



ANALYSIS OF PROMISING ELECTROPHYSICAL METHODS FOR FOOD PRODUCTS THAWING

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Abstract

This article summarizes the results of research published in scientific publications on application of innovative food thawing methods and their impact on quality of the food product. The thawing processes for food systems were scrutinized, which involve high hydrostatic pressure, ultrasound, electromagnetic waves of various frequencies, and electric fields. It has been established that gradient-free methods that use electromagnetic wave energy are the most effective. They reduce the duration of thawing processes, reduce the risk of microbial contamination, and help preserve the quality of food systems. The selection of the optimal thawing method should be based on a systemic approach and should consider multiple factors, including the type of food product, its geometric shape and dimensions, chemical composition, as well as the requirements to the final product quality and economic feasibility considerations.

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Introduction

The Strategy for improving food quality in the Russian Federation until 2030, approved by the Government of the Russian Federation on June 29, 2016 under No. 1364-r, sets the purpose of improving the quality of the population life and stimulating the development of production and market circulation of high-quality food products. Particular attention should be paid to maintaining the quality and ensuring the consumer safety of highly perishable food products [1,2]. Storing food products at low temperatures is one of the most effective preservation methods, as it slows down the biochemical and microbiological processes that take place in the food product [3,4].

During refrigeration processing and storage the food products can be in the following thermal states: chilled, supercooled, subfreezing and frozen [5,6].

Microbial growth, as well as enzymatic processes occurring at low positive temperatures, significantly limit the shelf life of chilled foods, including meat, fish, seafood, and others. Therefore, freezing is a key preservation technology, as it simultaneously maintains the due quality and microbiological safety of foods, thus making them suitable for both industrial processing and direct consumption after their thawing.

Currently, approximately 2.8 million tons of frozen fish and fish products are provided to the market [7] and approximately 125.000 tons of frozen meat are imported from abroad [8]. Almost all of these raw materials require

thawing for subsequent technological processing [9]. In this regard, thawing is becoming increasingly important as a technological process that affects the quality of food products due to the inevitable physicochemical changes [10].

During freezing, the molecular activity of water is significantly reduced, whereas thawing reactivates the water molecules in the food product. It should be noted that thawing is a longer process than freezing, even under the same temperature gradients. This is due to the fact that the water formed on the surface of the product has lower thermal conductivity compared to the ice layers formed during freezing [11,12].

Using of frozen meat raw materials in various technological processes involves thawing them in such a way as to approximate to the original quality of the raw material that used to be before thawing [13,14]. This is a complex task, as long-term storage is accompanied by processes that lead to color changes, proteolytic changes in protein structures, oxidation of lipids and intramuscular fatty acid composition, and to moisture loss during thawing [15–17].

Thawing can affect changes in food quality parameters, such as the formation of voids in the product structure, changes in texture, and changes in flavor. Some changes, like moisture migration and texture softening, are immediately apparent, while other changes, like oxidative and microbiological spoilage, become noticeable only during subsequent storage after thawing [18–22].

Changes in meat quality properties during thawing depend on the thawing method [23], duration [24], and temperature conditions of the thawing process [25]. It is necessary to select heat exposure conditions and methods that will maximally restore the original properties of the product.

Assessing changes in meat quality during thawing is based on comprehensive studies of various parameters: color, texture, water holding capacity, water losses during thawing, and the microbiological and chemical stability of the food product. A significant parameter to be observed is active acidity, which is directly related to the growth of microorganisms that cause food spoilage and protein denaturation. Volatile basic nitrogen and thiobarbituric acid reactive substances (TBARS) allow assessing the degree of lipid oxidation and nitrogen compound formation, which is crucial for determining meat quality [26–29].

Thawing losses are a key indicator of food quality after frozen storage. This parameter is directly related to damage to cellular structures and tissues caused by both the freezing process itself and subsequent thawing. Minimizing thawing losses is crucial for maintaining food quality, as emphasized by a number of researchers in their studies [26,30,31]. For meat in particular, thawing losses are caused not only by the mechanical action of ice crystals on muscle fibers but also by the denaturation of myofibrillar proteins, which leads to changes in the concentration of dissolved substances in the unfrozen phase during the freezing process [32]. These changes disrupt the protein structure, reducing the capability of muscle fibers to retain water and, consequently, increasing moisture loss during their thawing.

Based on the method of exposure to energy, the thawing processes can be divided into two major groups [3,33]. The first one covers the classical methods (gradient), based on the exposure of the food product to heat using warm air, irrigation, or immersion into a liquid medium [3,11]. These methods involve the transfer of heat to the surface of food products from an air or water environment and the internal dissipation of heat within the food product through thermal conductivity. They are quite economical and easy to operate, but have a number of significant drawbacks. The most modern methods in this group are: thawing in water, in air, in condensing saturated water vapor under a vacuum or at increased hydrostatic pressure [34,35].

The second is the methods of exposure to energy through application of the physical fields: constant and alternating electric fields [36–38], electromagnetic (EM) fields of a certain frequency (radio frequency, microwave and infrared heating) [39–41], as well as using infrasound or ultrasonic effects [42,43].

Objects and methods

Within this analysis a search for scientific information was conducted in the database of the electronic library eLIBRARY.ru, in the foreign websites of the International Institute of Refrigeration, scientific journals of the academic publishing house Elsevier — Science Direct and Springer Science.

The search for references sources for their systematization and analysis was conducted using the following keywords: thawing processes of the animal origin products, electrophysical effects, ultrasonic effects, electromagnetic fields, high hydrostatic pressure, electrostatic and pulsed electric fields, ohmic heating, radio frequencies, microwaves, and quality parameters. We analyzed reference sources in Russian and foreign languages, published in scientific journals and conference materials collections devoted to the analysis topic. In total, over 200 reference sources were analyzed and grouped by subject area. Articles were selected based on a preliminary analysis of titles, abstracts, and keywords. This review includes 150 publications from 2000 to 2024. Reference sources are predominantly foreign and indexed.

