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Fish technology

**INFLUENCE OF ADDITION OF FAT AND ITS DISTRIBUTION
IN MINCED HERRING MEAT ON COURSE OF PROCESS
OF FREEZING**

**WPLYW DODATKU TŁUSZCZU I JEGO ROZMIESZCZENIA
W ROZDROBNIONYM MIĘSIE ŚLEDZI NA PRZEBIEG
PROCESU ZAMRAŻANIA**

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The authors analysed the influence of addition of fat and its distribution in fish minced meat on time and phases of process of freezing. The material for study was minced herring meat, frozen at the rate of 4.9 and 5.4 cm/h and sunflower oil constituting a 20-% addition. It was determined that the oil in form of external envelope that was 3 mm thick lengthened total time of freezing almost three times and also decreased freezing rate. Presently used mathematical model can be applied to analyse freezing curves because of good consistence of values calculated with the empirical ones.

INTRODUCTION

Food products, depending on their physico-chemical composition, show different susceptibility to processes of deterioration what is reflected in their different suitability to long-term storage even at reduced temperatures. Fish are among products of the fastest deterioration rate. It is a consequence of high contents of water, proteins, and lipids in their meat and the presence of non-protein nitrogen substances and carbohydrates (Sikorski 1992).

Fish are subjected to freezing both at sea and on land, in the form of full fish, carcasses, fillets, and minced meat (Gruda and Postolski 1985). Freezing of minced meat enables its utilisation for further production directly after defrosting. While processed, they are usually enriched with various technological additives intended to shape properly their nutritional values and physical and organoleptic properties (Kołakowski et al. 1977a, b; Kołakowski et al. 1978; Lachowicz et al. 1978). The additives used cause changes of physico-chemical parameters of minced meat and its thermal properties. They influence parameters of freezing and quality of product related to the speed of ice front advancement

from surface to centre and on economical effects. Scientific literature on the subject of influence of technological additives on time of freezing is not abundant. It is also difficult to find works on determination of time of fish freezing in relation to general contents of fat as well as its distribution (subcutaneous or intramuscular), dependant on their species and biological cycle.

In view of the above authors entered model testing in order to establish influence of spatial distribution of fat in minced muscle tissue of herring on effective time of freezing and its individual phases.

An assumption was made that the fat layer localised in superficial layer of the product would have bigger influence on the dynamics of this process than the same amount of fat dispersed in its whole volume.

MATERIAL AND METHODS

The material used in the present study was Baltic herring, *Clupea harengus* L. with fat content of 4.5% and water content of 76.6%. The additive was sunflower oil available in retail. Herring were caught in spring season. They were delivered to the laboratory and were subsequently frozen at -20°C in portions weighing 1.5 kg. They are glazed and stored at -22°C . In such form they were successively sampled for analyses. They were kept 24 h in a cold chamber until they reached -1°C . Then, they were skinned and minced twice on a meat grinder using a 3-mm cutting plate. Minced meat was divided into two parts. After addition of oil to one of them both parts of minced meat were mixed separately under 14 000 rpm for 2 min. It allowed exact dilution of added fat and obtaining the same comminution of both samples.

The added oil constituted 20% of the herring meat weight. The following samples were frozen:

1. Minced herring meat without addition of oil;
2. Minced herring meat with 20% addition of oil;
3. Minced herring meat without addition of oil in 3 mm envelope equal to 20% addition of this fat to minced meat;
4. Sunflower oil ¹.

Samples of meat and oil were frozen in cylindrical aluminium containers, 44 and 37.4 mm in diameter and 13 cm high. Their weights were 150 and 100 g, respectively. In order to obtain a fat layer around frozen sample, smaller container with the sample was put into container with bigger diameter and oil was poured between their walls. The layer obtained in that way was 3 mm thick.

¹ In relation to oil, term "freezing" should be taken by convention.

Containers' profiled bottoms and special construction of lid having separate embossments on their upper edges prevented mutual displacement.

Minced herring meat was put into containers by small portions layer by layer to avoid formation of aerospace.

A probe for temperature measurement was inserted into geometric centre of the sample through a hole centrally drilled in the lid of container.

Because of small stiffness of the probe (thermocouple), it was placed in the hollow space of a medical needle previously inserted through the hole in the container lid. Blind end of the needle allowed pulling the thermocouple out immediately without the need of defrosting.

Temperature record was taken automatically every 24 s by means of a Z 9-CTF recorder manufactured by Ellab Co. Samples were frozen in a cryostat by immersion from initial temperature of +5°C down to -18°C. The freezing medium was circulating ethyl alcohol at temperature of -23°C ± 0.5°C.

