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STUDY OF THE PROCESS OF THE FROZEN RAW BEEF DEFROSTING WITH ITS SIMULTANEOUS MASSAGING IN INDUSTRIAL CONDITIONS

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Abstract
Many meat processing enterprises use the frozen raw meat. Its defrosting and thawing is a crucial technological operation that fundamentally affects the quality of food products. The experience and knowledge obtained directly in the workshop in the process of thawing the raw materials and their using to obtain a specific finished product are of great importance. Defrosting and thawing of the frozen beef meat, as one of the stages of raw meat processing, still remains a challenging process in industrial food production. The importance of this process is constantly increasing due to the growing volumes of frozen raw materials processed in food enterprises. Scientific research shows that one of the most efficient methods of defrosting and thawing is the process of meat thawing with saturated water steam under vacuum. When applying the steam the raw materials is heated at its least and minimal losses are observed, while the duration of the process is significantly reduced. This work examines the process of beef meat defrosting and thawing with simultaneous shaking and crumpling the frozen mass, which can be called as massaging of raw materials. As studies have shown, this method of thawing makes it possible to reduce losses down to almost zero and obtain raw materials with good structural characteristics for the production of a finished product with a wide range of consumer properties. The obtained experimental curves of changes in the mass and temperature of raw materials make it possible to analyze the kinetics of heat transfer and mass transfer processes at the macro- and micro levels of the food system, which serve as the basis for modeling and controlling the technological process. This study presents the results of conventional defrosting and thawing of the raw meat but combined with massaging. Studies of the parameters of processing modes have shown that the proposed program makes it possible to use efficiently the design and technological features of the defroster-massager in order to obtain the raw beef for the production of high-quality food products. The results of experimental studies and their analysis allow making conclusion about the prospects of applying this process for the other types of raw meat materials before the main technological processing of raw materials.

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Introduction

The freezing method plays a quite significant role in preserving the quality of highly-perishable food, including meat and meat products [1,2]. The freezing as the storage method is an important way of maintaining the nutritional value and organoleptic properties of meat and meat products during its processing, storage and transportation, and it's therefore widely used in the meat industry and their cold supply chains [3,4,5].

Currently, the overwhelming number of meat processing enterprises run on frozen raw materials, approximately 70% of which is frozen meat (in the form of blocks and boneless meat cuts) [6]. On the one hand, it happens due to the shortage of chilled raw materials for the production of high-quality products. On the other hand, the frozen raw materials allow the enterprise to run in a stable pace.

However, storing the frozen meat has its own "disadvantage" — the process of defrosting and thawing is necessary for the subsequent processing of the meat [7]. In this regard, thawing of raw meat is becoming increasingly important as a technological process that affects the quality of the finished product due to inevitable physical and chemical changes during its defrosting [8].

The use of frozen raw meat in various technological processes implies its thawing in such a way as to get as close as possible to the quality of the raw material before thawing (chilled state) [9,10]. In practice, this is quite difficult to do, especially since long-term storage causes changes in the color of meat, intramuscular composition of fatty acids, oxidation of lipids and proteins, as well as moisture loss during defrosting [11].

In addition, as a rule, the initial characteristics of raw meat and freezing regimes when it arrives at a processing plant from various suppliers are unknown. Thus, a number of works provide research data on the quality indicators of beef under the influence of the freezing-thawing process, depending on various characteristics of muscle fibers [3] and characteristics of cattle breeds [12]. In this regard, the experience and knowledge gained directly in production in the process of defrosting and thawing raw materials and using them to obtain a specific finished product has great practical importance.

The scale of qualitative changes in meat during its thawing depends on many factors [7], the main ones are the defrosting and thawing methods [13], duration (speed) [14] and temperature conditions of the process [15]. In this case, it is necessary to create conditions that ensure the most complete recovery of the original properties (characteristics) of the product. To do this, at a minimum, it is necessary to limit overheating of the product surface and loss of moisture, which causes the significant losses in the meat quality due to undesirable physical, biochemical and microbiological changes. Therefore, to improve the quality of defrosted and thawed meat, it is important to apply appropriate thawing methods [9].

According to the method of energy supply, defrosting processes can be divided into two large groups [1,6]. The first is classical methods based on the supply of heat to the surface of the product due to a temperature difference. This method uses warm air, water irrigation or the immersion of the frozen mass in a liquid medium [1,9]. This method is quite cheap and easy to use, but it has a range of significant disadvantages. The most modern defrosting methods of this group are: defrosting of a frozen mass in a water bath [14], exposure to the condensing saturated water steam under vacuum or vice versa at the elevated pressure [16], applying of infrasound or ultrasound [17,18,19] using ultra-high pressure, etc. [20].