Exclusion criteria covered the publications published before 2000 and researches devoted to non-food materials, including application of supplementary coolants agents in addition to cold itself, applied in the form of biological, chemical and other effects.

Full texts of the articles that matched the search criteria were analyzed, with most of the sources used published between 2016 and 2024.

Traditional thawing methods

Thawing in liquid media

Thawing via an aqueous medium features high speed, but yet has the following disadvantages. This method is associated with significant losses of soluble substances, which negatively impacts food product quality, particularly water holding capacity and its structure. Prolonged exposure to water also increases the probability of microbiological contamination due to the accumulation of microorganisms in the water. To prevent this, it is necessary to use sealed containers or packaging to prevent contamination of the food product and its contact with the cooling medium. Furthermore, thawing in water without forced medium circulation leads to the formation of an insulating defrosted layer on the surface, which impedes effective heat exchange and, in some cases, leads to refreezing of the surface layers [44].

Thawing in air

Among the methods of thawing in air two main approaches can be distinguished: thawing with natural air circulation and forced air circulation. These methods are cost-effective, but are characterized by a long process time and a significant occupied area. To increase their efficiency, the air is saturated with moisture, which helps reduce mass loss during thawing, but this leads to an increased rate of microorganism growth and a deterioration in the sensory properties of the food products [45–50]. Although thawing in a refrigeration chamber at a temperature of 4.0 °C is safe, it has significant drawbacks: a long time to achieve equilibrium between the internal temperature of the product and the temperature of the refrigeration chamber, as well as high moisture losses due to damage to cellular structures. These limitations demand further development of thawing

technologies that ensure an optimal balance between process time, quality, and food safety.

Thawing at reduced pressure

One of the thawing technologies, that is of interest for meat processing plants, is the thawing of bulky, large-piece, or crushed raw meat materials in a saturated steam environment under reduced pressure [33,51]. Analysis of the research results of domestic [52,53] and foreign scientists has shown that this method features a range of significant advantages over the other method [54–56]. For example, compared to the thawing in air method, vacuum defrosters take up less space, allow for a 30–50 % reduction in duration, and the vacuum environment has a beneficial effect on the sanitary condition of the raw materials, preventing the growth of bacterial contamination [51].

An additional positive effect can be achieved by combining the process of thawing meat raw materials with its massaging in a defroster chamber [33,52], which ensures uniform heating and reduces losses. In addition, thawing and salting meat raw materials in a vacuum increases the hydration of proteins and their water holding capacity, which helps reduce the loss of meat juice [52,53]. In the works of Russian authors devoted to the food raw materials thawing, the main patterns of the process are shown [57,58] and rational modes for its implementation are proposed depending on the thawing methods [59–63].

The thawing methods presented above — the use of air and water working environments, despite their simplicity and economic availability, have significant limitations that affect the quality of products [35,64,65].

The reduced pressure thawing method is widely used in the meat industry, but it cannot be scaled up to the other food industries.

High hydrostatic pressure (HHP) thawing

This technology is implemented at pressures from 100 to 800 MPa [66]. Thawing under IOP was first studied by Takai R. et al. [67], who demonstrated that this method allows thawing food products at the temperatures below 5.0 °C at a high speed, thus preserving the physicochemical properties of the food products, like color and texture. HHP technology involves packaging products under vacuum, placing them into a chamber filled with water or another liquid, in which a pressure of 100 to 800 MPa is created, which contributes to the destabilization of the crystalline structure of ice, ensuring the transition of ice to the liquid phase at temperatures below 5.0 °C. This method not only reduces the duration of thawing, but also reduces the risk of microorganism growth.

Despite its advantages — i.e. high heat exchange rates and reduced risk of bacterial contamination [68] — HHP thawing has not become widespread in the food industry due to the complexity of the technology and the need for specialized equipment.

Table 1 presents the results of studies of the thawing process via HHP. The abbreviations for physical values designations used in Tables 1–6 are given before the list of references.

The results presented in the Table 1 were obtained in the processes of thawing various products using HHP within the pressure range from 0 to 200 MPa, in comparison with the control samples defrosted at atmospheric pressure, at the same values of working environment temperatures.

Studies have shown that thawing via HHP method significantly reduces the thawing time compared to thawing in air or water at atmospheric pressure. This is explained by the fact that pressure increase reduces down the melting point of ice, which leads to increasing the temperature difference between the defrosted product and the heating medium,

Table 1. Results of studies of the process of thawing food products with HHP method