RESULTS AND DISCUSSION

Complexity of freezing process, and especially phase transition starting in cryoscopic point of frozen samples of fish minced meat and time-variable dynamics of the process decided that simple statistical methods could not be used for analysis of obtained freezing curves describing changes of temperature in time.

Therefore a mathematical model describing phases of the freezing process was used. These phases featured dynamic changes of temperature. The whole freezing process was divided into 3 phases:

1. Cooling from initial temperature (5°C) to the moment of cryoscopic temperature.
2. Phase transition in cryoscopic temperature.
3. Phase from cryoscopic temperature to -18°C.

In the mathematical description of dynamic model, above-mentioned three phases of process of freezing were treated as separate stages. The first and the third phases were analysed separately. It was assumed that co-ordinate of the process of freezing of above-mentioned two phases would be the spatial co-ordinate and description of dynamics would be based on the model with splitting constants².

The most general form of dependence of temperature from the other variables is:

$$\Theta = F[\Theta_p, \Theta_c, t, x, y, z]$$

where:

² Dynamic linear object with splitting constants in an object described by differential linear equations containing derivatives in relation to time and spatial co-ordinates.

Θ , sample temperature;

Θ_p , initial sample temperature;

Θ_c , temperature of cooling agent;

t , time;

x , variability caused by addition of oil;

y , parameter characterising type of material;

\underline{c} , vector characterising parameters of cooling device (overall dimensions, chambers, cooling agent, etc.).

In order to construct a model of analysed occurrences, partial differential equations describing occurrences of thermal conduction could be used, but then the model would be complex. Analytical estimation of proper coefficients would be very laborious and final effect (so-called consistence of model and experimental) would not be significantly better than for the method accepted in the paper. Equations of thermal conduction are partial differential equations of at least second order, and empirical objects are non-linear (Dreszer 1971).

Assuming homogeneity of the environment (frozen sample) and medium (cooling agent), dynamics of the process can be approximated by the dense model, where the control quantity is temperature of the cooling agent, and initial quantity—temperature of frozen sample (Douglas 1979). Effective method of approximation of dynamics of such process is presenting it in a form of serial connection of objects with dense constants³.

It was assumed that phases of cooling and wintering could be treated as dynamic linear process. These assumptions result from experiments of construction of models of real processes developed in automatics.

Form of curve of variability of sample temperature in time is typical for inertial occurrences (being characterised by particular inertia of reaction on changes of parameters of the process). In the simplest case, such occurrence is described by the following common equation:

$$T \frac{d\Theta(t)}{dt} + \Theta(t) = A(t) \quad (1)$$

with initial condition $\Theta(0) = \Theta_0$, where:

T , parameter called time constant being a measure of inertia of occurrence;

$\Theta(t)$, parameter characterising the process (e.g. sample temperature);

$A(t)$, quantity activating changes of parameter Θ (e.g. difference between temperatures of the sample and cooling agent).

³ Dynamic linear object with dense constants in an object described by differential linear equations containing derivatives in relation to time only.

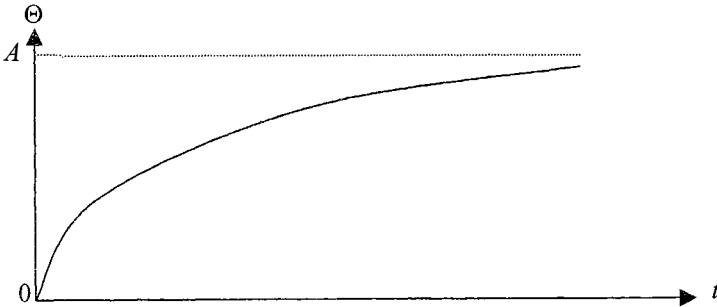
If $A(t)$ is constant, or when $A(t) = A$, solution of the equation (1) is:

$$\Theta(t) = \Theta_0 e^{-\frac{t}{T}} + A \left(1 - e^{-\frac{t}{T}} \right)$$

Because it is always possible to change the numerical scale characterising Θ , it could be set that $\Theta(0) = \Theta = 0$. Then:

$$\Theta(t) = A \left(1 - e^{-\frac{t}{T}} \right) \tag{2}$$

Course of dependence $\Theta(t)$ described by the equation (2) presents the following chart:



In the process of freezing considered in the paper, changes of temperature at the beginning of phase 1 and phase 2 proceed slowly. It is characteristic for multi-inertial objects that are described by differential equations of higher than first order. The general form of such equation is:

$$a_n \frac{d^n \Theta(t)}{dt^n} + a_{n-1} \frac{d^{n-1} \Theta(t)}{dt^{n-1}} + \dots + a_1 \frac{d\Theta(t)}{dt} + \Theta(t) = A(t) \tag{3}$$

with proper set of initial conditions.

