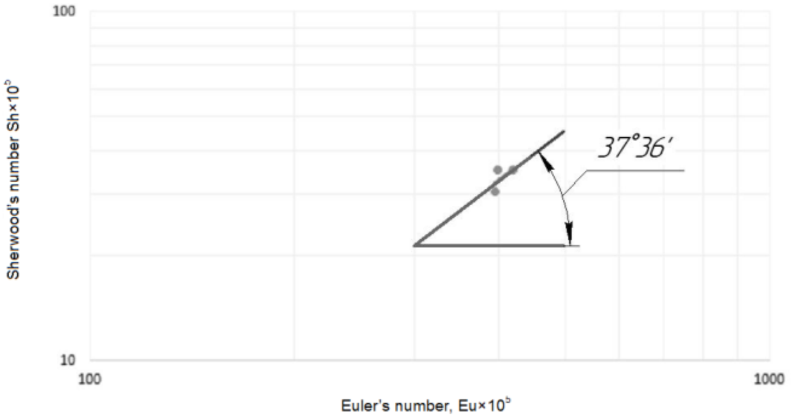

Figure 2 Graph of the function *Sh* = $_f$*(Eu)* for semi-finished beef products.

Then the value of the first power coefficient is determined.

$$m_c = tg = tg14.19° = 0.253 \quad (27)$$
$$m_я = tg\varphi = 37.36° = 0.763$$

Table 6 Calculated data for determining power coefficients.

Process parameter	Control	Experimental Sample No.1	Experimental Sample No.2	Experimental Sample No.3
Pork semi-finished products				
Dimensionless component $Fo_d^{-\Theta}\times10^5$	7.851	7.906	8.001	8.104
Dimensionless component $Fo_d^{\alpha}\times10^5$	133.324	135.579	139.445	143.745
Dimensionless component $Eu^m\times10^5$	106.766	79.442	83.237	97.405
Dimensionless component $Sh / Eu^m\times10^5$	9.642	7.122	7.015	7.451
Dimensionless component $\frac{Sh}{Eu^m \cdot Fo_\partial^{-\Theta}}\cdot10^7$	5.309	4.856	4.565	4.257
Dimensionless component $\frac{Sh}{Eu^m \cdot Fo_\partial^{-\Theta}\cdot Fo_\partial^{\alpha}}\cdot10^{11}$	398.205	358.159	327.364	296.132
$f(K)\times10^{11}$	3.715	3.582	3.400	3.209
Beef semi-finished products				
Dimensionless component $Fo_d^{-\Theta}\times10^5$	58.305	59.412	60.759	62.834
Dimensionless component $Fo_d^{\alpha}\times10^5$	1816.060	1880.241	1959.660	2084.989
Dimensionless component $Eu^m\times10^5$	312.830	303.674	320.460	300.622
Dimensionless component $Sh / Eu^m\times10^5$	0.383	0.364	0.350	0.318
Dimensionless component $\frac{Sh}{Eu^m \cdot Fo_\partial^{-\Theta}}\cdot10^7$	20.669	19.455	18.027	16.094
Dimensionless component $\frac{Sh}{Eu^m \cdot Fo_\partial^{-\Theta}\cdot Fo_\partial^{\alpha}}\cdot10^{11}$	1.138	1.035	0.920	0.772
$f(K)\times10^{11}$	1.691	1.691	1.691	1.691

Using the previous calculation method, a graph of the function $\frac{Sh}{Eu^m} = f(\mathrm{Fo}_\partial)$ was constructed using data from Table 6.

From this graph, the angle γ (Figure 3 and Figure 4) of its inclination to the abscissa axis was determined, and the value of the second power coefficient was found using the formula.

$$\Theta_c = -tg\gamma = -tg12.37° = -0.219 \quad (28)$$
$$\Theta_я = -tg\gamma = -tg23.2° = -0.428$$

