RESEARCH INTO THE THERMOPHYSICAL CHARACTERISTICS OF MUSCLE AND ADIPOSE TISSUES IN THE FREEZING–THAWING PROCESS

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Abstract. The paper presents a study of the thermophysical characteristics of meat systems based on minced beef and pork with different morphological compositions in the freezing–thawing process, and those of model systems based on minced beef with addition of adipose tissue (raw fat). The method used to detect and compare the thermodynamic changes consisted in determining the effective specific heat capacity by freeze-thaw thermograms and finding a set of informational parameters related to it (cryoscopic temperature, cryoscopic interval of temperatures, specific heat of phase transition in the cryoscopic temperature interval, change of enthalpy in the interval of temperatures of the sample tested, proportion of moisture that changes its physical state in the cryoscopic temperature interval). It has been shown that the morphological structure of meat (the ratio of muscle, connective, and adipose tissues) significantly affects the thermophysical parameters of meat systems during freezing and defrosting. It has been found that during a freeze–thaw cycle, an increase in the content of connective tissue leads to a higher proportion of moisture that changes its physical state in the cryoscopic temperature interval, while an increase in the adipose tissue content in a meat system reduces the moisture that changes its physical state in the cryoscopic temperature interval. When adipose tissue was introduced into the meat systems, the freezing process resulted in a higher rate of formation of ice crystals and a lower rate of moisture migration from cells to the intercellular space, and crystal formation became a controlled process. When manufacturing semi-finished frozen meat products, regulating the ratio of muscle and adipose tissues makes it possible to influence the stability of the properties of meat systems in the technological cycle “freezing – storage – thawing” and to create products with the required functional, technological, and thermophysical parameters. This research can be a basis for developing the recipe compositions and technological parameters of manufacturing semi-finished frozen meat products and finished products based on them.

Keywords: thermophysical characteristics, meat systems, cryoscopic interval, freezing–thawing, frozen moisture.

Introduction. Formulation of the problem

Global trends in the development of the food industry prove that manufacture of frozen meat products is one of the most effective food preservation techniques. It allows preserving the quality, safety, nutritional and biological value of food for a long time [1].

Frozen meat is now an important article of international commerce [2], and today’s consumer wants frozen products to be no worse in quality than chilled products are [3,4] – hence the importance of searching for new, modern, and cost-effective methods of preserving the quality characteristics of frozen meat products [5-7].

Literature offers plenty of information on how freezing–thawing affects meat raw materials [8,9], particularly when they are minced. However, the absolute values of their physicochemical, thermophysical, and other parameters range widely [10,11] (due to the individual chemical compositions of raw materials and different freezing methods) and, if not determined experimentally, cannot
be based upon in finding the most promising ways of ensuring their stability.

**Analysis of recent research and publications**

According to the fundamental theoretical principles of freezing food systems, there are a number of key factors in their production workflow: reversibility of the properties under low-temperature treatment conditions, stabilisation of the colloidal state of proteins in a food system, reduced mobility of moisture, appearance of fine ice crystals and reduction of their pressure on the morphological formations in the raw materials [12]. To preserve the nutritional value of meat, the freezing process itself is very important, and so are the physical, histological, chemical (colloidal), biochemical, and biological changes that take place in meat during its freezing and storage [13,14].

When food is being frozen, it undergoes irreversible negative changes due to the phase conversions and structural transformations resulting from aqueous phase crystallisation [15,16]. Ice crystals appearing in the intercellular space cause breaking of muscle fibres, protein denaturation and aggregation. Further, all the above tells on the functional and technological properties of defrosted meat and manifests itself, first of all, in significant loss of meat juice and in lower consumer characteristics of finished products [17,18]. Mostly, the negative effect of freezing reveals itself during low-temperature treatment of semi-finished minced meat products [19]: when meat is comminuted, the mechanical destruction of its cellular structure interferes with the integrity of muscle tissue, ruins the system of capillaries and cellular membranes, and extra moisture is released because of a reduction in osmotically bound and capillary bound moisture [20-23].