Theory of such types of differential equations says that process described by this equation is characterised by so-called roots of characteristic equation:

$$a_n \lambda^n + a_{n-1} \lambda^{n-1} + \dots + a_1 \lambda + 1 = 0 \tag{4}$$

The number of these roots is n . General form of solution in case, when there are no multiple roots, and $A(t) = A$ is constant, is as follows:

$$\Theta(t) = A \sum_{i=1}^n c_i e^{\lambda_i t}$$

where:

λ_i , i -th root of equation (4);

c_i , coefficient calculated from initial values.

Practice shows that for typical inertial processes all values of λ_i are real and negative. Moreover, where exact calculation of values of λ_i is not particularly important; many authors tend to simplify the process by showing it as connection of serially identical monoinertial blocks. Thanks to it, dimensionality of the problem is reduced—instead of “ n ” different parameters, only one is estimated. It is a measure of inertia of the whole process.

Such process is described by the following set of differential equations:

$$\begin{aligned} T \frac{d\Theta_1(t)}{dt} + \Theta_1(t) &= A \\ T \frac{d\Theta_2(t)}{dt} + \Theta_2(t) &= \Theta_1(t) \\ T \frac{d\Theta_n(t)}{dt} + \Theta_n(t) &= \Theta_{n-1}(t) \end{aligned} \quad (5)$$

with initial conditions $\Theta_i(0) = 0$, ($i = 1, \dots, n$).

After solving equations (5), the following equation is obtained (Douglas 1979):

$$\Theta_n(t) = \Theta(t) \left\{ 1 - e^{-\frac{t}{T}} \left[1 + \frac{t}{T} + \frac{1}{2} \left(\frac{t}{T} \right)^2 + \dots + \frac{1}{(n+1)} \left(\frac{t}{T} \right)^{n-1} \right] \right\} \quad (6)$$

After subsequent transformations and with accepted assumptions, the following relation arises:

$$\Theta(t) = A \left\{ 1 - e^{-\frac{t}{T_i}} \left[1 + \frac{t}{T_i} + \frac{1}{2} \left(\frac{t}{T_i} \right)^2 \right] \right\} \quad (7)$$

where:

i , 1, 3;

$\Theta(t)$, difference between sample temperature frozen at time t and the initial sample temperature measured in the geometrical centre;

A , difference between temperature of the cooling agent and the initial sample temperature measured in the geometrical centre;

\bar{T}_i , time constant of the i -th phase of the process (estimate);

t , time.

For the cooling phase (from 5°C to the cryoscopic temperature), it was assumed such forcing, as if temperature of the cooling agent was -2°C, and for wintering phase it was -23°C, or the actual temperature of the cooling agent.

If we accepted smaller forcing for the first phase, cryoscopic temperature would not be reached, as it results from the equation (7). Then, if the forcing was greater, the curve would reach the cryoscopic temperature too fast.

Time of freezing are characterised by three phases, so the whole process can be described by three time constants:

\bar{T}_1 , time constant of cooling (there is directly proportional dependence between T_1 and the time of reach of the beginning of the phase transition);

T_2 , time constant of the phase transition (area of the cryoscopic temperature),

\bar{T}_3 , time constant of wintering (it is directly proportional to the time of transition from the cryoscopic temperature to -18°C).

Time constants \bar{T}_1 and \bar{T}_3 are calculated on the basis of statistical analysis consists in use of relations in the equation (7). It consists in calculation of the constant \bar{T}_i ($i = 1; 3$) for every sample in subsequent moments. This constant is treated as random variable with normal distribution in consideration of large number of features influencing the results (inaccuracies of readings of time and temperature).

Estimate \bar{T}_1 is obtained in the following way: single measure of temperature Θ in time t is treated as source of single measure of time constant \bar{T}_i .

\bar{T}_i is calculated by solving the equation (7). A set of values \bar{T}_i is therefore obtained for various moments t . It is treated as the set of measures of time constant and on its basis (assuming normal distribution) \bar{T}_i and other parameters (e.g. standard deviation, α , β) are calculated.

Time constant T_2 is calculated directly from freezing curves and is expressed as an average length of lasting of cryoscopic temperature. In order to calculate time constants \bar{T}_1 and \bar{T}_3 from freezing curves, measuring point was taken every 24 seconds.