Product type, sample size	Conditions of the experiment	Result	References
<i>Longissimus dorsi</i> muscle of pig (rectangular samples with dimensions of 150×100×40 mm)	$p = 70, 140, 210 \text{ MPa};$ $t_{av} = 20.0 \text{ }^\circ\text{C}$	Reduced mass loss compared to thawing in air at 4.0 °C and water at 20.0 °C. Microstructure damage and increased protein denaturation with increasing pressure. The lowest losses and structural damage are observed at 140 MPa.	[69]
Chicken breasts (samples weighing approximately 220 g)	$p = 100, 150, 200 \text{ MPa};$ $t_{av} = 10.0 \text{ }^\circ\text{C}$	Reduction of losses compared to thawing in water at $p = 0.1 \text{ MPa},$ $t = 10.0 \text{ }^\circ\text{C}$	[70]
Fish — Atlantic salmon (samples weighing from 0.54 to 0.70 g)	$p = 100, 150, 200 \text{ MPa};$ $t_{av} = 20.0 \text{ }^\circ\text{C}$	Reduction of the thawing process duration compared to thawing in water at $p = 0.1 \text{ MPa}, t = 20.0 \text{ }^\circ\text{C}$	[71]
Fish — sea bream (samples weighing 100 ± 10 g)	$p = 100, 150, 200 \text{ MPa};$ $t_{av} = 20.0 \text{ }^\circ\text{C}$	Reduced thawing time and losses, preservation of quality and texture, and reduced lipid oxidation. Lowest losses at $p = 100 \text{ MPa}$ compared to thawing in water at $p = 0.1 \text{ MPa},$ $t = 20.0 \text{ }^\circ\text{C}.$	[72]
Fish — salmon (samples weighing about 400 g)	$p = 100, 150, 200 \text{ MPa};$ $t_{av} = 10.0 \text{ }^\circ\text{C}$	Reduction of losses during thawing compared to thawing in water at $p = 0.1 \text{ MPa}, t = 10.0 \text{ }^\circ\text{C},$ reduction of microbiological contamination	[73]
Fillets of various types of fish	$p = 100, 150, 200 \text{ MPa};$ $t_{av} = 10.0 \text{ }^\circ\text{C}$	Reduction of losses during thawing compared to thawing in water at $p = 0.1 \text{ MPa}, t = 10.0 \text{ }^\circ\text{C}$	[74]
Seafood (scallops)	$p = 100, 150, 200 \text{ MPa};$ $t_{av} = 10.0 \text{ }^\circ\text{C}$	Reduction of losses during thawing compared to thawing in water at $p = 0.1 \text{ MPa}, t = 10.0 \text{ }^\circ\text{C},$ increase in losses during cooking	[75]
Mango (samples with dimensions of 20×20×10 mm, weighing about 100 g)	$p = 75, 100, 125 \text{ MPa};$ $t_{av} = 20.0 \text{ }^\circ\text{C}$	Reduced thawing time, minimal color change; increased loss of vitamin C	[76]

and, consequently, to heat exchange intensification. Furthermore, a decrease in the melting point of ice (by 5–7 K) allows running the thawing process at lower temperatures, which contributes to the preservation of product quality, texture and color, and a reduction in spoilage due to the inhibition of microorganism growth and a decrease of enzymatic processes activity [76,77]. However, in some cases an increase in weight loss during thawing has been noted, as well as an increase of vitamin C loss in fruit.

When conducting HHP thawing, the key factors influencing the process duration are the dimensions and geometric shape of the food product. Large and heterogeneous food products require longer processing times. Disadvantages of this technology also include the high cost of equipment and, for some food products, changes in protein structure and color [72,78]. Furthermore, HHP thawing requires technique justification of the process parameters, especially when dealing with the food products of complex shapes or heterogeneous structures.

Electrophysical methods of thawing

Thawing with ultrasonic field exposure (hereinafter referred to as USE)

Ultrasonic waves are used in thawing food products in liquid media as a way to intensify the heat exchange process between the heating medium and frozen products [79],

such as pork, chicken breasts, and mango pulp [80,81]. This effect is associated with the destruction of the continuity of the liquid medium under the influence of ultrasonic waves — the formation and collapse of vapor-gas bubbles. This leads to generation of local shock waves and the emergence of acoustic flows of liquid, which contribute to the destruction of the boundary layer on the surface of the defrosted food product [40]. The efficiency of USF depends on the geometric dimensions and structure of the product, the frequency of oscillations and the energy flux density, the temperature and viscosity of the liquid medium.

In [65], the authors state that, compared to meat samples defrosted at room temperature, the weight loss of pork, beef, and lamb using USF thawing was approximately 43–45 % lower. Research by many authors has noted that USF thawing contributed to a reduction in losses, a decrease in the oxidation of proteins and lipids in meat, and an increase in the content of bound and immobilized water. Table 2 presents the results of studies by various authors on using of USF for food products thawing.

Studies on food thawing were conducted within the frequency range from 20 to 50 kHz and emitter power from 200 to 600 W. The authors stated that at higher power local overheating may occur, which contributes to increased oxidative degradation and loss of meat juice [83,90]. Research by many authors noted that USF thawing contrib-

Table 2. Results of studies of the thawing process of packaged food products with USF method