The second method is the method of supplying energy through the use of physical fields: an alternating electric field [21], an electromagnetic field of a certain frequency (high-frequency and ultra-high-frequency heating, microwave radiation, infrared heating) [22,23,24].

The above specified literature sources outline the advantages and disadvantages of these defrosting and thawing methods, their effect on the quality indicators of meat and other food products, as well as the results of their comparative analysis with each other and with traditional the methods. For example, in [25] the effect of various defrosting methods using physical fields and traditional methods on frozen meat was studied. The authors, based on an analysis of the published data and the results of their own research, concluded that defrosting and thawing methods in a physical field reduce losses and preserve the color and texture of the thawed meat. In comparison to the meat samples defrosted and thawed at room temperature, the losses in pork, beef and lamb were approximately 43%, 45% and 43% lower respectively when ultrasound was used. At the same time, the oxidation of proteins and lipids in meat decreases and the content of bound and immobilized water within increases.

One of the ways to improve the defrosting process is the combined application of methods from the first and second groups [26,27,28] or their combination with other physical processes. For example, it's possible to modify the vacuum-steam method of meat thawing combining the initial stage of freeze-drying or the new vacuum-sublimation-rehydration method of thawing [29,30] with gamma irradiation for frozen beef in vacuum packaging and its subsequent thawing [31], or combining of the frozen meat exposure to a low-voltage electrostatic field together with high-moisture way of thawing of pork steaks [23].

Promising defrosting option, successfully implemented in the meat processing plants, is thawing the frozen block, lump or ground raw materials in a saturated steam environment at the reduced pressure [6,33]. Analysis of existing domestic methods of defrosting meat by the Russian [34,35] and foreign researchers have shown that it has a number of significant advantages compared to other methods [29,36,37]. For example, the duration of defrosting is reduced by 30–50% compared to the "air showering" method, and vacuum defrosters occupy way bless space compared to the air blowing chambers or industrial HF and UHF ovens, which are also more energy-consuming and require high-potential energy. At the same time, the vacuum environment has a beneficial effect on the sanitary condition of raw materials as it prevents the spread of bacterial contamination [33].

The additional positive effect can be achieved by combining the process of defrosting and thawing of raw meat with massaging [6,34]. The massaging of the raw materials ensures uniform heating, improves its quality, prevents overheating, and reduces losses. At the same time, thawing and salting raw meat in a vacuum increases protein hydration, water-holding capacity and moisture absorption of muscle tissue, which prevents the loss of meat juice [34,35]. Thus, massaging simultaneously with defrosting the raw materials in vacuum defroster-massagers is an efficient and increasingly popular method.

In the scientific works of the Russian authors devoted to the defrosting of food raw materials, the main principles of the process are shown [38,39,40] and rational modes of its implementation are proposed depending on the methods of frozen meat defrosting [41,42,43].

The analysis of data sources has shown that modern methods of defrosting and thawing meat and their technical implementation are quite well developed, and therefore the main purpose is not to find the new processing methods, but to select and define on the scientific base selection the rational modes, taking into account the characteristics of raw meat and the "history of the meat freezing". Regardless of the defrosting method, the main technological parameters of the process are the ambient temperature and duration of the process. The higher is the coolant temperature, the faster is the defrosting process and the higher the quality of the product. But from the certain threshold these two parameters conflict with the quality of raw meat. High temperature leads to denaturation of the surface layers of the product, and increasing the duration increases the percentage of losses due to the dripping of meat juice.

The search for the rational processing parameters that allow obtaining the raw materials with the required properties is a sophisticated task consisting of optimizing the thermodynamic characteristics of the coolant and the physicochemical properties of the exposed meat. Its solution is complicated by the fact that the freezing regimes for raw materials are usually unknown and it is not always possible to link these two processes into a single thermodynamic chain that guarantees the required quality of raw materials. In addition, it is necessary to take into account that thawing is an irreversible process in relation to freezing (this fact is confirmed by the nature of the curves of these processes and their different rates of occurrence [44]). The humidity of the coolant (air, steam, air-steam environment) also plays a big role. For example, defrosting in water leads to washing off the protein substances and disruption of the structure of the surface layers, while air stream forms a surface dry crust and inhibits the heat transfer process.