From the equation (7), assumed in initial and final point of every phase and accepted models for every phase, relations between time constants \bar{T}_1 and \bar{T}_3 and times of lasting of first and last phase were as follows:

$$\tau_1 = \alpha \bar{T}_1$$

$$\tau_2 = T_2$$

$$\tau_3 = \beta \bar{T}_3$$

Values α , β result from the solution of equation (7) and are different for every sample. In order to estimate α , β , equation (7) was transformed into the following form:

$$\Theta = A \left[1 - e^{-x_i} \left(1 + x_i + \frac{1}{2} x_i^2 \right) \right]$$

For given A and Θ .

A value $\frac{t}{\bar{T}_i} = x_i$ is calculated.

Calculating numerically values x_i from the equation, $x_1 = \alpha$ and $x_3 = \beta$ are obtained.

Time of lasting of the whole process is as follows:

$$(\tau) = \tau_1 + \tau_2 + \tau_3$$

$$\tau = \alpha \overline{T_1} + T_2 + \beta \overline{T_3}$$

Values of time intervals τ_1 and τ_3 and the whole time of freezing presented on Figs. 1–4 are the graphical presentation of coincidence of obtained model with empirical values.

Obtained on the basis of the model times of lasting of particular phases of the process of freezing presented in the form of intervals present the scatter of parameters around the value of the estimate.

For the time of cooling τ_1 the following was accepted: $\Delta\tau_1 = \alpha S_1 + 24s$

For the time of wintering τ_3 the following was accepted: $\Delta\tau_3 = \beta S_3 + 24s$

For the whole time τ , on the basis of propagation of error, the following was accepted: $\Delta\tau = \alpha S_1 + \beta S_3 + 24s$

where $S_i (i = 1;3)$ = standard deviation;

$24s$ = accepted error of time quantisation of the recording device.

Differences of average values of time constants were analysed for statistical significance by means of the Cochran-Cox test (Table 1). Significance level was $\varepsilon = 0.1$, which means that probability of rejection of true hypothesis was 0.1. Such value of significance level was accepted because with less values, e.g. $\varepsilon = 0.05$, too large number of experiments showed independence between time constants and addition of oil.

Presented above mathematical model of the process of freezing allows to describe the dynamics of temperature changes of the process of freezing in relation to time with good accuracy. It also allowed using it in purposes of detailed analysis of experimental results.

On the basis of obtained results the authors stated that addition of fat and its spatial distribution influenced the effective time of freezing of minced herring meat as well as particular phases of the process in relation to time.

Obtained results were statistically analysed in order to check if there are significant differences between them (Table 1). On its basis the authors stated that addition of fat and particularly its spatial distribution significantly influenced both effective time of freezing of the minced herring meat and phases of the process. Also influence of this addition on time of freezing depended from the freezing rate.

20% addition of oil to the minced meat frozen in the rate of $5.4 \text{ cm}\cdot\text{h}^{-1}$ (1.8 cm thick) and $4.9 \text{ cm}\cdot\text{h}^{-1}$ (2.2 cm thick) in the medium with constant temperature of -23°C extended time of freezing for 6.5 and 12 percentage point, respectively. Therefore at not much slower (about $0.5 \text{ cm}\cdot\text{h}^{-1}$) freezing rate the same addition of fat caused significantly bigger extension of time of freezing.

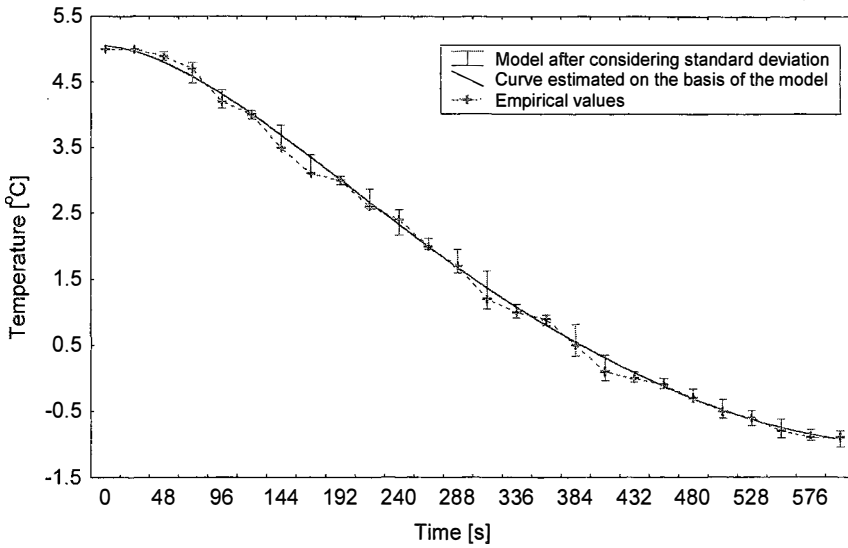


Fig. 1. Changes of temperature of minced herring meat without addition of oil in the cooling phase, $r = 18.7$ mm