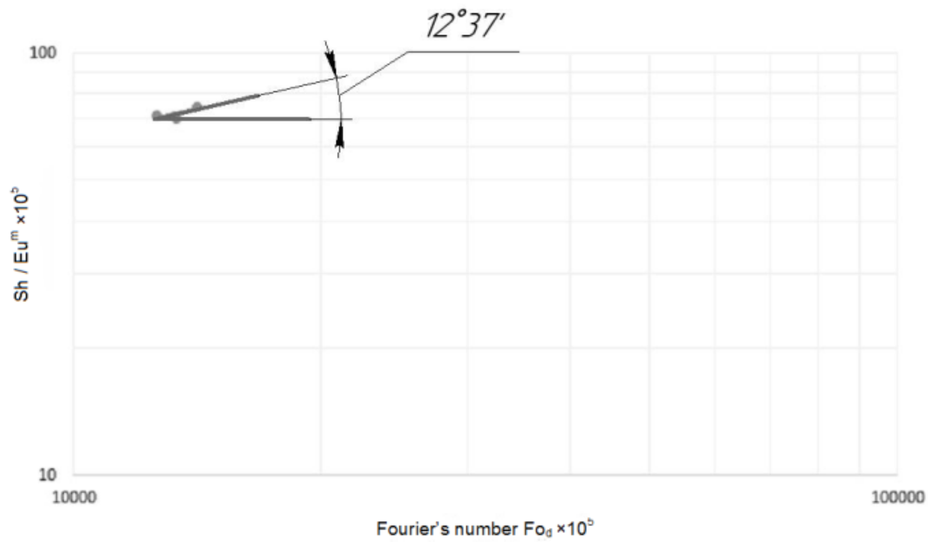

Figure 3 Graph of the function $\frac{Sh}{Eu^m} = f(\mathrm{Fo}_\partial)$ for semi-finished pork products.

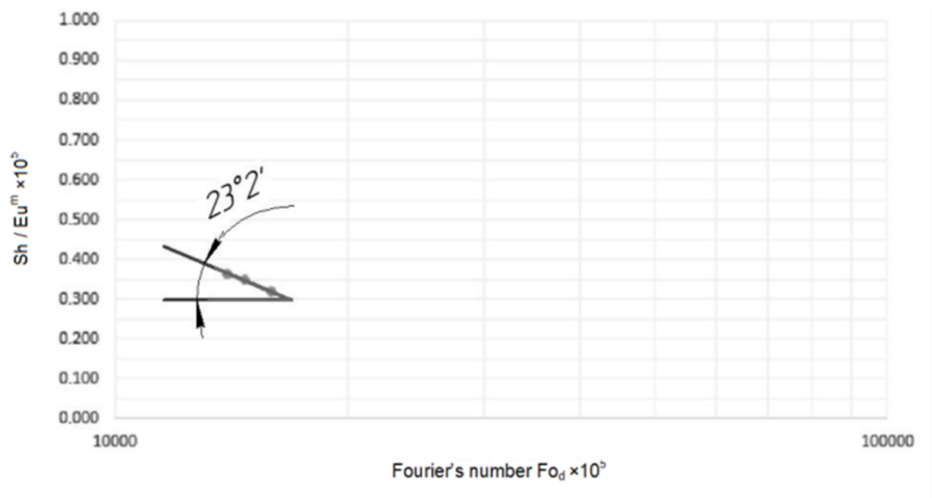

Figure 4 Graph of the function $\frac{Sh}{Eu^m} = f(\mathrm{Fo}_\partial)$ for semi-finished beef products.

Subsequently, a graph of the function was constructed $\frac{Sh}{Eu^m \cdot \mathrm{Fo}_\partial^{-\Theta}} = \mathrm{Fo}_\partial$ (Figure 5 and Figure 6) using the data from Table 6.

Figure 5 Function graph $\frac{Sh}{Eu^m \cdot \mathrm{Fo}_\partial^{-\Theta}} = f(\mathrm{Fo}_\partial)$ for semi-finished pork products.

