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THE EFFECT OF MAGNETIC AND ELECTRIC FIELDS ON THE PROCESSES OF FOOD FREEZING

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Keywords: *food products, cooling, freezing, phase transition, magnetic fields, electric fields, frozen food quality*

Abstract
The article summarizes the results of studies based on scientific publications on the effect of magnetic fields (MF) and electric fields (EF) on the kinetics of freezing processes applied onto biological tissue and on their properties. The processes of freezing food media on installations equipped with the Cells Alive System (CAS) magnetic system manufactured by ABI Co., Ltd., Japan are considered in this article. It is shown that the majority of researchers did not confirm the benefits claimed by the CAS system developers in comparison with the processes of fast freezing in the chambers without the magnetic field. In the case of using the alternating magnetic fields (AMF) with high field induction values, the effect is more pronounced. The application of strong static or alternating EF contributes to the creation of a fine-grained structure of ice, reduces the freezing duration and decreases mass loss during the food thawing.

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Introduction

Freezing as a way to preserve raw food materials, semi-finished food and ready-to-eat food is widely applied in the world. The main disadvantages of these technologies are irreversible violation of the biological tissues integrity during the cycle of freezing — thawing, which lead to a decrease of food quality parameters compared to a non-frozen food.

Lots of studies have been published in the scientific literature on the processes of water crystallization in food products [1,2] and it has been found that the shape and size of ice crystals mainly depend on the rate of freezing. If the freezing occurs at high speed, then heat is quickly removed from the object, the cell does not have time to lose moisture, and crystallization occurs both in the intercellular space and inside the cell, which reduces the risk of cell damage. As far as real size objects are concerned (meat, fish, poultry), it is practically not possible to maintain a high rate of phase transition of water into ice throughout the volume of the food, because the heat from the inside of the product is transferred due to the thermal conductivity of the flesh, therefore, in the central part the freezing process develops more slowly compared to the periphery and the reduced freezing rate forms larger ice crystals, thus causing tissue damage. In this regard, there is a growing interest in the search for new freezing technologies, including the use of additional aids to cold, which would help reduce the negative effect of low temperatures on changes of the food quality parameters and provide longer shelf life.

In a number of countries over the past 15 years the researches have been actively carried out to develop methods for controlling the process of water crystallization during freezing. Those methods include: super chilling under high pressure [3,4], ultrasound [5,6], various types of cryoprotectors, as well as electric and magnetic fields. This article focuses on the discussion only the results of research on the effect of magnetic and electric fields on freezing.

In the scientific community, patents for inventions by Owada N. [7,8], describing new technologies for freezing food products in a freezer using magnetic fields, induced a great response. The principal design of this installation, according to the description [9], look like (Figure 1) a refrigerating chamber (1) equipped with a refrigerating unit (2), fans (3) and a control system. To place food a number of shelves (4) are provided, around the shelves the several vertical rectangular coils frames are installed along the depth of the cabinet (5), in which coils generate alternating magnetic field.

The freezer can also be equipped with a certain number of permanent magnets (6) embedded into the door, top, bottom and walls of the freezer. The chamber runs various temperature conditions (down to –50 °C) and stepwise regulation of alternating magnetic field induction from 0 up to 100%, while at the 0% position of the regulator only the static magnetic field (SMF) is applied onto the food. The exact values of the air flow rate, the values of the magnetic field induction are not specified by the manufacturer of the freezer. The author [7,8] states that in the installation equipped with a CAS system, a food which quality differs

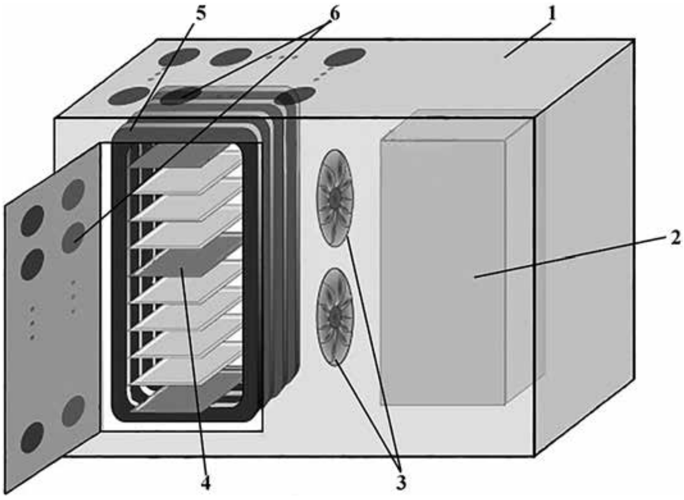

Figure 1. Schematic drawing of a freezer with a CAS magnetic system (model CAS-30B, ABI Co., Ltd., Chiba, Japan): 1 — refrigerator; 2 — refrigeration unit; 3 — fans; 4 — shelves for food placement; 5 — frame-coils for alternating magnetic field generation; 6 — permanent magnets [9]