The peculiar feature of this study is that the process of defrosting and thawing of the raw meat by the steam vacuum method is combined with its massaging. This combined method was studied in an industrial environment at a meat processing plant according to a predetermined program. The purpose of the study of the frozen meat block behavior during its technological processing in a rotary-type mechanism was to determine the efficiency of the proposed program for this type of meat raw material and the effect of the defrosting and thawing process modes on its tested parameters.

Objects and methods

The frozen blocks of beef of the 1st quality grade weighing from 8 to 15 kg were selected as the object of research. The process of vacuum defrosting of raw meat was studied in a defroster-massager of the brand *ScanMidiTRl 10* from the company *GEA*, which is used in a number of Russian meat processing plants (Figure 1). The key features of this device are as follows:

- cylindrical drum (working volume — 10 m^3, internal diameter — 2 m, opening size of the hatch for loading and discharge the of raw materials — 0.9 m) with a volume filling degree of 66%;
- hydraulical tilting of the drum in both directions and axial mixing of the raw materials for its massaging or tumbling due to 5 asymmetrical blades and a "smart" blade at the bottom of the drum;
- to create the necessary defrosting and thawing parameters the device is equipped with systems for supplying the saturated water steam, for creating a vacuum and for adding the curing ingredients.
- this piece of machinery is equipped with the control panel with color touch screen from GEA, which allows creating and saving the variety of work programs;
- the temperature of the coolant and processed raw materials is controlled using built-in factory temperature sensors, and the control panel allows controlling and adjust the operating parameters of the program;
- the availability of precision strain gauges ensures precise control of the raw materials mass and its change during processing.

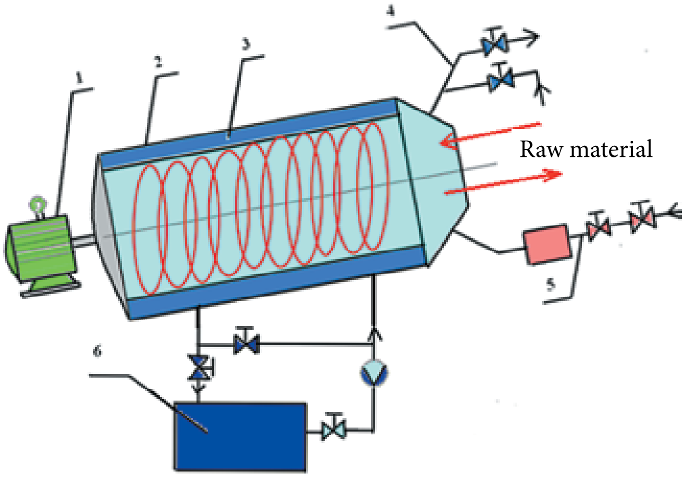

Figure 1. Schematic diagram of a vacuum defroster massager: 1 — electric motor; 2 — defroster drum; 3 — cooling jacket; 4 — system for vacuum creating and regulating; 5 — system for spraying the saturated water steam; 6 — system of cooling and supply of propylene glycol to the cooling jacket

The initial drum load during the experiments accounted for 2,510 kg. The controlled parameters of the defrosting process using the standard sensors of the device were as follows:

- temperature inside the frozen meat block (remote standard temperature sensor, rod-shaped with a screw spiral at the end) and on its surface (remote built-in pyrometer);
- water steam temperature was measured using built-in factory temperature sensors;
- the steam pressure inside the drum was measured with a standard built-in vacuum gauge;
- mass of defrosted raw materials (this parameter is measured with strain gauges installed in the defroster frame support);
- process time was measured with a timer.

The main advantage of the defroster is that, with its functional versatility, it allows full automation of the technological process, consisting of defrosting and simultaneous massaging of the raw materials. The low rotation speed of the drum eliminates surface damage to the raw meat as much as possible and creates favorable conditions for its massaging. The rotation of the drum allows even heating of the raw materials blocks. One of the advantages of this equipment is the opportunity to regulate the technological process if it deviates from the required processing parameters.

Results and discussion

Table 1 shows the program for defrosting and thawing of the raw meat in a defroster massager.

This program corresponds to the raw materials with outside temperature of the block = minus (4–6) °C, internal temperature of the block = minus (7–10) °C and a total maximum weight of raw materials up to 2,900 kg.