The number, size, shape, and location of ice crystals formed in the course of freezing depend on a number of factors: the rate of freezing, the physicochemical and structural properties of a meat system (degree of protein hydration, ionic and molecular concentration of solutions as parts of certain morphological formations of muscle tissue, ratio of muscle, adipose, and connective tissues), the dimensions of a product, etc. [24,25].

Domestic and foreign practices have accumulated a significant experience in storing frozen meat. This allows outlining the main tendencies in the development of this area of expertise [26,27]. However, most of these studies only consider whole, not minced tissues (carcases, half-carcases, joints) (Table 1) [28,29].

### Table 1 – Loss of meat during cold treatment (for unminced raw materials: carcases, half-carcases)

| Meat type | Category of fattening | Fat content, g/100 g of meat | Loss in weight, % |
|-----------|----------------------|-----------------------------|------------------|
|           |                      |                             | Medium freezing rate | Snap freezing |
| Beef      | I                    | 16.0                        | 1.60             | 1.40         |
|           | II                   | 9.8                         | 1.75             | 1.57         |
| Mutton    | I                    | 16.3                        | 1.70             | 1.51         |
|           | II                   | 9.6                         | 1.82             | 1.57         |
| Pork      | I                    | 27.8                        | 1.50             | 1.30         |
|           | II                   | 33.3                        | 1.50             | 1.30         |
|           | III                  | 49.3                        | 1.36             | 1.18         |

During cold treatment, the loss of meat is determined by its adipose tissue content [30,31]. This tissue is a natural emulsion. Its dispersed phase is fat droplets distributed throughout the intercellular substance, which is the dispersion medium [32,33]. It can reveal its characteristic mechanostructural properties, because the system includes connective tissue fibres that function as structure-formers of this system [34].

Centralised manufacture of semi-finished minced meat products intended for retail chains and public catering enterprises involves such operations as mincing raw meat, freezing it, and freeze-storing it [35,36]. However, these operations are usually accompanied by a decrease in the functional and technological parameters of frozen semi-finished products, and thermal treatment leads to bigger weight losses, due to quality changes in meat proteins (denaturation and breakdown of the protein structure, intense aggregative interaction of myofibrillar proteins) [37,38].

In a technological flow, the stability of minced meat as a system is determined by the stable state of individual elements of the whole system. Mince (the basis of semi-finished frozen minced meat products) is a coagulation-type polydisperse food system with a complex composition, state, and structure. Within this system, dispersed particles are interconnected by unstable coagulative bonds into a single three-dimensional network [39,40]. The dispersion medium of minced meat is an aqueous solution of mineral salts (sodium, potassium, calcium, etc.), organic compounds (proteins, peptides, amino acids, extractives), and other substances extracted from raw meat. The dispersed phase is particles of muscle, adipose, and connective tissues, chopped finely. By its classification characteristics, mince is an emulsion system from coarse-cut raw meat with a low degree of fat dispersion and with the partially retained morphological structure of meat tissues [41].

When mince systems undergo freezing, the process should develop towards the highest possible rate of the
formation of ice crystals and the lowest possible rate of moisture migration. Under these conditions, part of the liquid will be frozen where it was located before freezing [42,43], and evenly distributed small ice crystals will be formed and ensure the integrity of muscle fibres of the meat.

In a complex system like meat, ice crystal formation depends not only on the freezing rate, but also on the physicochemical and structural features of the tissue (the ratio of water and adipose, muscle, and connective tissues) [11,27,44].

During freezing, conversion of water into ice is accompanied by moisture migration and changes in the thermophysical and mechanical properties. A change in the phase state of water is the main factor inhibiting unwelcome diffusion, chemical, biochemical, and microbiological processes in food products during freezing [45,46].