little from the original can be obtained after thawing. However, these statements have not received proper scientific justification and confirmation by other research laboratories. Below there is an analysis of the results of studies on the use of magnetic and electric fields in the processes of freezing various food media, obtained both in installations equipped with the CAS system and on special research test-benches, in order to establish trends in the development of new methods for freezing food that provide maximum preservation of original properties after thawing.

Objects and methods

Systematic search of scientific literature was run onto the search engines: www.elibrary.ru, www.sciencedirect.com, www.springer.com and FriDoc of the International Institute of Refrigeration (www.iifiir.org) by the key phrases: food freezing, freezing in magnetic field, freezing in electric field, phase transition of water into ice. In total, the search inquiry gave 1,940 sources, which were grouped into thematic areas of the review. Articles were included based on a preliminary analysis of titles and abstracts. A total of 165 scientific studies were analyzed, including the reviews.

Inclusion criteria:

- researches publication within 2001–2023, and the work of leading scientists of other years devoted to the food refrigeration and food storage;
- the source must be indexed;
- the sources are predominantly foreign. The works published before 2001 were accepted and included in case of absence of new sources according to the specified search criteria.

Exclusion Criteria:

- publications published before 2001;
- works devoted to the study of the processes of freezing non-food media, including the use of additional aids to cold in the form of mechanical, chemical and other effects;
- publications duplicating research results;

Full texts of articles matching the search criteria were reviewed, while the majority of the used sources were published from 2017 to 2022.

Studies of processes of food media freezing in refrigerating chambers equipped with a CAS magnetic system

James et al. [10] studied the processes of freezing garlic bulbs on an experimental installation manufactured with the assistance of specialists from ABI Co., Ltd and equipped with a CAS system by the above-specified company with factory settings of magnetic field modes. The studies were run at an air temperature of –30 °C, an air velocity of 5 m/s, and at the values of the AMF induction equal to: 0.418 mT; 0.155 mT and 0.098 mT (oscillation frequency was not specified). The authors did not find a noticeable effect of magnetic fields either on the processes of super chilling or on the quality parameters of the food samples. Similar studies on the same installation, that had been used by James et al. [10], were run by Purnell et al. [11] for freezing the apples and potatoes samples at an air temperatures of –30 °C and –45 °C, an average air velocity of 0.9 m/s, and factory settings of the CAS system. The values of the AMF induction measured by the authors ranged from 0 to 0.4 mT when the frequency of the alternating magnetic field (AMF) varied from 60 to 6.5 Hz. The authors found that when potatoes and apples were frozen at –30 °C, the duration of the process using the CAS system did not differ significantly from the control time when freezing without the use of magnetic fields. In the case of freezing apples at a temperature of –45 °C, the duration of freezing significantly increased with the CAS within the entire range of magnetic field induction, while for potato samples at this temperature this dependence was not confirmed — the duration of freezing with the CAS system and without the CAS system showed no significant differences.

In general, the results of this study are consistent with those reported by Yamamoto et al. [12], which also found no effect of the CAS system on the freezing characteristics of food samples, contrary to the claims of the authors [7,8]. Almost in the same range of MF induction values and in the same chamber as James et al. [10] used, Rodríguez et al. [13] ran the experiments with freezing of pork loin samples. Freezing was run at a temperature of –30 °C and an air velocity of 1–2 m/s with a change of alternating magnetic field induction from 0 to 0.53 mT, the frequency of AMF was not specified. The authors of [13] did not find any significant effect of MF on the degree of super chilling in any of the samples; no correlation was found between the values of MF induction and the characteristic freezing time or the freezing rate. The magnetic field also did not affect the weight loss during thawing, the change in color characteristics and quality parameters. The higher values of the AMF induction ($B = 0...2$ mT; $f = 59...6$ Hz), were used by Otero et al. [9] in the CAS-30B freezer, ABI Co., Ltd., for freezing the crab sticks. The experiments were run at the stepwise factory settings for controlling the AMF induction of 10%, 50% and 100% at an air temperature of –25 °C in the freezing chamber. The authors [9] noted a significant non-uniformity of the magnetic field induction values over the inner volume of the chamber and did not establish any benefits compared to the control sample. The same values were observed in reference to the duration of the phase transition, weight loss during thawing, water-holding capacity, color characteristics. Despite the different freezing conditions, the number of authors: Fernández-Martín et al. [14,15] when freezing egg white and yolk; Suzuki et al. [16] and Watanabe et al. [17] when freezing radishes, sweet potatoes and spinach in the CAS chamber, found no differences in the duration of the freezing in comparison with the control samples, also they found no noticeable effect of magnetic fields on the microstructure, weight loss of the food during thawing, color, texture and organoleptic characteristics of the food products.