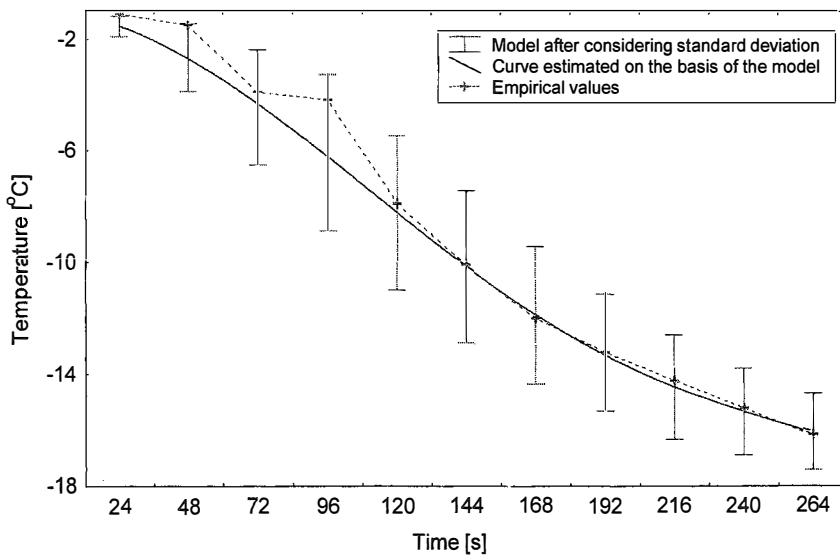


Fig. 2. Changes of temperature of minced herring meat without addition of oil in the wintering phase, $r = 18.7$ mm

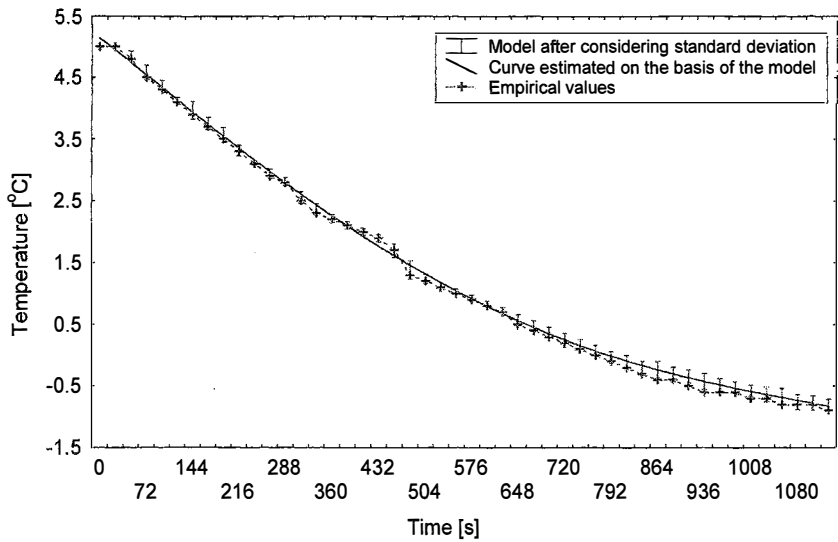


Fig. 3. Changes of temperature of minced herring meat in the cooling phase, $r = 18.7$ mm with 3 mm envelope of oil

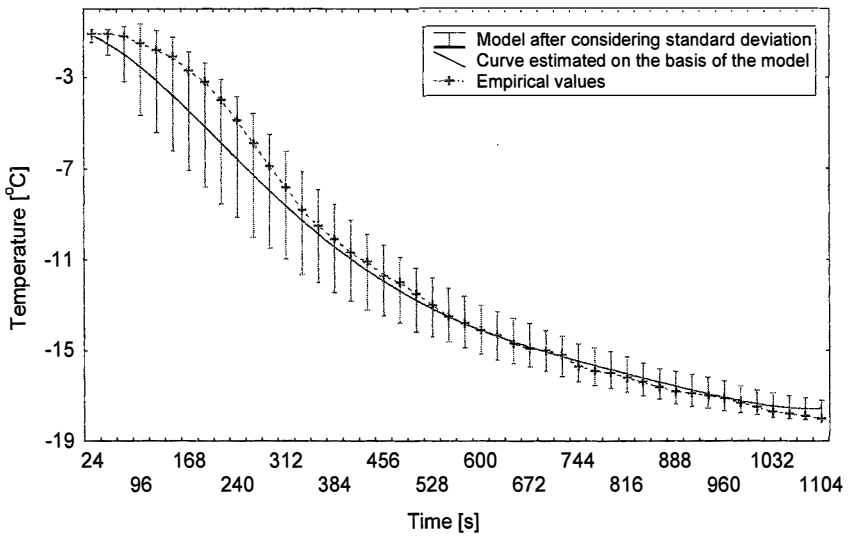


Fig. 4. Changes of temperature of minced herring meat in the wintering phase, $r = 18.7$ mm with 3 mm envelope of oil