Type of the product, sample size	Conditions of the experiment	Result	References
Yak meat (samples measuring 100×100×50 mm, weighing 600 g)	$P = 200, 400 \text{ and } 600 \text{ W};$ $f_{\text{USF}} = 20 \text{ kHz};$ $t_{\text{av}} = 25.0 \text{ }^\circ\text{C}$	Reduction of thawing duration, reduction of losses, preservation of color and microstructure of the product; the greatest effect is achieved at $P = 400 \text{ W}$	[42]
<i>Longissimus dorsi</i> muscle of pig (samples with dimensions of 120×60×35 mm, weighing 160 g)	$P_{\text{spec}} = 0.2; 0.4 \text{ W/cm}^{2*};$ $f_{\text{USF}} = 25 \text{ kHz};$ $t_{\text{av}} = 15.0 \text{ }^\circ\text{C}$	Does not provide a significant effect on the change in microbiological parameters and textural properties compared to thawing in water at $t = 15.0 \text{ }^\circ\text{C}$	[82]
<i>Longissimus dorsi</i> muscle of pig (samples with dimensions of 120×60×35 mm, weighing 160 g)	$P_{\text{spec}} = 0.2; 0.4; 0.6 \text{ W/cm}^{2*}$ $f_{\text{USF}} = 25 \text{ kHz};$ $t_{\text{av}} = 15.0 \text{ }^\circ\text{C}$	Features significant reduction in duration, preservation of microstructure and color; does not provide a significant effect on the change in losses compared to thawing in air and water at $t = 15.0 \text{ }^\circ\text{C}$	[80]
Sea cucumber (samples weighing $20.56 \pm 1.78 \text{ g}$)	$P = 200 \text{ W};$ $f_{\text{USF}} = 43 \text{ kHz};$ $t_{\text{av}} = 20.0 \pm 1.0 \text{ }^\circ\text{C}$	Reduction of thawing duration, preservation of quality parameters compared to thawing in water at $t = 20.0 \text{ }^\circ\text{C}$ and air at $t = 4.0 \text{ }^\circ\text{C}$	[84]
Cuttlefish (samples weighing $1100 \pm 50 \text{ g}$)	$P = 200 \text{ W};$ $f_{\text{USF}} = 53 \text{ kHz};$ $t_{\text{av}} = 25.0 \pm 1.0 \text{ }^\circ\text{C}$	Increased moisture holding capacity; preservation of quality parameters compared to thawing in a microwave and in air at $t = 4.0 \text{ }^\circ\text{C}$	[85]
Fish (samples weighing $215 \pm 25 \text{ g}$)	$P = 200 \text{ W};$ $t_{\text{av}} = 20.0 \pm 1.0 \text{ }^\circ\text{C}$	Preserving the same quality parameters as when thawing in water at $t = 20.0 \text{ }^\circ\text{C}$ with reducing of duration	[86]
Fish — silver carp (samples weighing $180 \pm 10 \text{ g}$ and length $(185 \pm 5 \text{ mm})$)	$P^1_{\text{spec}} = 0.135 \text{ W/ml}^{**};$ $f_{\text{USF}} = 28 \text{ kHz};$ $t_{\text{av}} = 25.0 \text{ }^\circ\text{C}$	Reduced thawing duration, color preservation, and reduced lipid oxidation, with no significant effect on texture compared to thawing in air and water at $25.0 \text{ }^\circ\text{C}$	[87]
Mango (samples weighing 200 g)	$P^1_{\text{spec}} = 0.037; 0.074 \text{ and } 0.123 \text{ W/ml}^{**};$ $f_{\text{USF}} = 28 \text{ kHz};$ $t_{\text{av}} = 4.0 \text{ and } 25.0 \text{ }^\circ\text{C}$	Reduction of thawing duration, preservation of organoleptic properties compared to thawing in water at $t = 4.0 \text{ }^\circ\text{C}$	[81]
Soybean seeds (soybeans) samples weighing 100 g	$P_{\text{spec}} = 3.18; 6.54; 8.69$ and 11.37 W/cm^{2*}	The best preservation of ascorbic acid, textural hardness, features the minimal moisture loss at $P_{\text{spec}} = 8.69 \text{ W/cm}^2$	[88]
Dough	$P^1_{\text{spec}} = 60 \text{ W/l}^{**};$ $f_{\text{USF}} = 40 \text{ kHz};$ $t_{\text{av}} = 25.0 \text{ }^\circ\text{C}$	Improved rheological properties, increased specific volume and homogeneity of the internal structure of the dough compared to thawing in water, air and microwave	[89]

* P_{spec} — is the specific power relative to the surface area of the generator plates.

** P^1_{spec} — is the specific power, related to the volume of the working medium in the ultrasonic bath.

uted to shortening of the thawing process, a reduction in weight loss, and a decrease in the oxidation of proteins and lipids in meat. Research presented in [14,40,91] showed that optimization of USF thawing power and frequency significantly ensures the preservation of the original quality properties of animal origin products.

However, the noted advantages of USF thawing technology require careful analysis, since excessive radiation power can lead to the destruction of cellular structures, oxidation of lipids and destruction of pigments, which negatively affects the texture and sensory properties [55]. A number of authors note that at high powers local overheating can occur, which contributes to an increase in oxidative degradation of lipids and loss of meat juice [90]. At present, it is difficult to conduct an analysis when comparing the results obtained by different authors, since various frequency and power ranges, USF duration, geometric dimensions, product shape and packaging materials are used in the studies. There is no any unified system for calculating specific power values. Additional scientific work is required using unified methods for organizing experimental studies, monitoring process parameters and processing experimental data.

Thawing with electrostatic field (hereinafter referred to as ESF) method

The use of ESF method offers a more efficient technology for thawing food products in air, while preserving their quality and reducing processing time. The mechanism of action is based on the generation of electron wind, created by a corona discharge in a needle-plate electrode system. The corona discharge ionizes the air between the electrodes, creating turbulent electron wind flows that improve heat transfer from the defrosted product. Furthermore, the electric field promotes the orderly arrangement and movement of ions within the food product, thus improving heat transfer efficiency [92].

The thawing rate depends on the electric field voltage, the distance between the needle electrodes, and their position in reference to the product [70]. The thawing process via ESF can be conducted using either alternating or direct high-voltage current. There are various designs of electrode systems (needle, multi-point, plate), which are targeted at increasing the efficiency of thawing processes [93].

ESF allows reducing the duration of the thawing process and minimizing the loss of meat juice [94]; for example, research by Qian et al. [95] showed that applying 2.5 kV to frozen beef samples reduced the thawing time by 42 % and decreased meat juice loss down by 20 %.

These results were confirmed in [96], where the authors used ESF at 20 kV to defrost rabbit meat, reducing the thawing duration by 60 % and decreasing thawing losses by 30 %. ESF is being actively studied as a non-thermal method for processing food products, including pork, chicken, tuna, carp, shrimp, and some fruits [37,97]. This method has been shown to contribute to the preservation of quality

properties — it reduces lipid oxidation and impedes development of microbial spoilage.

Research conducted by He et al. [98] showed that the use of ESF (10 kV) during pork thawing reduced the processing time and slowed down protein denaturation. After 5 days of storage after thawing, an increase of volatile basic nitrogen values from 10.64 to 16.38 mg/100 g was noted in the product exposed to ESF, while in the control group this value reached up to 19.87 mg/100 g, which proves a positive effect of ESF on the shelf life of the product. It was noted that an increase in the intensity of the corona discharge due to a decrease in the inter-electrode gap, led to a decrease in protein solubility and intensification of lipid oxidation [37,92].

Thawing with pulsed electric field (hereinafter referred to as PEF)

Electric fields are widely used in the food industry, in extraction, drying, and preservation processes. Pulsed electric field processing, based on the application of short-term high-voltage pulses (microsecond duration), accelerates mass and heat transfer [99,100] and allows for a significant reducing of the process duration compared to classical technologies [101,102].