Unlike most researchers who found no benefits from the use of CAS for freezing, Okuda et al. [18] obtained pretty positive results on freezing mackerel muscle tissue at low temperatures (–30 °C and –50 °C). The authors state that samples frozen in CAS chambers and thawed in ice water show virtually no tissue damage caused by the ice crystals. To a large extent, the positive result may have been induced probably by the speed of freezing at low temperatures, the thickness of the product and the thawing conditions.

Studies of the food media freezing processes with application of SMF and AMF on the specialized test-benches

A number of researchers have studied the effect of magnetic fields in a wider range of changes of the magnetic induction SMF and AMF. Tang et al. [19,20] studied their effect on the freezing processes and the microstructure of blackberries and cherries. The objects of study were blackberries and cherries slices, which were placed in the center of a microscope cooling stage chilled with nitrogen at a rate of 4 °C/min to a temperature of –30 °C. The system of magnetic field generation consisted of permanent magnets and AC coils that generated AMF. When being exposed to SMF, the size of ice crystals decreased by 33.6%, and when AMF was applied — by 53.8%. The AMF values were in the range of 0.05…1.74 mT at the frequency f = 50 Hz. The phase transition became shorter compared to the control experiment. When freezing cherries with SMF, the size of ice crystals decreased by 67%, and using AMF — by 78%. Freezing carrot slices in SMF gave the following values: B = 1.8 and 3.6 mT. Chen et al. [21] also obtained a positive effect, expressed in the homogeneity of the structure and minimal damage of cell. The authors believe that the magnitude of the field strength should be individually selected for each type of vegetable and fruit. The results obtained by Tang et al. [19,20] and Chen et al. [21] significantly contradict the data of other authors. One of the reasons of this difference may be different experimental conditions. When freezing thin slices, their freezing was implemented at high rate, which rather could lead to a decrease in the ice crystals size than the effect of the magnetic field. This is supported indirectly by Tang et al. [22] in the experiments with freezing pork samples of larger sizes, cut into cubes 6 × 6 × 6 mm in size.

The effect of stronger fields with induction above 7 mT was studied by Leng et al. [23] during freezing of channel catfish. This mode decreased the freezing process duration and reduced weight loss after thawing. However, these data contradict the results of Otero et al. [24], who ran series of experiments at even stronger SMF (B = 40–200 mT) to freeze potato samples prepared at a temperature of –25 °C. The results obtained in this study showed that exposure to SMF with an induction of up to 150 mT provided no significant effect on nucleation, kinetics of the freezing process, the quality of the thawed product, moisture loss, color change and structural changes.

Baryshev et al. [25] studied the effect of a low-frequency alternating magnetic field on the formation of ice crystals in the beef muscle tissues during freezing in an alternating magnetic field (B = 0.5 mT, f = 18 Hz). During the experiments, it was found that AMF provided a positive effect on the meat structure. In the control samples frozen in conventional way an uneven structure with randomly located centers of crystallization was observed, while in the samples frozen under the AMF exposure those crystallization centers were more ordered. The efficiency of AMF has been shown by Panayampadan et al. [26] while freezing samples of purified guava. The field was generated with a ring inductor with an induction of 2.4; 5.6 and 8.8 mT, with frequency from 2 to 40 kHz. The duration of the freezing process with AMF reduced by 27%, 44% and 62% was found for samples with side sizes of 2, 3 and 4 cm, respectively. The authors note that there is a possibility that the obtained results were generated by the electric field generated in the inductor.

The technical devices for freezing food products using SMF and AMF are described and specified in the patents CN1054860A [27], CN111520948 [28] and CN113819701 [29]. The authors believe that application of permanent magnets can reduce the size of ice crystals in the food product during its freezing and will help maintain the original quality of the food. The technical solutions for applying the combined and multidirectional fields are proposed. However, the patents do not provide any examples of the practical implementation of the proposed devices, nor the modes of processing the food product, which does not allow us to judge their technical performance.