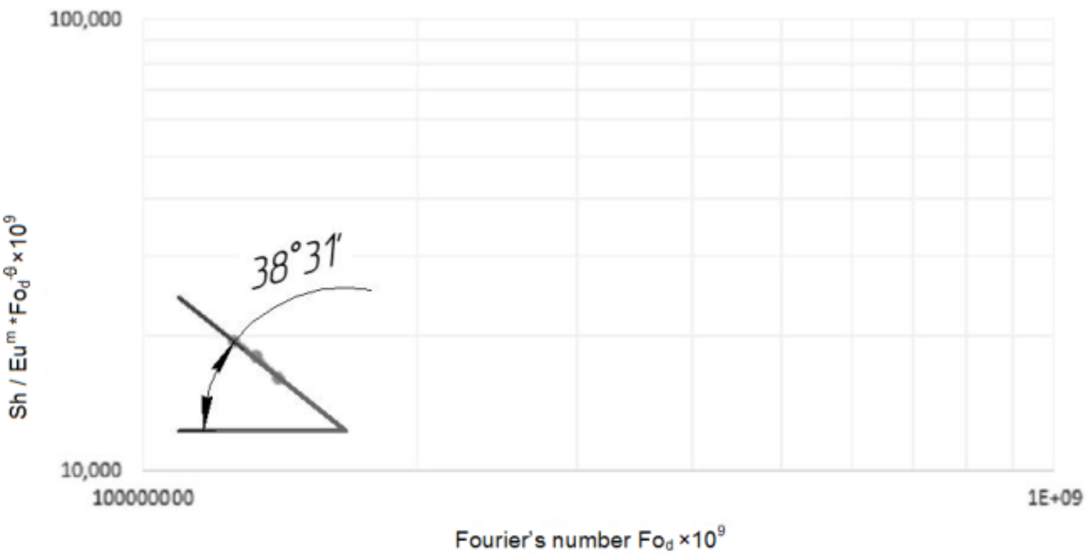

Figure 6 Function graph $\frac{Sh}{Eu^m \cdot \mathrm{Fo}_\partial^{-\Theta}} = f(\mathrm{Fo}_\partial)$ for semi-finished beef products.

From this graph, the angle γ (Figure 7 and Figure 8) of its inclination to the abscissa axis was determined, and the value of the second power coefficient was found using the formula.

$$a_c = tg\Theta_c = tg27.47° = 0.52 \quad (29)$$
$$a_я = tg\Theta_я = tg38.31° = 0.79$$

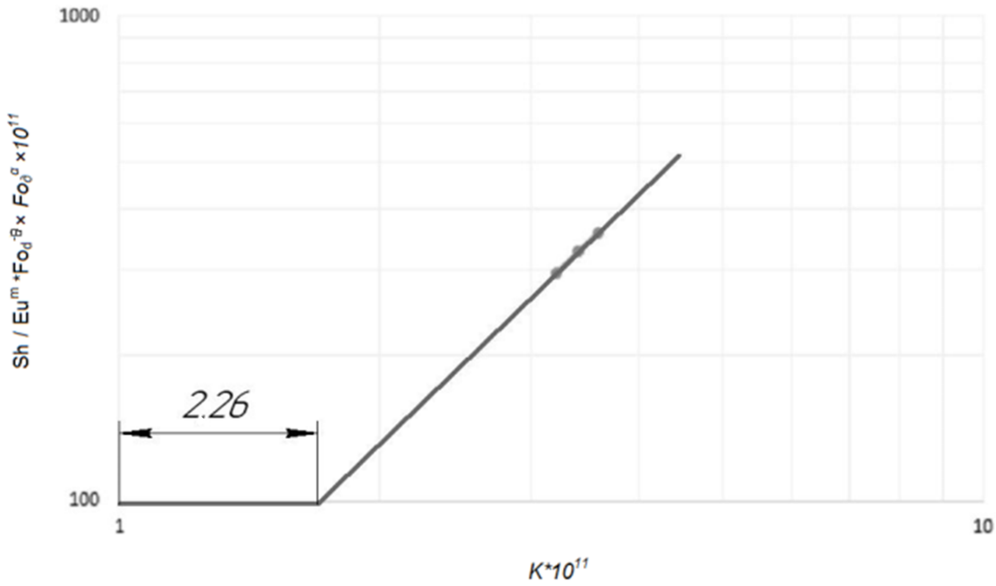

Figure 7 Function graph $\frac{Sh}{Eu^m \cdot \mathrm{Fo}_\partial^{-\Theta} \cdot \mathrm{Fo}_\partial^{\alpha}} = f(K)$ for semi-finished pork products.