For example, the use of pulsed electric fields for thawing pork at a voltage of 10 kV [37,103] made it possible to reduce the duration of the process, as well as to reduce the damage to muscle proteins, preserve their gelling properties, and improve their water holding capacity. Similar results were obtained during the thawing of duck meat; pulsed electric fields contributed to the slowing down of the denaturation of myofibrillar proteins, while preserving the emulsifying and gelling properties [100]. These data confirm that pulsed electric fields thawing can be considered an innovative method that helps to preserve the quality of meat products and reduce losses during processing. Table 3 presents the results of studies on using the electrostatic and pulsed electric fields for thawing food products process.

Research shows that ESFs and IEFs are effective methods of applying heat during food thawing, helping to preserve quality and reduce processing losses. The proposed technical solutions primarily involve using high-voltage needle electrodes and flat grounded electrodes. The products to be thawed are placed between the electrodes. Research shows that using ESFs and IEPs significantly reduces thawing duration, preserves quality, and reduces losses compared to thawing in water or air without an electric field exposure. The authors define optimal electric field voltages that maximize the preservation of the original properties of food systems. Increasing the electric field voltage above 4 kV/cm has been shown to reduce quality.

Despite the low cost of the equipment, these technologies have not found widespread industrial application and still remain in the laboratory research stage. Ensuring the safety of such systems in processing facilities with high relative humidity in the food processing area so far remains an unresolved issue.

Table 3. Results of studies of the thawing process via electrostatic field (ESF) and pulsed electric field (PEF)

Type of thawing	Type of product, sample size	Conditions of the experiment	Result	References
ESF	Beef (samples size 35×35×35 mm, weight 42 G)	The distance between the electrodes is 100 m, between the needles is 60 mm; $U = 12, 16, 20, 24$ and 28 kV; $t_{av} = 25.0^\circ\text{C}$	Reduction of thawing duration, maintaining quality indicators compared to thawing at $U = 0$ kV	[102]
ESF	Pork tenderloin (samples weighing approximately 35 g)	The distance between the electrodes is 60 mm, between the needles 30 mm; $U = 4, 6, 8, 10$ kV	Increased shelf life, reduced thawing time, no changes in quality indicators during thawing at $U = 0$ kV	[98]
ESF	Pork tenderloin (samples with dimensions of 20×50×50 mm, weighing 50 g)	The distance between the electrodes is 60 mm, between the needles 30 mm; $U = 8, 10, 12, 14$ kV	Reduced thawing duration, high temperature field uniformity; increased lipid oxidation compared to thawing at $U = 0$ kV	[38]
ESF	Pork tenderloin (samples with dimensions of 50×50×10 mm, weighing 45.3 ± 2.5 g)	The distance between needle electrodes is 50 mm; $U = 10$ kV	Increased water holding capacity and preservation of meat tenderness, reduced denaturation of myofibrillar protein compared to thawing in water and air	[37]
ESF	Chicken breast (samples with dimensions of (20×20×20 mm)	The distance between the needle electrodes is variable; $U =$ from 4.5 to 18 kV $E = 1.5; 2.25; 3$ kV/cm	Reducing the thawing duration, maintaining quality indicators; optimal results were observed at $E = 2.25$ kV/cm	[92]
ESF	Chicken thighs (190g samples, 28 mm thick)	The distance between the needle electrodes is 20 mm; $U = 20$ kV	Reducing thawing duration and reducing losses during thermal processing	[104]
ESF	Rabbit meat (samples with dimensions of 30×30×20 mm)	The distance between the electrodes is 50 mm; between the needles = 20 mm; $U = 15, 20, 25$ kV	Reduction of thawing duration, at $U = 20$ kV the best preservation of quality indicators, moisture-holding capacity and texture	[96]
ESF	Beef (samples with dimensions of 40×40×20 mm)	The distance between the electrodes is 40 mm; between the needles — 26, 52, 78 mm; $U = 10$ kV	Decrease in quality indicators with an increase in the number of electrodes	[105]
ESF	Tuna (samples with dimensions of 20×40×40 mm)	Distance between electrodes — 30, 45, 60 mm; $U =$ from 4.5 to 14 kV; $E =$ from 1.25 to 3.5 kV/cm; $t_{av} = 20.0^\circ\text{C}$	Decreased thawing duration, with increased voltage, increased fat oxidation and thiobarbituric acid levels	[106]
ESF	Tuna (samples with dimensions of 20×40×40 mm)	Distance between electrodes — 30, 45, 60 mm; $U =$ from 4.5 to 14 kV; $t_{av} = 20.0^\circ\text{C}$	Reduction of thawing duration, reduction of losses, preservation of quality indicators compared to thawing in air at $t = 20.0^\circ\text{C}$	[107]
ESF	Fish — carp (samples with dimensions of 40×30×15 mm, weighing 25.3 g)	The distance between the electrodes is 40 mm; the distance between the needles is 30 mm; $U = 6$ and 12 kV; $t_{av} = 23.0^\circ\text{C}$	Reduction of thawing duration, reduction of losses, preservation of quality indicators compared to thawing in water $t_{cp} = 15.0^\circ\text{C}$ and air $t = 23.0^\circ\text{C}$	[108, 111]
ESF	Fish — mackerel (rectangular samples, size not specified)	$U = 15, 25, 35$ and 45 kV; $t_{av} = 20.0^\circ\text{C}$	Reduction of thawing duration, reduction of losses, preservation of quality indicators compared to thawing in air at $U = 0$ kV, $t = 20.0^\circ\text{C}$	[109]
ESF	Tuna (samples with dimensions of 20×40×40 mm)	The gap between the electrodes is 30, 45, 60 mm; $U = 4.5; 6; 7.5; 10.5; 13.5; 14$ kV; $t_{av} = 20.0^\circ\text{C}$	Reduction of the thawing duration compared to thawing in air at $U = 0$ kV, $t = 20.0^\circ\text{C}$; the shortest duration at $U = 10.5$ kV and a gap of 30 mm	[110]
ESF	Shrimp (10g samples)	$U = 15, 30, 45$ kV; $t_{av} = 20.0 \pm 1.0^\circ\text{C}$	Reduction of thawing duration, maintaining quality indicators compared to thawing in air at $U = 0$ kV, $t = 20.0^\circ\text{C}$	[93]
ESF	Tofu (samples with dimensions of 35×35×35 mm)	The distance between electrodes is from 8 to 12 m; $U =$ from 4 to 28 kV; $t_{av} = 20.0 \pm 1.0^\circ\text{C}$	Reduction of the thawing duration compared to thawing in air at $U = 0$ kV, $t = 20.0^\circ\text{C}$	[97]
PEF	Peking duck meat (samples with dimensions of 50×50×30 mm, weight 50 g)	The distance between electrodes is 55 mm; $U =$ from 5.5 to 22 kV; $f = 50$ Hz; $E =$ from 1 to 4 kV/cm; $t_{av} = 12.0^\circ\text{C}$	Reduction of the thawing duration compared to thawing in air at $U = 0$ kV, $t = 12.0^\circ\text{C}$	[112]
PEF	Fish — Atlantic salmon (samples with dimensions of 50×40×20 mm, weighing 10 g)	The distance between electrodes is 50 mm; $U = 5.5$ kV; $E = 1.0$ kV/cm; $f = 50$ Hz; $t_{av} = 10.0^\circ\text{C}$	Reduction of thawing duration, reduction of losses, preservation of quality indicators compared to thawing in air at $U = 0$ kV, $t = 10.0^\circ\text{C}$	[99]