Literature offers plenty of information on how freezing–thawing affects meat raw materials. However, the absolute values of their physicochemical, thermophysical, and other parameters range widely (due to individual chemical compositions of raw materials and different freezing methods) and, if not determined experimentally, cannot be based upon in finding the most promising ways of ensuring their stability.

Most thermal analysis methods are based on data contained in thermograms, which show how the temperature of a sample analysed depends on a certain physical parameter [47]. These dependences allow developing methods of measuring thermophysical characteristics, thermal effects of phase transitions, chemical and biochemical reactions. Most of these methods can only be used if the physical characteristics are stable, if there are no thermal effects of a different nature, if the sample is geometrically regular, if measurements are performed at regular intervals, etc., which are essential limitations. Meat products belong to wet dispersed systems. With these, experiments are performed without regard to most of the above limitations, which accounts for the essential variance in the values of thermophysical characteristics obtained by different researchers using different methods.

Thus, to detect and compare the thermodynamic changes caused by freezing or thawing, one should objectively analyse the course of thermophysical processes in meat systems during freezing–thawing. In particular, effective specific heat capacity should be established by means of freezing–thawing thermograms. This will allow determining the strategy of stabilising meat systems: creating the colloidal stability of meat proteins and restoring the original properties of raw meat after its storage and defrosting.

The purpose of the research is establishing the regular features in the course of thermophysical processes during freezing–thawing of meat raw materials with various morphological compositions.

To achieve the purpose, the following objectives were defined:

- to study the thermophysical characteristics of meat systems based on the muscle and adipose tissues of beef during their freezing and thawing;
- to study the thermophysical characteristics of meat systems based on the muscle and adipose tissues of pork during their freezing and thawing;
- to study the thermophysical characteristics of meat systems based on the muscle and adipose tissues of beef with addition of a fat component (raw fat) during freezing–thawing.

Research materials and methods

To obtain beef-based and pork-based meat systems, the following materials were used:

1) category 1 chilled beef (according to State Standard of Ukraine (DSTU) 6030:2008 “Meat. Beef and veal in carcasses, half-carcasses, and quarters. Technical specifications”):
- top-grade trimmed beef (muscle tissue with no apparent inclusions of adipose and connective tissues);
- first-grade trimmed beef (muscle tissue with the mass fraction of adipose and connective tissues not more than 10%);
- second-grade trimmed beef (muscle tissue with the mass fraction of adipose and connective tissues not more than 20%);
- raw beef fat;

2) category 2 pork (according to DSTU 7158:2010 “Meat. Pork in carcasses and half-carcasses. Technical specifications”):
- low-fat trimmed pork (muscle tissue with the mass fraction of adipose tissue 10%, with or without the skin);
- medium-fat trimmed pork (muscle tissue with the mass fraction of adipose and connective tissues 30–50%, with or without the skin);
- high-fat trimmed pork (muscle tissue with the mass fraction of adipose and connective tissues not more than 80%, with or without the skin);
- sausage fatback (in accordance with effective regulatory documents).

Meat systems were obtained by comminuting beef or pork in a meat mincer with the holes in the plate sized (2–5)×10⁻³ m. From the minced raw material, samples to be studied were made, shaped as low cylinders 5×10⁻² m in diameter and 1×10⁻² m high.

Meat systems with raw fat added were obtained by mixing beef and raw fat, both comminuted in a meat mincer with the holes in the plate sized (2–5)×10⁻³ m. The quantities of raw fat added to the meat systems were 10%, 20%, and 30%. The systems were mixed thoroughly till the raw fat was evenly distributed in the mixture, and then samples were made, shaped as low cylinders 5×10⁻² m in diameter and 1×10⁻² m high.

The thermophysical characteristics of the meat systems were studied using a laboratory test unit within the temperature range −20 to +20°C (the interval of temperatures for the processes of technological treatment of the systems tested). The test unit was...
equipped with an 8-channel multifunctional measuring regulator OWEN TPM 138-R with an automatic interface converter OWEN AS 4 (made in Ukraine) that was used to change and maintain the selected temperature range. The thermocouples were placed in several points of a sample: in its centre, on the top and bottom surfaces, and above the sample in the refrigerating chamber. The temperature of the samples was measured automatically in steps of $\Delta T = 1 \times 60\text{ s}$.