Table 1. Parameters of the raw meat defrosting program (recommended by the equipment manufacturer)

№ of the stage	Total time, minutes	Steam regulation		Type of the process	Vacuum value, mbar	Drum rotation speed, rpm	Method of impact, mild/hard	Angle of the drum tilt, degree	Max. steam addition, %	Steam pressure, mbar
		On, s	Off, s							
1	15	60	0	heating	50	15	mild	10		
2	90	60	0	heating	50	15	mild	10	60	800
3	90	60	0	heating	50	15	mild	10	40	800
4	45	60	0	heating	50	15	mild	10		

The technological processing parameters were determined experimentally during the research process and adjusted in accordance with the goals and objectives of the research, as well as taking into account the recommendations of the equipment manufacturer.

Structurally, the defrosting program consisted of 4 stages. Each stage has its own duration and implements certain functions. The raw materials are most affected at stages 2 and 3. At these stages of technological processing, the working environment features the highest parameters of time and thermodynamics. Despite the step-by-step differences in the impact parameters, in general the program creates a mild mode of defrosting the raw materials, including the kinematics of its movement along the ribs located on the internal surface of the drum at a low speed of rotation, which provides the necessary conditions for the homogenous heating and massaging.

The results of the process of defrosting and thawing raw meat in the form of graphs are shown in the Figures 2–4. The peculiarity of these graphs is that the given curves reflect as much as possible all real spikes and fluctuations of the parameters. This makes it possible to obtain a true picture of the process of industrial defrosting of the frozen raw materials, taking into account its characteristics at each moment in time, which does not violate the general idea of the tendency of the processes being observed.

Beef features denser structure compared to most other types of meat raw materials and lower thermo physical characteristics, therefore processes of the heat transfer and mass transfer occur in it at a low speed, as evidenced by the total duration of the defrosting process. To increase the speed, it's possible to increase the rotation speed of the defroster drum and the steam pressure up to a certain value. The consistency of raw meat at the exit of the machinery, and therefore the quality of the finished product in the form of its structure and organoleptic properties, largely depends on the results of these processes.

The kinetics of the process of defrosting and thawing of the frozen raw meat and its completion is mainly controlled by temperatures. Figures 2 and 3 show the changes in heating temperature at the inlet, outlet and inside the drum, as well as on the surface and inside the tested block of frozen beef during its defrosting.

The analysis of the above graphs, first of all, draws attention to two points: the low speed of the defrosting process and the relatively high driving force of the heat exchange process. If the speed of the defrosting process is expressed through the rate of temperature increase in the raw material, then for beef it will be on average 0.51 degrees/hour (0.0085 degrees/min). The low speed of the defrosting process is explained by the low coefficient of thermal conductivity in the raw material (depending on the grade of the raw material, the thermal conductivity coefficient is ~ 0.45 W/(m·K)) [45], which plays a key role in the heating process (Figure 2). To increase the speed of the defrosting process, it's possible to increase the driving force of the heat exchange process, in this case by increasing the parameters of the heating medium, i. e. water steam. But an uncontrolled increase in the temperature of the heating medium can lead, as mentioned above, to initial denaturation of the protein surface, which is unacceptable from the point of view of maintaining due product quality. The drawn graph (Figure 2) shows that the driving force of the heat exchange process when defrosting beef varies within the range of (20–30) °C (at a steam temperature of no higher than 20 °C) and does not have any significant fluctuations. Small fluctuations in the temperature difference between steam and raw materials ensure a relatively constant rate of the heat exchange process, which guarantees stable efficiency throughout the entire process of defrosting and allows obtaining a high-quality product.

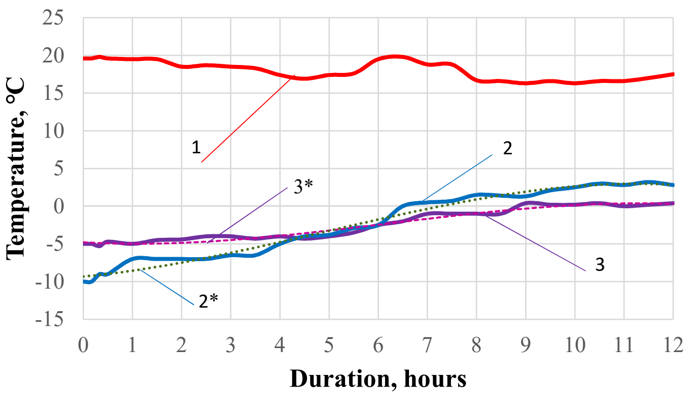

Figure 2. Change in temperature depending on the duration of the defrosting and thawing process: 1 — inside the drum; 2 — inside the beef block (2* — trend line); 3 — on the surface of the block (3* — trend line)