Table 1

Results of significance test for time constants \bar{T}_1 , T_2 , and T_3 on significance of differences of time of freezing of minced herring meat in relation to addition of oil, its spatial distribution and sample thickness

		Minced meat + 20% oil $r = 22.0$			Minced meat + 20% oil $r = 18.7$			Minced meat + env.** $r = 18.7$			Minced meat + 20% oil + env. $r = 18.7$		
		\bar{T}_1	T_2	\bar{T}_3	\bar{T}_1	T_2	\bar{T}_3	\bar{T}_1	T_2	\bar{T}_3	\bar{T}_1	T_2	\bar{T}_3
Minced meat $r^* = 22.0$	\bar{T}_1	+						+					
	T_2		+						+				
	\bar{T}_3			+						+			
Minced meat $r = 18.7$	\bar{T}_1				+			+			+		
	T_2					+			+			+	
	\bar{T}_3						-			+			+

+, based on the Cochran-Cox rejection of hypothesis about equality of means;

-, on the basis of the Cochran-Cox lack of basis for rejection of hypothesis about equality of means;

*, thickness of frozen samples in mm equal to the container's radius;

**, freezing with 3 mm thick envelope of oil around the sample.

Extension of effective time of samples freezing at the rate of $5.4 \text{ cm}\cdot\text{h}^{-1}$ was caused by extension of all three phases. Freezing with the rate of $4.9 \text{ cm}\cdot\text{h}^{-1}$ extended two last phases of the process and shortened the cooling phase to the cryoscopic temperature (Table 2).

Change of freezing rate caused that the same addition of fat did not have the same influence on time of lasting of particular phases of the whole process. It may result from different thermal properties of oil in various temperature intervals. In Table 2, duration times of phases 1, 2, and 3 for oil were shown (dividing into phases in case of fat is not formally correct, but it visualises differences in dynamics of changes of temperature in comparison with minced meat). It can be seen that oil cools more efficiently when it remains in liquid state. Cooling it to the temperature of -1°C was four times faster than it was for minced meat (Fig. 5). Further cooling of solidified fat to the temperature of -18°C required four times longer time. It explains extension of two last phases, and particularly wintering phase of minced meat with addition of oil.

Decreased thickness of minced meat or its high thermal conductivity has impact on decrease of time of freezing. However, time of freezing depends in higher degree on the coefficient of heat exchange than on thermal conductivity. Influence of thermal conductivity on extension of time of freezing is stronger for thicker product or when this conductivity decreases. But it is the strongest when these both factors exist simultaneously.

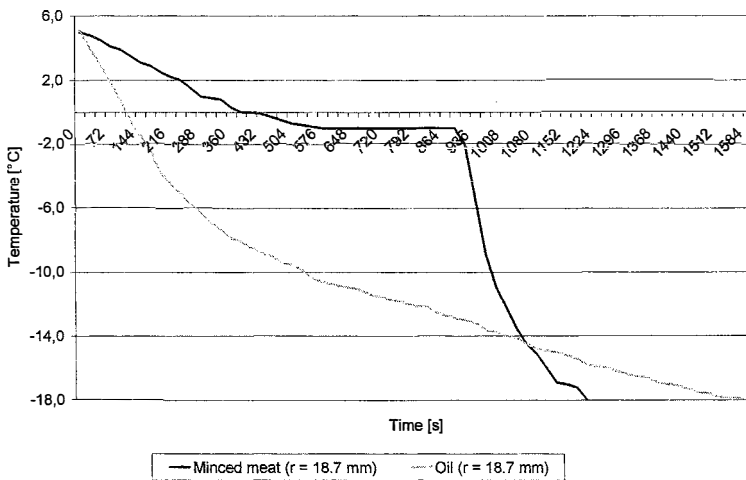


Fig. 5. Course of the process of freezing of minced meat and cooling of sunflower oil

Table 2

Results of estimation of time constants and duration of particular phases of the process of sample freezing