The results of the experiment were processed using the software Owen Process Manager (the company OWEN, Kharkiv, Ukraine) by means of constructing thermograms in the selected temperature range.

The freeze–thaw thermograms were analysed by the method of analysing the kinetics of transport phenomena in non-equilibrium thermodynamic systems [48].

To detect and compare the thermodynamic changes in the meat systems during cold treatment, we determined the effective specific heat capacity by freeze–thaw thermograms and a complex of information parameters related to it. This method is based on an approximate solution to the boundary value problem of heat exchange for a body of arbitrary geometry, with inhomogeneous boundary conditions [49].

Effective enthalpy and effective specific heat capacity are physical characteristics that embrace all types of thermal effects taking place during freezing and thawing of a system: temperature changes of heat capacity, heat of phase transitions, heat of chemical and biochemical reactions. The thermograms were analysed with these parameters taken into account.

By the temperature dependences of effective specific heat capacity, the following informational parameters were obtained: $T_{cr}$ – cryoscopic temperature, °C; $\Delta T_{cr}$ – cryoscopic interval of temperatures, °C; $\Delta H_{cr}$ – specific heat of phase transition in the cryoscopic interval of temperatures, J/K; $\Delta T$ – change of enthalpy in the interval of temperatures ($\Delta T$) of a sample measured, J/K.

The characteristic peak of effective heat capacity corresponds to the water/ice phase transition, and the position of its maximum establishes the system’s cryoscopic temperature. The width of the peak at its bottom determines the cryoscopic interval of the temperatures at the start and the end of the phase transition, and the area below the phase transition peak shows the specific heat of the phase transition in the cryoscopic temperature interval.

Taking into consideration that

$$\Delta H_{cr} = L_o \Delta \omega, \quad (1)$$

where $L_o$ is the specific heat of the water/ice phase transition (335 kJ/kg).

$\Delta \omega$ is the proportion of moisture that changes its state of matter in the cryoscopic temperature interval (the quantity of frozen or thawed moisture) calculated by the formula

$$\Delta \omega = \frac{\Delta H_{cr}}{L_o}, \quad (2)$$

the change in enthalpy $\Delta H$ was found by the area below the whole curve of effective specific heat capacity in the temperature range considered.

### Results of the research and their discussion

At the first stage, the thermophysical parameters of the meat systems based on muscle and adipose tissues of beef were studied. Fig. 1 presents the thermograms of the freeze–thaw process in the meat systems from beef of different grades and from raw fat.

From the data presented in Fig.1, one can see that generally, the curves of freezing and thawing of the beef meat systems look the same (except for raw fat), but differ in the absolute values. Thus, irrespective of the morphological composition of the meat systems, the process of their cooling down to the cryoscopic temperature is described by the curves that are almost identical. In the freezing process, there are three distinguishable stages.

![Fig. 1. Thermograms of the freeze–thaw process in the beef meat systems: 1 – top-grade beef; 2 – first-grade beef; 3 – second-grade beef; 4 – raw fat](image-url)
At the first stage, when the samples are cooled down from +15°C to +1°C, the temperature decrease is proportional to the quantity of work spent on heat removal. At the second stage, the temperature of the samples decreases from +1°C to (1.2–2.5)°C, the system overcools, and approximately 70% of the product’s liquid phase crystallises. At the third stage, the samples are further frozen to -20°C, but no new crystals are formed. Instead, the crystals already formed begin growing. The temperature decreases proportionally to the heat removal work.

Fig. 2 shows the temperature dependences of the effective heat capacity of the beef and raw fat systems.