In a number of works, the effect of SMF on the processes of freezing water and salt solutions as more homogeneous media has been studied.

Zhao et al [30] studied the effect of SMF on the freezing of deionized water, 0.9% NaCl aqueous solution, and 5% ethylene glycol aqueous solution placed in 5 ml glass vials. The solutions were frozen at –16 °C under the effect of SMF

(B = 0.5 mT). When freezing a 0.9% aqueous solution of NaCl, the use of SMF allowed super chilling the solution by 3 °C compared to freezing conditions without the use of the magnetic field. The authors attribute this effect to the presence of ions in the solution, as they increase their mobility in a magnetic field, and increase of the coefficient of diffusion. It was shown that the duration of freezing of the NaCl solution was reduced by 53% compared to the control sample, however, when the ethylene glycol solution was frozen, the duration of freezing increased. When freezing deionized water, SMF provided almost no effect on the kinetics of the process and the temperature of super chilling. Cai et al. [31], while studying the change in the properties of water in magnetic fields, found that SMF (B = 0.5 mT) in a flow water system significantly affected the surface tension and viscosity of water. So Cai et al. [31] came to the conclusion that the effect of SMF on aqueous hydrogen bonds is similar to the effects of temperature reduction.

Otero et al. [32] noted the absence of univocal position of the researchers on estimation of the SMF effect on water super chilling and freezing kinetics. They studied the freezing of water and 0.9% NaCl solutions. The magnetic field induction ranged from 107 to 359 mT in the experiments with "attraction of the poles", and ranged from 0 to 241 mT in the experiments with "repulsion of the poles" (opposite switching of the magnets). As a result of the research, no effect was found from the SMF, regardless of the induction values and the field orientation, neither on the magnitude of super chilling, nor on the kinetics of freezing, both for pure water samples and 0.9% NaCl solutions.

The freezing kinetics and physical properties of pure water and cucumber tissue fluid were studied by Yang et al. [33] when the samples were exposed to a pulsed magnetic field (PMF) with an induction of 2.4–6 mT with fixed duty factor ratio of 0.5 and a frequency of 25 Hz. It was established that PMF exposure increased the degree of super chilling of water and cucumber tissue fluid, reduced the duration of freezing of cucumber tissue fluid and its super chilling. Compared with the control sample, PMF exposure allowed reducing the freezing temperature of water and cucumber tissue fluid by 0.59 °C and 0.74 °C, respectively. The authors believe that PMF's effect on the charged particles in the processed sample, that inhibited the growth of ice crystals. The results of studies of effects of alternating magnetic fields (AMF) and static magnetic fields (SMF) are systematized below in the Tables 1 and 2.

Table 1. Effect of an alternating magnetic field (AMF)

Type of effect	Product type. Sample's shape and size	Experiment conditions	Result	Source
AMF	Apples. Cylinder: d=17mm; l=20mm	Installation with the CAS system. B = 0…0.4 mT; f = 8…60 Hz; T= –30 °C and T= –45 °C	*At T = –30 °C no effect was observed. At T= –45 °C, the duration of freezing increased.*	Purnell et al. [11]
AMF	Potato. Cylinder: d=17mm; l=20mm	Installation with the CAS system. B = 0…0.4 mT; f = 8…60 Hz; T = –30 °C and T = –45 °C	At T= –30 °C, the duration of the phase transition shortened. At T= –45 °C no effect was observed	Purnell et al. [11]
AMF	Pork loin. Cylinder: d =13.6; 21,8 and 30,3 mm; l =22mm	Installation with the CAS system T= –30 °C; B =0… 0.53 mT	*Weak effect*	Rodriguez et al. [13]
AMF	Crab sticks. Sticks: 15x15x38 mm	Installation with the CAS system. B = 2 mT; f = 6…59 Hz; T= –25 °C	*No changes found*	Otero et al. [9]
AMF	Mackerel. Carcasses: l=37.9 mm; of which fillets 20.6 mm thick	Installation with the CAS system. B =0.1–0.5 mT; T= –30 °C и T= –50 °C.	Inhibition of histological damage, reduction of losses during thawing in ice water.	Okuda et al. [18]
AMF	Egg white and egg yolk	Installation with the CAS system. B = 1.66 mT; f = 6 Hz; T= –50 °C	*No benefits found*	Fernandez et al. [14,15]
AMF	Blackberry. Slices: 10x3x0.1 mm	Specialized test bench. B =0…1.74 mT; f = 50Hz; T= –30 °C	Reducing the size of ice crystals by 53.8%, decreasing of the total duration of freezing, increasing the duration of the phase transition	Tang et al. [19]
AMF	Cherry. Slices: 10x3x0,1 mm	Specialized test bench. B = 0…1,74 mT, f = 50 Hz; T= –30 °C	Reducing the size of ice crystals by 53.8%, reducing the total duration of freezing, increasing the duration of the phase transition	Tang et al. [20]
AMF	Pork. Cubes: 6x6x6 mm	Specialized test bench. B = 0…1,74 mT, f = 50Hz; T = –30 °C	Increase in the phase transition time, an increase in the nucleation temperature	Tang et al. [22]
AMF	Meat. Slices of 10 mm thick	Specialized test bench. B = 0,5 mT, f = 18 Hz	Reduced damage to the structure, increased plasticity	Baryshev et al. [25]
AMF	Sweet potato potato, fish. Cylinder: d=40 mm; l=40 mm,	Specialized test bench. B = 0.5mT, f = 50Hz …10кHz T = –35 °C	*No clear effect was found on either the degree of super chilling or the duration of freezing.*	Suzuki et al. [16]