Type of sample	\bar{T}_1 [s]	α	n_1	s_1	T_2 [s]	\bar{T}_3 [s]	β	n_3	s_3	τ_1 [min]	τ_{1rz} [min]	$\Delta\tau_1$ [min]	τ_2 [min]	τ_3 [min]	τ_{3rz} [min]	$\Delta\tau_3$ [min]	τ [min]	τ_{rz} [min]	$\Delta\tau$ [min]
Minced meat $r^* = 18.7$	94.2	5.9	22	7.9	4.9	57.6	6.0	10	11.1	9.4	9.5	1.2	4.9	5.8	5.7	1.5	19.9	21.0 (5.4)	2.3
Minced meat + 20% oil $r = 18.7$	105.2	5.9	25	9.6	5.0	63.5	5.6	14	13.1	10.3	9.3	1.1	5.0	5.9	5.9	1.6	21.2	22.0 (5.1)	2.6
Minced meat + env.** $r = 18.7$	155.0	7.2	45	24.7	21.4	152.6	7.5	46	21.9	18.6	18.6	3.4	21.4	19.1	18.7	3.1	59.1	58.7 (1.8)	6.1
Minced meat $r = 22.0$	131.1	6.5	33	13.0	6.4	73.1	6.3	16	8.7	14.2	13.5	1.8	6.4	7.7	7.6	1.3	28.3	27.5 (4.9)	2.7
Minced meat + 20% oil $r = 22.0$	122.6	6.3	31	13.8	7.2	89.7	7.3	21	18.0	12.9	12.9	1.8	7.2	10.9	8.9	2.6	31.0	29.0 (4.3)	4.0
Minced meat + 20% oil + env. $r = 18.7$	154.1	6.8	43	25.5	19.9	154.7	8.0	50	24.8	17.5	17.8	3.3	19.9	20.6	20.8	3.7	58.0	58.8 (1.8)	6.6
Oil $r = 18.7$	196.0	—	—	—	—	—	—	—	—	—	2.0	—	0.2	—	24.4	—	—	26.5 (4.1)	—
Oil $r = 22.0$	265.9	—	—	—	—	—	—	—	—	—	2.4	—	0.4	—	33.9	—	—	36.7 (3.6)	—

*, thickness of frozen samples in mm equal to the container's radius;

**, freezing with 3 mm thick envelope of oil around the sample;

in the column τ_{rz} freezing rate was given in italics in brackets.

It should be stated that it is the reason why addition of oil extended time of freezing of minced meat in the container of larger diameter far more than in the container of smaller diameter in spite of the fact that difference in freezing rates was only $0.5 \text{ cm}\cdot\text{h}^{-1}$.

Interpretation of obtained results is not easy (Stodolnik and Knasiak 1981; Zarzycki 1982). It appears that influence of addition of oil on time of freezing of minced fish meat depends in high degree on fish species. Reduction of the freezing rate from 7.6 to $2 \text{ cm}\cdot\text{h}^{-1}$ caused decrease of time of freezing of cod minced meat, while in case of herring minced meat these relations were reverse (Stodolnik and Knasiak 1981; Zarzycki 1982).

In the present work, fat in the form of 3-mm thick external envelope, extended total time of freezing of minced herring meat almost three times, regardless of the fact, whether the meat contained addition of oil, or not (Table 2). Freezing rate decreased in both cases from 5.4 to $1.8 \text{ cm}\cdot\text{h}^{-1}$ and the biggest, almost quadruple, slowing down, referred to the time of freezing of minced meat without addition of fat, was observed for the phase transition in the cryoscopic temperature and after crossing it. Decrease of freezing rate of minced meat with addition of oil to $1.8 \text{ cm}\cdot\text{h}^{-1}$ by creation of external oil envelope resulted in decrease of time of cooling and time of phase transition of minced herring meat without addition of oil frozen at the same rate.

Comparing these three phases of freezing of minced herring meat without and with addition of oil in the system where thermal flux passes through the layer of fat being around the frozen sample, it was stated that oil added to the minced meat resulted in shortening of cooling phase and phase transition. However, considerable extension of time of wintering resulted in extension of total time of freezing for the addition of oil.

It is evident for the present study that spatial distribution of fat in minced meat is very important. It is possible that type of fat added and its physical features (mostly state of aggregation) have significant impact on the process, but it requires further research.

Obtained results have a practical aspect and they could be referred to freezing of every kind of minced meat and meat products that contain fat or it is added in a technological process. In both cases its spatial distribution can be diversified. Fat accumulated in surface layer will extend time of freezing significantly. It can refer to every kind of products that are first fried and then frozen. Surface layer dripped with oil increases thermal resistance, particularly after solidification. It results in extension of time of freezing. Similar occurrence can exist during freezing of meat of slaughter animals and poultry, containing layer of subcutaneous fat. Extension of time of freezing caused by presence of fat in raw materials and products results in higher energy consumption and increase of costs.