Mathematical processing of the experimental data in the Figure 2 allowed obtaining a correlation dependence of the temperature within the meat block and on the surface of the beef block (trend lines 2* and 3*, respectively) from the duration of the meat defrosting process (the equation (1) and the Table 2):

$$t_i = a \cdot \tau_{defr.}^3 + b \cdot \tau_{defr.}^2 + c \cdot \tau_{defr.} - d \quad (1)$$

Table 2. Numerical values of the coefficients included in the equation (1)

Coefficients in the equation (1)	Unit of measurement	Temperature of the meat block, °C	
		On the surface of the block, t_{ext}	Within the block, t_{int}
a	°C/h³	–0.0125	–0.0100
b	°C/h²	0.1834	0.1860
c	°C/h	0.1834	0.3671
d	—	9.3143	4.7701
Squared mixed correlation for the equation (1)			
R^2	—	0.9822	0.9623

The value of the approximation reliability (squared mixed correlation R2) when calculating the changes over time in the values of the external and internal temperatures of a block of meat indicates a high close relationship between the quantities included in equation (1) and the statistical reliability of the obtained empirical dependence for comparable conditions of the defrosting process. The mathematical model (regression equation (1) expressed in the form of a third-degree polynomial), obtained as a result of processing the experimental data presented in the Figure 2, has its advantages and disadvantages. The main advantages of the resulting model are its simplicity and good convergence with the experimental data, and its disadvantages are its discreteness and formalized nature, which initially does not reflect the physical essence of the processes that take place in the object. The resulting mathematical model has its practical value and can be considered as a certain stage in modeling of biotechnological processes in order to predict the properties of the obtained product, taking into consideration the patterns of their occurrence and mutual impact.

To provide the additional control over the temperature of the heating medium, the measurements were taken separately at the inlet and outlet of the drum machinery. The results are shown below in the graph (Figure 3).

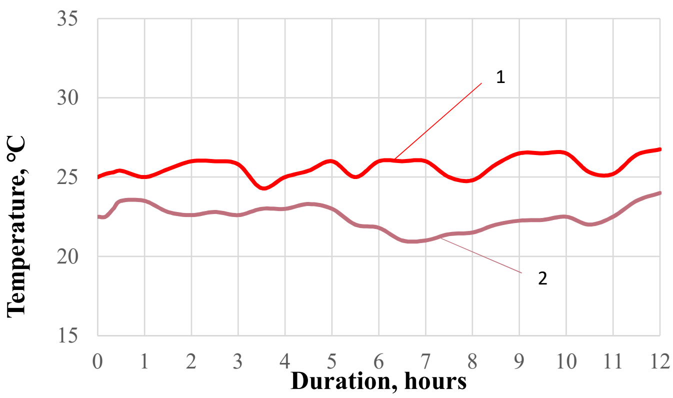

Figure 3. Change of heating temperature at the inlet (1) and outlet (2) of the drum during the frozen beef defrosting

Thermographs of the heating medium prove that the required processing conditions for raw meat are complied with and that the defrosting process occurs under relatively stable conditions, i. e. without sharp fluctuations of the heating medium parameters.

Figure 4 below shows a curve of dependence of the beef blocks mass change on defrosting time. The peculiar feature of the process in an environment of saturated water steam is the steam condensation, which gradually increases the total mass of the raw material.

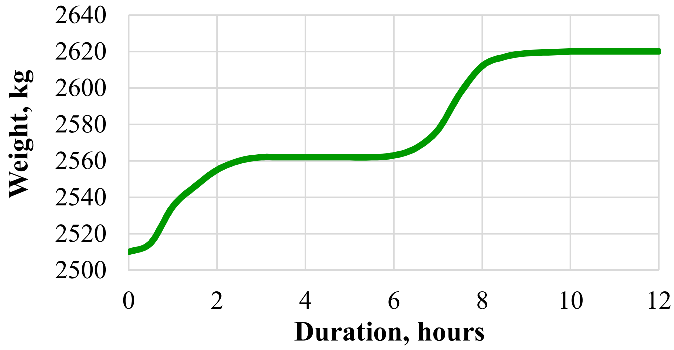

Figure 4. Change in the total mass of the beef blocks depending on the defrosting process duration