End of Table 1

Type of effect	Product type. Sample's shape and size	Experiment conditions	Result	Source
AMF	Daikon, sweet potato.	B = 0–100 mT, T = –35 °C	*No clear effect was found on either the degree of super chilling or the temperature and duration of freezing.*	Watanabe et al. [17]
AMF	Garlic bulb, weight 40,4 g	Installation with the system CAS. B = from 0 to 0.418 mT; T = –35 °C	*No clear effect was found on either the degree of super chilling or the temperature and duration of freezing.*	James et al. [10]
IMF (impulse magnetic field)	Water and tissue fluid of cucumber. Test tube, 3.5 ml of capacity	Specialized test bench. B = 2.4 and 6 mT, porosity 0.5; f = 25 Hz; T = –15 °C	Decreasing the freezing point, Changing the freezing time: ➢ at B = 6 mT increased; ➢ at B = 2...4 mT has not changed. Freeze time reduced by up to 62%	Yang et al. [33]
AMF	Guava. Cubes of the sides sizes: 2, 3 and 4 cm	Specialized test bench. B = 2.4; 5.6; 8.8 mT; f = 2...40 кHz. T = –25 °C.	Freeze time reduced by up to 62%	Panayam-padan et al. [26]

Table 2. Effect of static magnetic field (SMF)

Type of effect	Product type. Sample's shape and size	Experiment conditions	Result	Source
SMF	Blackberry, slices: 10x3x0.1 mm	Specialized test bench. B = 0...10 mT, T = –30 °C	Reducing the duration of freezing; reduction in the size of ice crystals	Tang et al. [19]
SMF	Cherry, slices: 10 × 3 × 0.1 mm	Specialized test bench. B = 0...10 mT, T = –30 °C	Reducing the duration of freezing; reduction in the size of ice crystals	Tang et al. [20]
SMF	Pork, cubes: 6x6x6 mm	Specialized test bench. B = 0...16 mT; T = –30 °C	Reducing the size of ice crystals. Raising up the degree of super chilling	Tang et al. [22]
SMF	Deionised water; 0,9% NaCl. Vials, V=5 ml.	B = 11.4 mT	When freezing water, no effect was found. Freezing 0.9% NaCl: ➢ reduction of freezing duration by 53%; ➢ of super chilling by 3 °C	Zhao et al. [30]
SMF	Pure water; 0,9% NaCl Vial, capacity = 10 ml	B = 107...359 mT and 0...241 mT	*No effect found*	Otero et al. [32]
SMF	Carrot, slices	B = 0.46 and 0.92 mT	*No effect found*	Chen et al. [21]
SMF	Carrot, slices	B = 1.8 and 3.6 mT	Homogeneous crystals, minimal tissue damage	Chen et al. [21]
SMF	Potato. Cylinder: d= 20 mm, l = 45 mm	B = 40–55 mT B = 150–200mT	*No significant effect was found either on the kinetics of the freezing process or on the quality of the food product.*	Otero et al. [24]