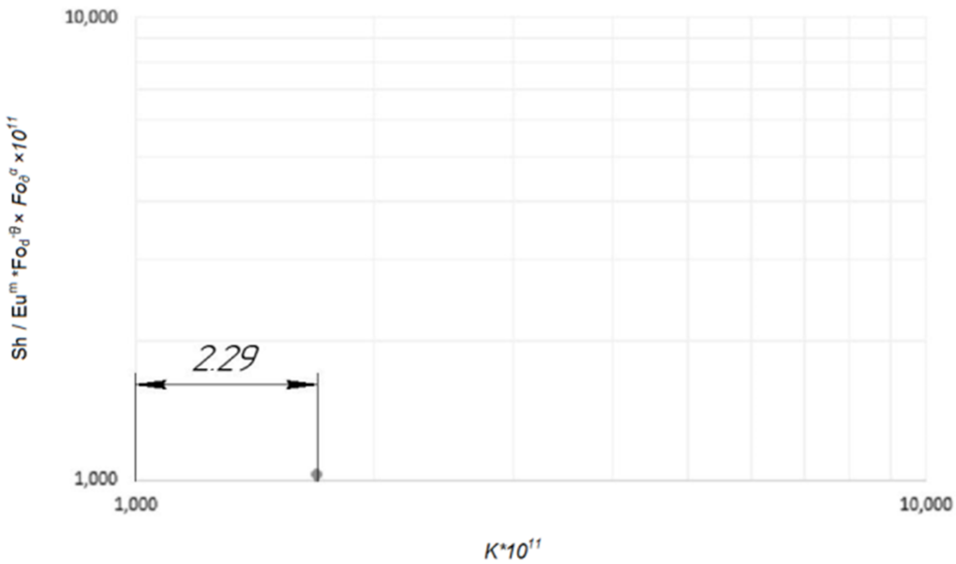

Figure 8 Function graph $\frac{Sh}{Eu^m \cdot \mathrm{Fo}_\partial^{-\Theta} \cdot \mathrm{Fo}_\partial^{\alpha}} = f(K)$ for semi-finished beef products.

Then, the sought difference was determined.

$$a_c - \Theta_c = 0.52 - (-0.219) = 0.739 \quad (30)$$

$$a_я - \Theta_c = 0.79 - (-0.428) = 1.218 \quad (31)$$

Using the data from Table 6, the process constant K was determined. In this case, the function on the left side of this equation consists of

$$f(K) = \frac{\ell^{(1+\lambda-\alpha)}}{D} \cdot \upsilon^{(2m+\delta)} \cdot t^{\Theta} \quad (32)$$

Thus, considering the obtained dependencies (28-31) – the final criterion equation of the vibrational mixing process was determined for pork ingredients (equation (33)) and beef ingredients (equation (34)) in the kneading process, which can be represented in the form of **[38]**.

$$Sh = Eu^{m_c} \cdot \mathrm{Fo}_\partial^{(\alpha_c - \Theta_c)} \cdot K_c = 2.26 \cdot Eu^{0.253} \cdot \mathrm{Fo}_\partial^{0.739} \quad (33)$$
$$Sh = Eu^{m_я} \cdot \mathrm{Fo}_\partial^{(\alpha_я - \Theta_я)} \cdot K_я = 2.29 \cdot Eu^{0.763} \cdot \mathrm{Fo}_\partial^{1.218} \quad (34)$$

The presented mass exchange equation illustrates the predominant influence in the studied kneading process of changes in the concentration of sunflower, rapeseed, or olive oil in product ΔC, on the value of the diffusion coefficient D, the size of dispersed phase particles, and the mass transfer coefficient in the load mass β. Using the derived equations (33) and (34) and the developed program, a recommended set of working regime parameters is found for the marinating operation of semi-finished pork and beef products under the conditions of the specified factors' influence. The analysis of the composed heat exchange equations allows the assessment of the dynamics of changing these parameters when altering the operational modes of the studied kneading process, respectively for pork (equation (35)) and beef (equation (36)).

$$\frac{\beta \cdot \ell}{D} = 2.26 \cdot \left[\frac{\tau}{\rho \cdot \upsilon^2}\right]^{0.253} \cdot \left[\frac{D \cdot t}{\ell^2}\right]^{0.739} \quad (35)$$
$$\frac{\beta \cdot \ell}{D} = 2.29 \cdot \left[\frac{\tau}{\rho \cdot \upsilon^2}\right]^{0.763} \cdot \left[\frac{D \cdot t}{\ell^2}\right]^{1.218} \quad (36)$$

CONCLUSION

The research results indicate that the derived mass exchange equation demonstrates a predominant influence on the studied kneading process, where changes in the concentration of sunflower, rapeseed, and olive oil in the product have a significant impact on the diffusion coefficient, size of dispersed phase particles, and mass transfer coefficient within the load mass. By using the complex equations and developed program, we determine the recommended set of operating parameters for the massaging operation in the marinating process of semi-finished products from pork and beef, considering the effects of the specified factors. Clearly, the analysis of the formulated heat exchange equations allows assessing the dynamics of these parameters as the operating conditions of the investigated massaging process change for pork and beef.

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