From the graph in Figure 4 it is visible that the increase in the mass of raw materials during the defrosting process occurs stepwise, incrementally. Moreover, the intervals of the raw materials mass increment are different. From this it can be concluded that the temperature-time interaction between the raw materials and steam is not smooth. In addition, this interaction implies the process of absorption of water condensate by the raw meat. The moisture formed during two parallel processes: defrosting and condensation must be absorbed by the raw materials, and only in this case a high-quality product can be obtained. But starting from a certain moment the moisture-absorbing capacity of the raw material becomes insufficient to solve this problem, and therefore a certain amount of salt is added to the defroster. For beef, the last increment of the meat mass occurs during a period of ~ (7–8) hours, when 25 kg of salt was added to the defroster so that the product absorbs all free moisture. The process of defrosting beef lasts no more than 12 hours, which is an advantage in comparison with the other methods. During the process (defrosting + massaging), the weight gain of the product amounted to 114 kg.

Thus, the defrosting modes being considered make it possible not only to defrost raw meat to cryoscopic temperature in a time not exceeding 10 hours, but also to bind free moisture released during technological processing (moisture during steam condensation and defrosting of raw materials) to a hygroscopic state. This makes the beef consistency suitable for producing high quality whole muscle food.

The considered experimental graphs allow formulating a physical model of the defrosting process based on the phenomenological parameters of the process being studied, which are the temperature and mass of the raw material. Defrosting of the raw meat is a complex process and it is accompanied by the following physical processes that can be controlled:

- heating from the initial temperature up to the temperature of the beginning of defrosting, phase transition

from a frozen state to a defrosted state, heating of the defrosted raw materials up to the final temperature;
- condensation of water steam on the surface of the raw meat;
- diffusion of moisture into the raw meat;
- massaging the raw meat.

These processes are related to each other and occur simultaneously, excluding moisture diffusion and massaging. The efficiency of this combination begins to manifest itself after the raw material reaches cryoscopic temperature.

The nature of changes in temperature and mass of the raw materials over time makes it possible to analyze the patterns of thermal and mass transfer processes at the macro level and predict phenomena that take place at the micro level, which is necessary to determine and evaluate the sustainable and costs-efficient technological processing modes.

The considered experimental graphs show that the main phenomenological parameters of the process under study are the temperature and mass of the raw material. Changing these parameters allows prediction of the heat transfer and mass transfer processes occurring in raw meat and technological equipment in general. Moreover, the most important role in forming the quality of raw materials during defrosting is played by mass transfer processes. The structure of raw meat depends on these processes. Temperature provides only the conditions for the transfer, or more precisely, the rate of mass transfer processes [39].

First of all, the mass transfer processes affect the yield of the finished product, which is one of the main economic parameters of the technological process and can serve as a criterion for its completion [38]. The yield of the finished product is understood as the ratio of the final product mass to the initial raw material (main raw material) mass. In our case, the product yield was 104%. The change in yield can occur mainly due to the moisture penetration into the product from the surrounding media during the technological processing or loss of the moisture from the meat mass.

The conditions for the mass transfer processes in the defroster-massager can be conditionally divided into two stages: the first stage takes place before reaching the cryoscopic temperature on the surface of a piece of raw meat; the second takes place after reaching the cryoscopic temperature on the surface of the meat block. The first stage is characterized by the condensation of saturated water steam and free moisture formation. Due to low temperatures and frozen moisture in the product, it is unlikely that significant mass transfer processes can occur during this period. Heating increases the speed of movement of molecules and, provided there is a temperature gradient, the process of heat transfer occurs. In turn, temperature affects the change in the molecules bond energy, which is reflected in the kinetic dependencies of chemical reactions and diffusion expressed through the kinetic constant and coefficient of the diffusion transfer, respectively. At the initial moment of heat treatment at a raw material temperature not exceeding (25–30) °C, which corresponds to the conditions of technological processing in a defroster in the second period, swelling of muscle fibers can be observed due to external moisture formed during condensation of steam.

The nature of mass change during heat exposure, depending on the type of meat raw material and production technology, can be described, essentially, by one of the curves in Figure 5, obtained by the authors and presented in the study [39].