Studies of the processes of freezing food media using electric fields

It is known that the quality of frozen food and the preservation of tissue microstructure largely depend on the rate of nucleation. At the same time, the nucleation process has a stochastic character and in practice, with conventional freezing methods, this metastable state is difficult to control [34]. Orlowska et al. [35] proposed a new approach to controlling of the ice nucleation within the frozen objects using an electrostatic field and creating appropriate freezing conditions. This effect has been experimentally confirmed by water freezing under the effect of low temperatures and a static electric field with a strength of 0 to 6.0×10^6 V/m. The experiments were carried out at electrostatic voltage ranging from 2.0 to 12 kV. The creation of higher voltages (over 12.6 kV) led to the ionization of air. It was found that the use of static electric field (SEF) allowed to significantly reduce the duration of the phase transition in the water sample and increased the nucleation temperature, while the highest degree of super chilling was obtained at a field strength of 5×10^6 V/m. The authors have shown that SEF exposure makes it possible to change the degree of super chilling and initiate the nucleation of the crystals. Similar studies were run by Dalvi-Isfahan et al. [36] on freezing mutton when exposed to SEF. The experimental setup consisted of 2 horizontal copper plate electrodes, which were installed in a freezer with forced air circulation at a temperature of minus 20 °C. The applied voltages were 0; 4; 8 and 12 kV. It was found that during the freezing with an increase in the SEF voltage from 0 to 12 kV, the equivalent diameter of ice crystals decreased by almost 3 times and their sphericity increased (Table 3).

Table 3. Results of microscopic analysis of ice crystals

Tension of SEF, (V/m)	0.0	1.9×10^5	3.9×10^5	5.8×10^5
Equivalent ice crystals diameter, μm	30.15 ± 5.12	17.64 ± 7.05	14.97 ± 4.2	11.95 ± 3.54
Sphericity, (0–1)	0.42 ± 0.05	0.59 ± 0.1	0.49 ± 0.03	0.56 ± 0.06

The effect of SEF on some parameters of the food products was evaluated by Fallah-Joshaqani et al. [37] when freezing distilled water, an aqueous solution of NaCl, an extract of a fungus and mushrooms. The field strength varied from 0.0 to 9.6×10^5 V/m at voltage of 0; 4.5; 9 and 13.5 kV. The results also confirmed the correlations [35] on the decrease of water super chilling on the increase in field strength. The highest nucleation temperature in pure water was observed at an electric field with strength of 6.4×10^5 V/m, and a further increase in the field strength to 9.6×10^5 V/m provided no significant effect on the nucleation temperature. For the NaCl solution, a decrease of the super chilling degree was observed only with an increase in the field strength to 3.2×10^5 V/m; a further increase in the field strength led to its increase also. The similar studies on the effect of a pulsed electric field (PEF) on the parameters of the rice flour gel freezing process were run by Roujia [38]. The results showed that the application of a pulsed electric field in the range from 0 to 25 kV led to a decrease of duration of the phase transition, in formed the smaller and more spherical ice crystals. The effect of PEFs on the freeze-thaw quality of the Atlantic salmon was studied by Li et al. [39]. The salmon was frozen at the electric field with strength of 1 kV/cm, current voltage of 5 kV, frequency of 50 Hz, and pulse width of 200 μs. As a result of the research, it was found that exposure to PEF under the conditions of air ionization made it possible to preserve the structure of the food product better, significantly reduce the duration of the thawing process and reduce the loss of moisture during thawing to 6%. The authors draw attention to an increase of the shelf life of this product after its thawing due to additional surface treatment with ionized air. At the same time, the authors point to a slight increase in losses during cooking and this is associated with a possible denaturation of the protein under the effect of ozone generated by the PEF. Babakin et al. [40,41] obtained experimental data on the effect of electrostatic fields on the processes of meat freezing. The object of the study was beef samples of various quality groups (PSE, NOR and DFD), pieces with size of 120 × 30 × 30 mm. the beef was frozen in a refrigerating chamber at a temperature of minus 25 °C in an electrostatic field with a strength of $(7.5...9) \times 10^5$ V/m under electroconvection conditions. The electroconvection was generated by a corona discharge which initiated a turbulent flow of ionized air [42], the velocity of the "electric wind" was 2–3 m/s. The control samples were frozen without their exposure to the field, at the same air velocity provided by the cooling fans. Figure 2 below shows the kinetic curves of the samples' freezing.

The frozen beef was stored at a temperature of minus 12 °C. It was found that the use of electroconvection reduced the duration of the freezing process by 27–41%, depending on the meat quality groups, and reduced the weight loss of unpacked meat during its freezing and storage.