Ohmic thawing (hereinafter referred to as OT)

This method of electric thawing has been considered for use in the food industry in recent years due to its technological advantages over the traditional methods. The basic principle of the technology is the passage of an electric current through a food product, where the energy is converted into heat due to the internal resistance of the material. This ensures volumetric heating and a more uniform heat distribution compared to convective or microwave thawing [113,114]. As a result, thawing significantly reduces processing time, preserves product quality, reduces microbial growth on the surface, and improves energy consuming efficiency [115,116].

An important advantage of OT is using of alternating current, which eliminates negative effects compared to the using of direct current, which involves electrolysis, leading to the degradation of food components and corrosion of electrodes [68]. One of the key advantages of OT is the preservation of the physicochemical properties of food products, including color, texture, and lipid stability, by minimizing mechanical damage [117].

Research of Çokgezme et al. [118] showed that the sample's shape, voltage gradient, surface profile, and electrode contact with the food product determine the energy and economic characteristics of the process. It was noted that electrodes with needle-shaped and pyramidal surfaces provide better adhesion and minimize overheating [119].

Indiarto and Rezaharsamto [120] noted in their studies that high fat content in meat reduces electrical conductivity. Selecting optimal voltage values helps minimize changes in product quality, preserve texture and moisture-binding capacity [118,121–123]. Experimental studies conducted by Fattahi and Zamindar [117] indicated the need to ensure high-quality contact between the electrodes and the food product for uniform heat distribution. According to [121], thawing of minced meat and fish using OT method reduces meat juice loss and protein denaturation.

Table 4 presents the results of studies on OT using for various food products.

OT is presented as a technology for thawing food products, including meat and fruit. Analysis shows that this technology can be effective in both air and liquid (brine) thawing. It has been established that the concentration of salts in the brine can have a significant impact on the efficiency of the heating process, which helps to reduce the thawing duration and losses [117,128]. It has been noted that the chemical composition of the product affects changes in electrical conductivity [126], which in turn causes non-uniformity in the distribution of temperature fields across the volume of the defrosted object under the influence of an electric field. Non-uniformity leads to the formation of overheated or unthawed spots of the product [116,119].

Table 4. Results of studies of the thawing process with ohmic thawing method

Type of product, sample size	Conditions of the experiment	Result	References
Beef tenderloin (samples with dimensions of 50×100 mm, weighing 200–250 g)	$U = 50 \text{ V}$	Reduction in thawing duration and loss of meat juice compared to thawing in air at $t = 20.0^\circ\text{C}$ and 3.0°C	[124]
Beef — biceps muscle (samples with dimensions of 25×25×50 mm)	$E = 10, 20, 30 \text{ V/cm};$ $f = 50 \text{ Hz}$	Reduction of textural and histological changes compared to thawing in air at $t = 25.0^\circ\text{C}$	[125]
Beef — minced meat (samples with dimensions of 130×60×20 mm)	$E = 10, 13, 16 \text{ V/cm};$ $t_{av} = 4.0 \pm 0.5^\circ\text{C}$	Dependence of electrical conductivity changes within the temperature range from minus 18.0 to minus 1.0°C was established. Decrease in electrical conductivity was noted along with increasing fat content.	[126]
Pork (samples with dimensions of 20×40×100 mm)	Thawing in brine; $U = 0, 20, 40, 50 \text{ V}$	Color preservation, reduced fat oxidation compared to thawing in brine without OT using	[127]
Beef — biceps muscle (samples with dimensions of 25×25×50 mm; 25×50×50 mm; 50×50×50 mm)	$E = 10, 20, 30 \text{ V/cm};$ $f = 50 \text{ Hz}$	Reducing the thawing duration did not have a significant effect on juice loss and color characteristics compared to thawing at $t = 25.0^\circ\text{C}$.	[115]
Beef — minced meat (samples with dimensions of 130×40×30 mm; 130×60×20 mm; cylinder $h = 13 \text{ cm};$ $d = 3.91 \text{ cm}$)	Three types of electrodes. $E = 10, 13, 16 \text{ V/cm};$ $t_{av} = 4.0^\circ\text{C}$	The lowest power consumption was obtained at $E = 16 \text{ V/cm}$ using pyramidal electrodes.	[118]
Tuna (samples with dimensions of 30×30×30 mm)	Thawing in brine. $E = 40, 50, 60 \text{ V/cm};$ $t_{av} = 4.0^\circ\text{C}$	Reduced thawing duration, preservation of protein structure compared to thawing in air and water	[128]
Tuna (samples with dimensions of 30×30×30 mm)	Thawing in brine. $U = 40–60 \text{ V};$ $t_{av} = 4.0^\circ\text{C}$	Significant reduction in thawing duration and loss. Increased fat oxidation compared to thawing in air and water.	[117]
Surimi — minced fish (samples with dimensions of 56×50×55 mm)	Thawing in brine. $U = 20 \text{ V};$ $f = 60 \text{ Hz}$	High uniformity of temperature distribution in the product, increased thawing speed compared to thawing in air at $t = 0.0^\circ\text{C}$	[129]
Spinach puree (vessel with dimensions of 30×50×100 mm, weight 125 g)	The distance between electrodes is 100 mm; $E = 10 \text{ and } 15 \text{ V/cm}$	Reduction of the thawing process duration by 70–80 % compared to thawing process at $t = 4.0^\circ\text{C}$	[130]