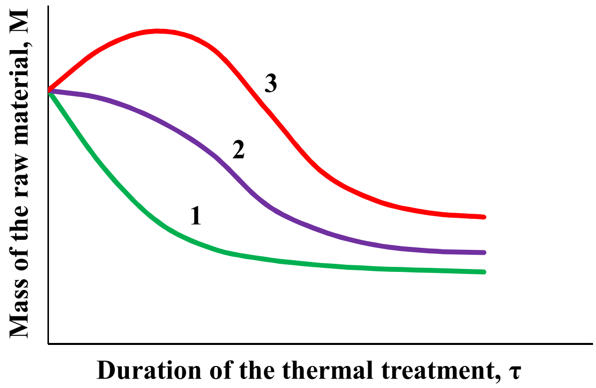

Figure 5. Change of mass of the various types of raw materials depending on the duration of the heat exposure process: 1 — raw materials with a high fat content, prone to dehydration; 2 — raw materials in which the processes of dehydration and swelling occur simultaneously; 3 — raw materials with a high content of components prone to swelling

For raw materials consisting of muscle tissue with a high fat content, curve 1 is quite distinctive and specific (Figure 5). The change of raw materials mass occurs mainly due to the release of free moisture and part of the immobilized moisture by both diffusion and filtration. Most defrosting methods are characterized by this very mass transfer process which is their serious drawback.

Meat products have become widespread in which the moisture, that increases the yield, is specially injected into the product during the pre-processing process: when preparing minced meat, when brine forcing into the meat and similar operations. Moisture introduced in a free state upon contact with the components of the raw material (mainly protein) forms more or less strong bonds, thereby passing into an immobilized state or more bound state. The part of the added moisture may remain in a free state or weakly bound state. The kinetic picture of the yield increase is directly affected only by the tightly bound part of the forced moisture. In this defroster, constant gentle massaging of raw meat and the addition of special ingredients (salt) allows firm binding of the moisture formed during steam condensation and thereby increases the yield of raw materials after its defrosting. The variety of moisture forms leads to the fact that during heat exposure, moisture transforms from one form into another without leaving the product mass. This explains the change in mass during heat treatment, corresponding to curve 2 (Figure 5). In this case, loosely bound moisture is able to leave the product faster than moisture contained within the tissues of the product itself.

The increase in mass in an atmosphere of saturated water steam can be characterized by the dependence in the form of curve 3. This mainly applies to raw materials containing a lot of components prone to swelling. Thus, the change in the yield of raw meat during heat exposure, within the accepted assumptions, is explained by the occurrence of two opposite processes: dehydration and swelling. The conditions for the heat exposure process, as well as the ratio of muscle and connective tissue proteins, determine the kinetics of the process of changing of the raw materials yield. In a defroster, the change of the raw materials mass occurs due to the swelling of muscle fibers with free moisture from the steam condensation, since dehydration of raw meat occurs only at temperatures close to (40–42) °C, when denaturation-coagulation processes begin.

In order to give the mathematic description of the output change over the time line, the basic mass transfer equation is used [39,40]:

$$\frac{M}{V\cdot\tau} = K_M\cdot\Delta \quad (2)$$

Where:

M — is the mass of the product, kg;

V — is the volume of the product, м³;

τ — time, s;

Δ — driving force of the process, (unit of movement. f);

K_M — mass transfer coefficient, kg/(m²·s·(unit of movement. f));

Since mass yield of raw materials increases or decreases due to the transfer of several components in different ways, the equation (2) will have the following form:

$$\frac{\Sigma M}{V\cdot\tau} = \Sigma K_M\cdot\Delta \quad (3)$$

where ΣM — total increment of the product mass, kg

It is obvious that the adopted expression for the output mass is related to the quantities included in the expression (3) as follows:

$$M' = \frac{M_0+\Sigma M}{M_0} = 1 + \frac{\Sigma M}{M_0} \quad (4)$$

where:

M_0 — is the mass of raw materials at the beginning of the process, kg.

M' — is the yield of the raw material, fraction of a unit

In equation (2) the ratio makes sense to increase the volume concentration. In this regard, the equation (1) can be considered as an equation of chemical kinetics for the reaction of the 1st order with a shifted reference point along the ordinate axis.

To approximate the dependence of yield on process duration within the limited time interval, it is possible to use functional dependencies that include rate constants of the dehydration and swelling processes, taking into account the specifics of the initial conditions. The obtained dependencies can be used to optimize the duration of heat treatment of the newly designed types of meat products based on non-traditional sources of meat raw materials and food additives.

Using the obtained experimental data, thermal technical parameters were calculated based on balance correlations, which allowed evaluating the efficiency of steam thermal energy directly for the process of beef defrosting.