The effect of microwaves (UHF) on the processes of freezing apples and potatoes was studied by Jha et al. [43]. The conducted studies have shown that the use of microwaves during freezing of these products did not affect the parameters of the freezing process, the forms of the obtained freezing curves during conventional freezing of the apples and the potatoes exposed to the microwaves were almost identical. It was found that the microwaves exposure did not reduce the duration of the freezing process, but led to a more uniform distribution of ice crystals, which reduced the loss of juice during thawing, and ensured better preservation of the food hardness. Xanthakis et al. [44] also studied the process of food freezing under microwave exposure using pork as an example. In contrast to [43], it was shown that the use of a microwave field increased the duration of the freezing process compared to the control mode, and reduced the degree of super chilling as the power increases. Data that confirmed the formation of smaller ice crystals have been obtained. Zhang et al. [45] proposed a device for quick freezing of a cooked rice dish (patent CN114009660A). The device contains a moving conveyor belt on which the food to be frozen is placed. The pulsed electric field is formed by two electrodes, which are fed with a current voltage of 5 to 20 kV, a frequency of 200 to 600 Hz, with a pulse width of 150 ... 300 μs. An alternating magnetic field is generated using Helmholtz coils

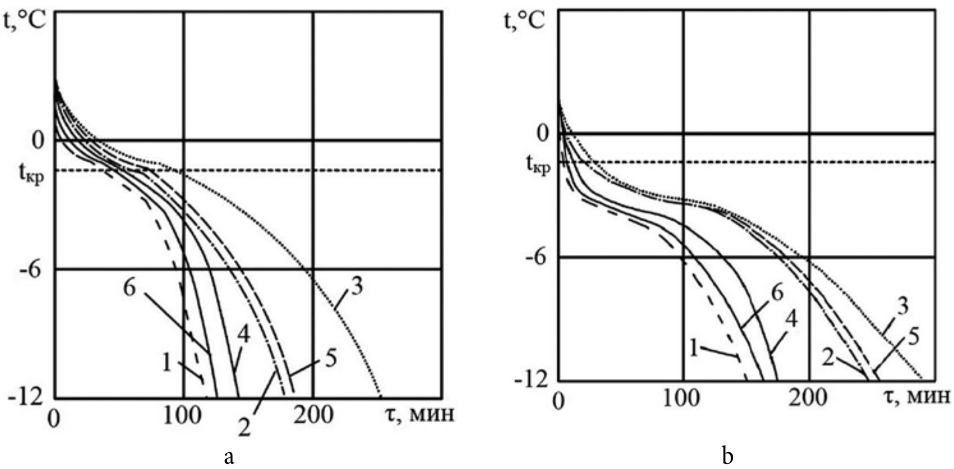

Figure 2. Change of temperature of the beef meat samples: a — on the surface, b — in the center (1,4,6, — experimental sample; 2,3,5 — control sample; 1,2 — DFD meat, 3,4 — PSE meat, 5,6 — NOR meat)

with a frequency of 50 to 150 Hz and an induction of 0.6 to 1.2 mT. PEF and AMF act together synergistically during the freezing process. The authors believe that this technical invention will increase the freezing rate, provide finer crystalline structure in the food product and maintain its original properties. However, the authors do not provide any experimental data confirming the above-specified parameters. The results of studies on the effect of variable and static magnetic fields are systematized below in the Table 4.

Discussion

The results of studies on the MF efficiency in the process of freezing food are controversial. This is predominantly explained by the fact that experiments are run by different researchers on heterogeneous objects under different freezing conditions and with different induction of magnetic fields, which does not allow unambiguous comparison of the obtained results. Most of the studies were run on installations equipped with the CAS system; the results proved that magnetic fields with induction from 0.4 to 2 mT provided no significant effect on either the freezing kinetics or the change in product properties. However, Okuda et al. [18] applied a field induction of no more than 0.5 mT and obtained the positive results in preserving the original structure of the mackerel fillet after its freezing and subsequent thawing in ice water. To a large extent, the positive result could be affected by the properties of the product being frozen, by freezing conditions at low temperatures, as well as by the thawing conditions.

Studies run on the specialized test benches allowed obtaining the results in a wider range of changes in the magnetic fields induction; however, most researchers who ran experiments on the real sizes samples of food did not find a clear effect of magnetic fields on either the freezing kinetics or the food properties. Positive results were obtained by Tang et al. [19,20] who froze blackberries and cherries samples at 10 mT while exposing the samples to SMF induction, the same was observed by Chen et al. [21] when freezing carrots. However, it should be noted that these studies were run on thin-sliced samples that were frozen at a high rate, therefore it is incorrect to extend the results obtained to objects of real sizes that are processed in the food industry, but they may be of interest for the implementation of special freezing technologies. It will be necessary to study the processes of freezing food media at higher values of SMF induction, taking into account the obtained results.