The characteristic peak of effective heat capacity corresponds to the water/ice phase transition, and the position of its maximum establishes the system’s cryoscopic temperature. The width of the peak at its bottom determines the cryoscopic interval of the temperatures within which free moisture is frozen. The area below the phase transition peak shows the specific heat of the phase transition in the cryoscopic temperature interval.

The informational parameters presented in Table 2 reflect the temperature dependence of the effective heat capacity of the beef and raw fat systems.

Analysis of the data obtained (Fig. 2, Table 2) allows deriving the following conclusions. In the course of freezing–thawing, one can observe an increase in the percentage of moisture that changes its physical state (Δω), in the cryoscopic temperature interval (ΔTcr), and in the heat of phase transition within the cryoscopic temperature interval (ΔHcr). This is due to the formation of a big amount of free moisture, which is caused by denaturation-related changes in the protein component and a decrease in the hydrophilic characteristics of the systems.

The lowest values of phase transition heat and the lowest percentage of frozen moisture are those of the top-grade beef, though its moisture-retaining power is still worse when it is thawed (Δω increases from 0.22 to 0.46). For the first and the second-grade beef, the difference in these parameters is insignificant, and their resistance to freezing–thawing is weak: ΔTcr changes by 1.8–3.0 times. This is consistent with the data that water in the crystalline form concentrates in the areas with well-developed connective tissue formations [27].

Structural changes in the fat take place within all the temperature range studied, which indicates that the proportion of bound moisture prevails in it. This is confirmed by the low value of the temperature at which the maximum thermal effect is observed during the freezing of fat (Tcr=-5.1°C).

![Graph](image-url)  
*Fig. 2. Temperature dependences of the effective specific heat capacity of the beef meat systems: 1 – top-grade beef; 2 – first-grade beef; 3 – second-grade beef; 4 – raw fat*  

| Parameter          | Beef        | Beb            | Table 2 – Temperature dependence parameters of the effective heat capacity of the beef and raw fat systems (n=5, П≥0.95) |
|--------------------|-------------|----------------|---------------------------------------------------------------------------------------------------------------|
|                    | top-grade   | first-grade    | second-grade                                                                                                  |
| Freezing           |             |                |                                                                                                              |
| Tcr, °C            | -1.1        | -1.1           | -0.9                                                           | -5.1                                           |
| ΔTcr, °C           | 5.1         | 2.4            | 4.4                                                           | –                                               |
| ΔHcr, kJ/K         | 73          | 92             | 99                                                            | –                                               |
| ΔH, kJ/K           | 196         | 218            | 230                                                           | 239                                             |
| Δω                 | 0.22        | 0.27           | 0.3                                                           | –                                               |
| Thawing            |             |                |                                                                                                              |
| Tcr, °C            | -2.2        | -2             | -1.8                                                           | 0.7                                             |
| ΔTcr, °C           | 7.7         | 7.4            | 8.2                                                           | –                                               |
| ΔHcr, kJ/K         | 153         | 100            | 154                                                           | –                                               |
| ΔH, kJ/K           | 280         | 207            | 296                                                           | 215                                             |
| Δω                 | 0.46        | 0.3            | 0.46                                                          | –                                               |
When raw fat is defrosted, this partially changes its native structure, which reveals itself in the increase of $T_{cr}=0.7^\circ C$. Its moisture-retaining power, though, remains the same, which results in less heat spent on thawing (from $\Delta H=239$ kJ/K to $\Delta H=215$ kJ/K).

According to the total percentage change of such informational parameters as cryoscopic temperature interval, specific heat of phase transition, and proportion of moisture that changes its physical state, the sample most resistant to freezing–thawing is the one containing raw fat. Besides, it requires the least energy $\Delta H$ to change the temperature in the freeze–thaw cycle.

The next stage involved studying the thermophysical parameters of the pork-based meat systems. In Fig. 3, one can see the thermograms of the freeze–thaw process for the meat systems with pork of different grades and with pork fatback.