Despite the advantages of OT, the technology features implementation challenges related to ensuring reliable contact between the electrodes and the food product. This requires the use of electrodes tailored to the shape and structure of various products [118]. Researchers focus attention on optimization of the process parameters (electric field voltage, working environment temperature, brine concentration) and adapting the electrode design to the specific product. This method enables thawing of both unpackaged and packaged food products, provided the following conditions are met: the packaging must withstand high temperatures, possess good dielectric properties, and ensure close contact between the product and the electrodes.

Thawing with EM fields method

Thawing in the high frequency range (hereinafter referred to as HF)

Microwave methods employ electromagnetic radiation that causes dielectric heating and are a promising approach to developing food thawing equipment. Significant number of studies [131–135] are devoted to investigating thawing processes at frequencies of 27.12 MHz, which falls within the high-frequency range of waves according to GOST 24375-80¹.

The mechanism of HF action is based on the dipole interaction of polar molecules in an alternating electromagnetic field. This leads to the conversion of EM energy

¹ GOST 24375-80. "Radio communication. Terms and definitions". Moscow: Publishing House of Standards, 1980. — 58 p. Retrieved from <https://docs.cntd.ru/document/1200015766> Accessed November 17, 2025 (In Russian)

into thermal energy directly in the food product, thus increasing the efficiency and reducing thawing process duration [68,133].

Volumetric heating is particularly useful for large-piece samples, such as bulky blocks of meat, fish, and seafood, as it ensures uniform temperature distribution and preserves the original quality. Thawing technologies at 27.12 MHz frequencies have been implemented in many countries, including France, Turkey, Italy, and Japan. Their efficiency has been proven compared to traditional and ultra-high-frequency technologies.

When using high-frequency heating during the thawing of products with a high fat content, uneven temperature is observed throughout the volume of the product due to the higher heating rate of fat tissue, which leads to more intense oxidation of lipids and denaturation of proteins [136,137].

Table 5 presents the results of studies of radiofrequency thawing of food products with the high-frequency range.

Thawing in ultra-high frequency (hereinafter referred to as UHF) range

The study of thawing at frequencies of 915 and 2.450 MHz relates to the UHF range in accordance with GOST 24375–80¹. These technologies have found wide application in both industrial and domestic settings. They offer a number of advantages: they are energy efficient, easy to operate, and highly productive [55]. UHF in meat thawing ensures a reduction in processing time, a reduced risk of bacterial contamination [142], and the preservation

Table 5. Results of studies of thawing food products process in the high-frequency range

Type of product, sample size	Conditions of the experiment	Result	References
Ground beef (containers with dimensions of 190×125×27.5 mm)	The distance between electrodes is from 90 to 190 mm; $f=27.12$ MHz; $P=6$ kW; conveyor belt speed varies from 1 to 60 m/h	Experimental data on the distribution of temperature fields in the product at different gaps between the electrodes were obtained.	[136]
Chicken breasts (weighing 225 g)	Distance between electrodes 65, 75, 85 mm; $f=27.12$ MHz; $P=10$ kW	Reduction of meat juice loss, preservation of structure compared to thawing in air at $t=4.0$ °C	[41]
Beef (block with dimensions of 200×200×100 mm)	$f=27.12$ MHz; P = from 200 to 600 W	Reduction of thawing duration, increase in heating uniformity compared to thawing in air at $t=4.0$ °C	[40]
Beef (block with dimensions of 200×200×200 mm; 100×100×100 mm)	$f=27.12$ MHz; $P=400$ and 500 W	Reduction of moisture loss compared to thawing in air at $t=4.0$ °C	[135]
Beef (samples with dimensions of 160×102×60 mm; 220×140×60 mm; 285×190×60 mm)	The distance between electrodes is 115 mm; $f=27.12$ MHz; $P=3$ kW	The influence of the geometric shape of the samples on the uniformity of temperature distribution was established	[138]
Fish — tilapia fillet (samples with dimensions of 140×70×15 mm)	The distance between electrodes is 100, 120 and 140 mm; $f=27.12$ MHz; $P=600, 800$ and 1000 W	Reduction of thawing duration, preserving quality parameters compared to thawing without HF	[50]
Fish — tilapia fillet (sample length 188 ± 10 mm)	The distance between electrodes is 100, 120 and 140 mm; $f=27.12$ MHz; $P=300, 600$ and 900 W	Reduction of thawing duration, improvement of structural and mechanical properties compared to thawing without HF	[139]
Minced fish (samples with dimensions of 250×150×50 mm)	The distance between electrodes is 140, 160, 180, 200 and 240 mm; $f=27.12$ MHz; $P=6$ kW; $t_{av}=20.0$ °C	Best quality performance was achieved with 160 mm electrode spacing	[140]
Salmon (samples with dimensions of 100×80×25 mm)	$f=40.68$ MHz; $P=400$ W; $t_{av}=10.0$ °C	Reduction of thawing duration, reduction of lipid oxidation and protein denaturation compared to thawing in water and air at $t=10.0$ °C	[141]

of nutritional properties and organoleptic indicators [70]. A number of studies have noted that thawing at these frequencies causes uneven heating and localized overheating of the product due to the low penetration depth of microwaves [55]. When processing bulky large-sized chunks of products, the issue becomes more acute, since the thermal gradient increases the unevenness of heating, which negatively affects the quality and safety of food products and hinders large-scale implementation in industrial processing.