Analysis of obtained results confirms and visualises the fact that change of even one of physical parameters characterising frozen raw material influences the course and effective time of the process. Therefore it is obvious that mathematical equations used for theo-

retical calculation of time of food freezing can be applied only to particular type of material, for which they were developed.

The mathematical model applied in this work, consisting in calculation of time constants \bar{T}_1 and \bar{T}_3 , characterising the course of the process of freezing shows good consistency of course of changes of temperatures calculated using the equation with empirical values. Presented curves show that temperatures are contained in the area estimated by standard deviation (Figs. 1–4). Model and empirical curves presenting phases of cooling and wintering of minced meat samples without addition of fat ($r = 18.7$ mm) and minced meat ($r = 18.7$ mm) with 3 mm oil envelope run within the limits estimated by the standard deviation.

In case of cooling phase (Figs. 1, 3), empirical curves differed from the model ones in a very small degree (about 0.1 to 0.2 percentage points).

The curve illustrating wintering phase of sample of minced herring meat without addition of oil was deviated from the model curve in a very small degree in the upper area of the chart, but it did not exceed the limits of standard deviation. Similar situation was observed in case of sample of minced meat with 3-mm envelope of oil.

CONCLUSIONS

1. 20% addition of oil to minced herring meat extends effective time of freezing.
2. Influence of 20% addition of oil to minced herring meat on effective time of freezing depends on the freezing rate. Smaller freezing rate ($1.8 \text{ cm}\cdot\text{h}^{-1}$) causes that influence of addition of oil on extension of total time of freezing is bigger than in higher freezing rate ($5.4 \text{ cm}\cdot\text{h}^{-1}$).
3. Spatial distribution of fat in herring minced meat has crucial influence on time of freezing. Existence of fat in the surface layer of the minced meat extends time of freezing several times more than the same quantity in the whole volume of minced meat.
4. Used mathematical model may be applied for analysis of freezing curves of fish materials because it shows good consistency of calculated values with the empirical ones.

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WPLYW DODATKU TŁUSZCZU I JEGO ROZMIESZCZENIA W ROZDROBNIONYM
MIĘSIE ŚLEDZI NA PRZEBIEG PROCESU ZAMRAŻANIA

STRESZCZENIE

W pracy analizowano wpływ dodatku tłuszczu i jego rozmieszczenia w farszu rybnym na czas oraz fazy procesu zamrażania. Do badań zastosowano rozdrobnione mięso śledzi z dodatkiem oleju słonecznikowego w postaci powierzchniowej warstwy lub zdyspergowanej, które zamrażano dwoma różnymi prędkościami ($4,9$ i $5,4$ $\text{cm}\cdot\text{h}^{-1}$) w cylindrycznych aluminiowych pojemnikach. Medium zamrażające stanowił cyrkulujący alkohol etylowy o temperaturze -23°C .

Złożoność procesu zamrażania oraz zróżnicowana dynamika zmiany temperatury układu w funkcji czasu sprawiły, że do analizy tych zmian nie mogły znaleźć zastosowania proste metody statystyczne. W związku z tym skonstruowano model matematyczny umożliwiający opis faz zamrażania, w których występowała dynamiczna zmiana temperatury w funkcji czasu. Przyjęto, że współrzędną procesu zamrażania będzie współrzędna przestrzenna, a opis dynamiki oparty zostanie o model o stałych rozłożonych opisanych równaniami różniczkowymi liniowymi zawierającymi pochodne względem czasu i względem współrzędnych przestrzennych. Istotność różnic wyznaczonych stałych czasowych zweryfikowano stosując test Cochran-Coxa, przyjmując poziom ufności $\varepsilon = 0,1$.

Stwierdzono, że olej w postaci 3 mm otoczki wydłużał całkowity czas zamrażania rozdrobnionego mięsa śledzi prawie trzykrotnie, niezależnie od tego, czy mięso zawierało dodatek oleju w formie zdyspergowanej czy też nie i powodował zmniejszenie szybkości zamrażania z $5,4$ do $1,8$ $\text{cm}\cdot\text{h}^{-1}$. Dodatek 20% oleju do całej objętości farszu wydłużał efektywny czas zamrażania o kolejne 6% gdy grubość prób zwiększono z $18,7$ do $22,0$ mm.

Zastosowany w pracy model matematyczny może znaleźć zastosowanie do analizy krzywych zamrażania farszów rybnych ze względu na dobrą zgodność wartości wyliczonych z rzeczywistości.

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