The general aspect of the freeze–thaw curves for the pork meat systems shows tendencies similar to those for the samples of beef meat systems. However, due to the morphological difference (the bigger mass fraction of adipose tissue), pork samples pass the overcooling and crystallisation stages sooner. As the fattiness of the samples increases, one can observe that in fatty pork, the time of hitting the required freezing temperature decreases by 1.25 times, compared to low-fat pork. The freezing rate, too, becomes higher, which is one of the factors of the formation of small ice crystals. When the rate of freezing is not high enough, moisture starts crystallising first in intercellular zones, and then inside cells. This destroys the product’s cellular integrity, thus worsening its physicochemical and sensory qualities [2,7,11].

Fig. 4 shows the temperature dependences of effective heat capacity during freezing and defrosting the systems of pork meat and pork fatback.

The informational parameters contained in Table 3 describe the temperature dependence of effective heat capacity of the meat systems based on different grades of pork meat and on pork fatback.

The data in Table 3 and Fig. 3, 4 allow establishing that pork fat has no phase transition in the studied temperature range (there is no characteristic peak). This is due to its morphological structure and chemical composition: pork fat has no free moisture, and its amount of bound moisture is insignificant, that is why the characteristic peak of phase transition is absent.
Table 3 – Parameters of temperature dependence of effective heat capacity of the meat systems with pork of different grades and pork fatback (n=5, P≥0.95)

| Parameter | Pork |          |          |          |          |
|-----------|------|----------|----------|----------|----------|
|           | low-fat | medium-fat | high-fat | pork fatback |
| **Freezing** |          |          |          |          |          |
| $T_{cr}$, °C | -0.7 | -1 | -0.4 | - |
| $\Delta T_{cr}$, °C | 1.5 | 1.9 | 2.6 | - |
| $\Delta H_{cr}$, kJ/K | 88 | 74 | 55 | - |
| $\Delta H$, kJ/K | 207 | 189 | 179 | 258 |
| $\Delta \sigma$ | 0.26 | 0.22 | 0.17 | - |
| **Thawing** |          |          |          |          |          |
| $T_{cr}$, °C | -1.7 | -2.1 | -1.9 | - |
| $\Delta T_{cr}$, °C | 8.1 | 8.8 | 7.2 | - |
| $\Delta H_{cr}$, kJ/K | 95 | 59 | 51 | - |
| $\Delta H$, kJ/K | 180 | 164 | 154 | 103 |
| $\Delta \sigma$ | 0.28 | 0.18 | 0.15 | - |

During freezing–thawing, the specific heat capacity of pork is of a different character than that of beef. The wider cryoscopic interval, lower heat of phase transition, and free moisture proportion smaller by 10–20% in the medium-fat and high-fat pork can indicate irreversible structuring of meat during the freeze–thaw process.

The fattier the samples, the lower the phase transition heat $\Delta H_{cr}$ is, and the higher the values of the cryoscopic temperature interval are. This can be attributed to a smaller proportion of free moisture in high-fat pork and to a lower concentration of the substances dissolved in it (for pure water $\Delta T_{cr} \rightarrow 0$). The expenditure of energy on the process hardly depends on the fattiness of the pork.

Thus, the cryoprotective properties of fattier pork are better than those of the muscle tissue of beef. First of all, this is confirmed by the decrease in the specific heat of phase transition, which is accompanied by an increase in the cryoscopic interval of temperatures $\Delta T_{cr}$ during defrosting.

These findings (Fig. 1–4, Table 2–3), which showed the best cryoprotective properties in the fattier samples (raw fat, pork fatback, high-fat pork), were the basis for further study of how different raw fat concentrations affected the thermophysical characteristics of beef muscle tissue.

Fig. 5 shows the thermograms of freezing and thawing of the meat systems “beef muscle tissue: raw fat.”

The freezing of systems based on minced beef can be viewed as a process of freezing of interstitial fluid, a solution with relatively low molarity. At a temperature below the cryoscopic point of the interstitial fluid of meat, water/ice phase transition begins. Since meat juice is a solution of salts, its initial freezing point (cryoscopic point) is within the range -0.6°C to 1.2°C.