The amount of heat expended in the process of beef defrosting is determined using the modified Planck equation:

$$Q_1 = M\cdot[C_{af}\cdot(t_{ct} - t_{init.}) + r_{ice}\cdot w\cdot \text{ɷ} + C_{bf}\cdot(t_{fin.} - t_{ct})],\ \text{kJ} \quad (5)$$

where:

C_{af} — is the specific mass heat capacity of the product after freezing, kJ/(kg·K);

C_{bf} — specific mass heat capacity of the unfrozen beef, kJ/(kg·K);

M — mass of beef before defrosting, kg;

$t_{init.}$ — temperature of beef at the beginning of the defrosting process, °C;

$t_{fin.}$ — beef temperature at the end of the defrosting process, °C;

t_{ct} — cryoscopic temperature of the product, °C;

r_{ice} — heat of phase transition (specific heat for ice melting), kJ/kg;

w — product moisture;

ɷ — fraction of frozen moisture;

According to scientific research, all moisture is frozen out at the freezing temperature (minus 60 °C), which is extremely rare in real practice [46]. Most often, the freezing process is run at temperatures from minus 18 °C to minus 25 °C, and under these conditions the proportion of frozen moisture is much less and can range from 0.4 to 0.8.

The total amount of heat Q (1) required for the process of defrosting of beef block weighing 2,510 kg, calculated by formula (5), is equal to 362,355 kJ. Knowing the amount of heat that steam gives off during its condensation, it is possible to determine the theoretical steam consumption that must be spent for defrosting of the raw meat based on the following equation (6):

$$Q_2 = D\cdot r_{steam},\ \text{kJ}; \quad (6)$$

where

D — is the steam consumption, kg;

r_{steam} — is the latent heat of steam condensation at 20 °C and reduced steam pressure, kJ/kg;

Assuming that $Q_1 = Q_2$, let's write it down in the following way:

$$M\cdot[C_{=af}\cdot(t_{ct}-t_{init.})+r_{ice}\cdot w\cdot \text{ɷ}+C_{bf}\cdot(t_{fin.}-t_{ct})] = D\cdot r_{steam},\ \text{kJ} \quad (7)$$

whence the theoretical steam consumption is equal to:

$$D = M\cdot[C_{af}\cdot(t_{ct}-t_{init.})+r_{ice}\cdot w\cdot \text{ɷ}+C_{bf}\cdot(t_{fin.}-t_{ct})]/r_{steam},\ \text{кг} \quad (8)$$

Thus, the performed calculations showed that the process of defrosting of beef block weighing of 2,510 kg theoretically requires spending of 142.45 kg of water steam. However, in reality, when defrosting the frozen meat in vacuum, the mass of raw materials at the end of the process increased by 114 kg. Using Planck's formula for calculation the overestimated steam consumption is obtained,

i. e. theoretically there is certain reserve of steam for the defrosting of raw materials (for this case the steam reserve is equal to 20%).

To assess the energy efficiency of the defrosting process as a whole, it is necessary to take into consideration not only the consumption of thermal energy for defrosting of the raw meat, but also other types of energy must be taken into account, i. e. energy balance should be drawn up, since there are other items of energy consumption. To a first approximation, these items include the following: heat loss to the environment; heating the equipment itself, heating the ingredients, raw meat during massaging; energy consumption for drum rotation; consumption of cold supplied to the drum cooling jacket; energy for creating a vacuum, etc. To determine them, special additional research is required.

Defrosting of frozen raw meat with the mechanical impacts in water steam environment at reduced pressure is a rather complicated and insufficiently studied process, especially in terms of kinetic impact of the raw materials massaging and its influence on the main parameters of technological processing.

Conclusions

The conducted studies showed that the proposed technological processing program (Table 1) can be successfully used for defrosting and thawing the frozen raw beef supplied in blocks along with simultaneous massaging for the production of whole muscle products. The studied modes of defrosting and thawing together with simultaneous massaging of the raw materials in an environment of saturated water steam under vacuum make it possible to increase the raw materials yield while simultaneously achieving the required organoleptic properties of the processed raw materials.

Experimental research in industrial conditions is the most rational means for improvement and refinement of the existing processes and for developing of the new processes and new types of equipment, as they allow obtaining more reliable data without such an intermediate stage as a large-scale transition from a laboratory experimental installation to industrial production machinery.

The study of the process of the raw beef defrosting combined with simultaneous massaging, in real industrial conditions made it possible to trace the patterns of complicated processing of the raw materials and to evaluate the mutual influence of heat, mass transfer and mechanical processes on the consistency of the defrosted beef. Using the opportunity to obtain data from experimental tests run on the industrial equipment, we had the chance to trace and record not only the processes occurring at the macro level based on phenomenological parameters, but to predict the phenomena occurring in the raw materials of animal origin at the micro level also.

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