To prevent thermal unevenness, measures are proposed to optimize the sizes of products chunks, develop special design solutions for wave distribution, and arrange the frequency of on/off cycles of wave generators.

In addition, studies are being conducted on the combined effects of UHF with other technologies. For example, Cai et al. [79] investigated the combination of UHF and USF for thawing fish (perch) and showed that the combined method made it possible to increase the uniformity of temperature distribution and maintain the stability of protein structures.

Similar results were obtained in the work of Cao et al. [143], who used a combination of microwaves and magnetic nanoparticles during the thawing of sea red bream fillets, which improved the uniformity of heat distribution and preserved the stability of secondary and tertiary protein structures. These combined methods features significant potential; however, their practical implementation is hindered by high technological complexity and economic costs.

Table 6 presents the results of studies on using the UHF range for thawing food products.

Analysis shows that a large body of experimental research on thawing food systems is conducted within 27.12, 915, and 2.450 MHz frequency ranges. Thawing at 27.12 MHz ensures uniform heating, but is significantly inferior in performance to the systems operating at 915 and 2.450 MHz. However, the latter frequency requires special conditions to ensure the safety of operating personnel and is characterized by high capital costs. Experience of its ap-

plication demonstrates the key contradiction between systems operating at these frequencies: heating rate (performance) and the uniformity of temperature distribution across the volume of the heated product (quality).

Tables 5 and 6 show that 27.12 MHz technologies provide better temperature uniformity, preservation of the original product structure, and reduced weight loss after thawing compared to the frequency of 2.450 MHz. Thawing systems that operate at 2.450 MHz frequency ensure high throughput, but provide a negative impact on product microstructure and quality, while localized overheating occurs, especially for the products with complex geometric dimensions and shapes.

An alternative solution to this problem could be the using of a new range of radio frequencies — particularly high ones, which would combine the advantages of defrosters operating in the HF and UHF ranges [149,150].

To improve the performance of heating systems, it is proposed to use a higher frequency up to 150 MHz. Within this frequency range, the specific volumetric heating power is several times higher than at 27.12 MHz, and the radiation penetration depth into frozen muscle tissue is greater than at 2.450 MHz reaching over 30 cm, thus ensuring uniform heating of virtually any frozen product of animal origin.

Conclusion

Thawing technologies that involve high hydrostatic pressure, ultrasonic and ohmic heating are characterized by a high rate of heat exchange compared to convective methods and methods of conductive heat transfer, but they require application of specialized expensive equipment and the justification of rational processing modes taking into account the geometric shape and heterogeneity of the food products structure.

Using of electrostatic field and pulsed electric field during food thawing helps maintain quality and reduce processing losses. However, their using in industrial settings is restricted due to safety risks for service personnel.

Table 6. Results of studies of the thawing process using the effect of EM field within UHF range on food products

Type of product, sample size	Conditions of the experiment	Result	References
Chicken thighs, wings, breasts (100 g samples)	$P = 120 \text{ W};$ $f = 2.450 \text{ MHz}$	When thawing in UHF, no significant difference in acrylamide accumulation was detected compared to thawing in air at $t = 4.0^\circ\text{C}$ and water at $t = 20.0^\circ\text{C}$	[144]
Fish fillet — Nile perch (samples with dimensions of $30 \times 30 \times 20 \text{ mm}$)	$P = 400 \text{ W};$ $f = 2.450 \text{ MHz}$	Reduction of thawing duration, reduction of bacterial contamination, reduction of negative impact on the microstructure of the product compared to thawing in water at $t = 20.0^\circ\text{C}$	[145]
Cuttlefish (samples weighing $1100 \pm 50 \text{ g}$)	$P = 400 \text{ W};$ $f = 2.450 \text{ MHz}$	Negative impact on quality parameters	[85]
Fish — mackerel (samples weighing $215 \pm 25 \text{ g}$)	$P = 400 \text{ W};$ $f = 2.450 \text{ MHz}$	Reduced thawing duration, uneven heating	[86]
Potatoes (6mm thick slices)	$P = 1250 \text{ W};$ $f = 2.450 \text{ MHz}$	Negative impact on quality parameters compared to thawing in air	[146]
Unfermented wheat dough (samples weighing 60 g)	$P = 1000 \text{ W},$ $f = 2.450 \text{ MHz}$	Negative impact on rheological properties compared to thawing in air at $t = 25.0^\circ\text{C}$	[147]
Dough (samples weighing 120 g)	$P = 100 \text{ and } 300 \text{ W};$ $f = 2.450 \text{ MHz}$	Uneven temperature distribution and decreased survival of yeast cells compared to thawing in air at $t = 20.0^\circ\text{C}$	[148]

Thawing methods with electromagnetic waves are the most promising area of research in the development of efficient industrial defrosters. They reduce thawing duration, reduce the risk of microbial contamination, and preserve food quality. However, at high frequencies (915 MHz, 2.450 MHz), they fail to provide a uniform field of temperature. Researches of using VHF (100–200 MHz), which combines the advantages of defrosters operating both HF and UHF frequencies, is now a topic of scientific and practical interest for developing a new generation of defrosters.

The technological selection of the optimal thawing method should be based on a systemic approach that takes

into consideration the type of food product, its geometric shape and dimensions, chemical composition, quality requirements for the final product and the economic feasibility component.

Accepted abbreviations and designations:

p — hydrostatic pressure, Pa;

P — electrical power, W;

f — frequency of electromagnetic field, Hz;

f_{USF} — frequency of ultrasonic field exposure, Hz;

U — electric field voltage, V;

E — electric field strength, V/cm;

t_{av} — temperature of the working environment, °C.

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