Based on these data, one can distinguish three ranges of freezing temperatures in the systems considered: from +15°C to +1°C, from +1°C to -2.5±0.2°C, and from -2.5±0.2°C to -20°C. For technological reasons, it is recommended to pass the second temperature range as quickly as possible so that smaller and more uniformly distributed ice crystals can be formed. With an increase in the raw fat content in the systems, the time of passing the second range is by 1.4–1.8 times shorter.

Fig. 5. Thermograms of the freeze–thaw process in the meat systems “beef muscle tissue: raw fat”:
1 – muscle tissue + 0% of raw fat; 2 – muscle tissue + 10% of raw fat; 3 – muscle tissue + 20% of raw fat; 4 – muscle tissue + 30% of raw fat; 5 – raw fat
The quantity of frozen water in the product is the function of temperature. Fig. 6 shows the temperature dependences of the effective heat capacity of the meat systems “beef muscle tissue : raw fat” during freezing–thawing, and Table 4 gives their information parameters.

Analysis of the experimental results obtained allows drawing the following conclusions. Adding raw fat to beef tissues reduces free moisture in a system, which is indicated by lower $\Delta T_{cr}$ values. If the percentage of fat is small (10%), the cryoprotective effect is hardly observed at the freezing stage. The amount of frozen moisture in the samples does not change, as compared with pure muscle tissue: $\Delta \omega = (0.41–0.42)$. An increase in fat (20–30%) results in lower values of cryoscopic temperature $T_{cr} = -1.9 – -3.0^\circ C$ and in smaller amounts of frozen moisture (up to $\Delta \omega = 0.37$). During thawing, the cryoprotective properties of fat are especially pronounced. With raw fat added, the free moisture content in the samples $\Delta \omega$ decreases by 11–26% when the proportion of fat grows from 10% to 30%. This is also confirmed by a decrease in the phase transition heat $\Delta H_{cr}$ from 212 kJ/K to 93 kJ/K. The overall energy expenditure ($\Delta H$) on thawing is reduced, which speaks in favour of this conclusion, too. Defrosting of pure tissues takes more energy than their freezing does (because the micellar structures are destroyed and the percentage of moisture $\Delta \omega$ increases from 0.41 to 0.63), whereas systems with raw fat added show lower energy expenditure during thawing, which is evidence of the higher moisture-retaining power of these systems.

Adipose tissue forms a hydrophobic layer, a sort of protective barrier between fragments of muscle fibres and ice crystals, and thus it creates conditions for the formation of small ice crystals. The more resistant the fat system itself is to the impact of freezing–thawing, the better are its cryoprotective properties when it is a component of minced meat systems.

Fig. 6. Temperature dependences of the effective heat capacity of the meat systems “beef muscle tissue : raw fat”: 1 – muscle tissue + 0% of raw fat; 2 – muscle tissue + 10% of raw fat; 3 – muscle tissue + 20% of raw fat; 4 – muscle tissue + 30% of raw fat; 5 – raw fat

Table 4 – Parameters of the temperature dependence of the effective heat capacity of the meat systems “beef muscle tissue : raw fat” ($n=5$, $P \geq 0.95$)

| Parameter | Sample of beef muscle tissue |
|-----------|-----------------------------|
|          | +0% of raw fat | +10% of raw fat | +20% of raw fat | +30% of raw fat | raw fat |
| $T_{cr}$, $^\circ C$ | –3.3 | –1.9 | –2.4 | –3.0 | –5.1 |
| $\Delta T_{cr}$, $^\circ C$ | 8.9 | 5.1 | 6.8 | 4.6 | – |
| $\Delta H_{cr}$, kJ/K | 136 | 140 | 142 | 124 | – |
| $\Delta H$, kJ/K | 259 | 263 | 268 | 253 | 239 |
| $\Delta \omega$ | 0.41 | 0.42 | 0.42 | 0.37 | – |

| Parameter | Sample of beef muscle tissue |
|-----------|-----------------------------|
|          | Freezing | Thawing |
| $T_{cr}$, $^\circ C$ | –3.8 | –3.2 | –3.4 | –3.3 | 0.7 |
| $\Delta T_{cr}$, $^\circ C$ | 9.8 | 8.6 | 8.4 | 6.5 | – |
| $\Delta H_{cr}$, kJ/K | 212 | 125 | 130 | 93 | – |
| $\Delta H$, kJ/K | 334 | 233 | 246 | 224 | 215 |
| $\Delta \omega$ | 0.63 | 0.37 | 0.39 | 0.28 | – |
Conclusion

The findings from determining experimentally the regular features of the thermophysical processes during freezing and thawing of raw meat with different morphology have been generalised, which has allowed concluding the following.

Studying the thermophysical characteristics of meat systems based on muscle and adipose tissues of pork has shown that according to the total percentage change of such informational parameters as cryoscopic temperature interval, specific heat of phase transition, and proportion of moisture that changes its physical state, the raw fat sample is the most resistant to freezing–thawing. Besides, in this sample, a temperature change in the freeze–thaw cycle requires the least energy expenditure $\Delta H$.

Studying the thermophysical characteristics of meat systems based on muscle and adipose tissues of pork has shown that the best cryoprotective properties are those of fattier pork, as compared to the muscle tissue of beef. This is confirmed by the decrease in the specific heat of phase transition, which is accompanied by an increase in the cryoscopic interval of temperatures $\Delta T_c$ during defrosting. Also, the values of phase transition heat $H_{cr}$ are observed to decrease. This can be attributed to a smaller percentage of free moisture in high-fat pork and to a lower concentration of the substances dissolved in it. The expenditure of energy on the process is almost independent of the fattiness of the pork.

Studying the thermophysical characteristics of meat systems based on muscle tissue of beef with a fat component (raw fat) added has proved that this addition increases the system’s resistance to freezing–thawing. An increase in fat (from 20% to 30%) results in lower values of cryoscopic temperature $T_c = -1.9$ – $-3.0^\circ C$ and in smaller amounts of frozen moisture (up to $\Delta \omega = 0.37$). During thawing, the cryoprotective properties of fat are especially pronounced. With raw fat added, the free moisture content in the samples $\Delta \omega$ decreases by 11–26% when the proportion of fat grows from 10% to 30%.

Thus, the complex of informational parameters obtained has shown that the morphological structure of meat has an essential effect on the thermophysical parameters of meat systems during freezing–thawing. An increase in adipose tissue during freezing results in a lower rate of moisture migration from cells to the intercellular space, in smaller ice crystals formed, and in the crystal formation becoming a controlled process.

When manufacturing semi-finished frozen meat products, regulating the ratio of muscle and adipose tissues makes it possible to influence the stability of the properties of meat systems in the technological cycle “freezing – storage – thawing” and create products with the required functional, technological, and thermophysical parameters that ensure the high quality and safety of this cycle. Our research can be the basis for the development of the recipe compositions and technological parameters of manufacturing semi-finished frozen meat products and finished products based on them.

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Важливі зоотехнічні та технологічні аспекти холодильної обробки харчових продуктів та матеріалів. Нові види сировини / Chemistry of food products and materials. New raw materials
ДОСЛІДЖЕННЯ ТЕПЛОФІЗИЧНИХ ХАРАКТЕРИСТИК М'ЯЗОВОЇ ТА ЖИРОВОЇ ТКАНИНИ В ПРОЦЕСІ ЗАМОРОЖУВАННЯ-РОЗМОРОЖУВАННЯ

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Анотація. Здійснено дослідження теплофізичних характеристик м'ясних систем на основі подрібненого м'яса, що змінює свої агрегатні характеристики. Аналізовано зміну величини кріоскопічного інтервалу температур, яка впливає на змінність фізико-хімічних характеристик м'ясних систем.

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