In general, the evidence base on the effect of SMF on the kinetics of freezing processes and food quality parameters currently is still insufficient. The articles do not answer to the question of what exactly reacts in a biological tissue or in water to a weak static magnetic field and what effect can be expected when strong fields are applied to it.

Research results show that AMFs can be more efficient than the static ones, especially at the stage of the water crystallization process. In some cases, they reduce the size of ice crystals, inhibit the histological damage, decrease of the nucleation temperature, and reduce the moisture losses after thawing.

It is shown that low-intensity AMFs practically have little effect on the freezing processes, but at high field induction values (more than 100 mT) and at frequencies (20 kHz and more), their effect can be observed, and it is apparently associated with the generating of an alternating magnetic field of the electric field, which strength is proportional to the amplitude and frequency of the AMF. At frequencies within the range of several tens of kHz, intense

Table 4. Effect of the electric fields

Type of effect	Product type. Sample's shape and size	Experiment conditions	Result	Source
SEF	Distilled water. Measuring cell, V = 1.6 ml	U = from 0 to 12 kW E = (0…6) × 10^6 V/m T = –16 °C	Phase transition reduction, nucleation temperature increase, nucleation initiation.	Orlowska [35]
SEF	Mutton. Cylinder: d = 10mm; l = 10mm	U = from 0 to 12 kW E = (5.8 × 10^5) V/m T = –20 °C	The effect on the kinetics of the process is weak. Reducing the size of ice crystals by 2.5–3 times, sphericity of crystals, reducing losses.	Dalvi-Isfahan [36]
SEF	Distilled water, NaCl solution, mushroom extract, mushrooms. Measuring cell. Cylinder: d = 20 mm; h = 20 mm	U = from 0 to 13.5 kW E = from (0 to 9.6) × 10^5 V/m, T = –30 °C	Increasing the nucleation temperature	Fallah-Joshaqani [37]
IEF (electric convection)	Meat, bar 130 × 30 × 30 mm	E = (7.5…9) × 10^5 V/m. Temperature T = –12 °C	Reduced freezing time, reduced wastage	Babakin et al. [41]
IEF (electric convection)	Atlantic salmon, cubes 50 × 40 × 20 mm	U = 5 kW; *f* = 50Hz Width of impulse 200 ms Temperature: of freezing –18 °C; of thawing 10 °C	Reduced ice crystal size, reduced thawing time, 6% reduction in wastage	Li, J. et al. [39]
UHF	Apple and potato	P = 167 and 222 Wt/kg, width of impulse 10 s, interval 20 s. T = –30 °C	Preservation of microstructure, even distribution of ice crystals, reduction of loss during thawing	Jha [43],
UHF	Pork, cylinder: diam. d = 7.5 mm; h = 6 mm	P = 700 Wt, T = –30 °C	Reducing the size of ice crystals, reducing the duration of freezing	Xanthakis [44]

dielectric losses are observed in biological tissues, which can improve the freezing kinetics as Kolodyazhnaya et al. [46] found, and, as a consequence, it leads to the destruction of the dendrites during the phase transition.

The research results show that exposure to the strong SEF with strength of (105…107) V/m leads to a decrease in the degree of super chilling, accelerates the beginning of water crystallization in the food product, reduces the duration of freezing. This indicates that the effect of reorientation of polar water molecules along the field direction (so called ordering) is achieved, which in its turn counteracts the thermal fluctuations and accelerates the freezing process. In addition, the authors [39,40] note that when salmon and meat are being frozen in an electric field under ionization, an electroconvective movement of the air medium take place, which intensifies the process of heat transfer. To achieve the positive results on the use of EF in laboratory conditions, it was necessary to create electric fields with strength of up to 10^6 V/cm. To ensure the same values of specific tension in the real workshop conditions at the place of food production and storage, it is necessary to achieve even stronger SEFs, which can be dangerous for the working personnel. In this regard, it is difficult to scale this method in the real industry. A number of authors have used a high-frequency field in freezing processes: Jha et al. [43] froze potatoes and apples, while Xanthakis et al. [44] froze pork. It was found that exposure to the microwave field can increase the duration of the freezing process compared to the control sample, but it decreases the degree of super chilling as the power increases, thus contributing to a significant reduction in the ice crystals size. These results are consistent with those obtained by freezing meat under exposure to the high-frequency radio frequency waves by Anese et al. [47]. One of the main limitations of this method is the generation of heat during the food processing; therefore, optimization of plant power is necessary. The same effect is also observed when radio frequency affects a frozen object, but in this case, scaling and safety are provided easier at any power of radio signals, since a radio signal can be introduced into the refrigerating chamber in a non-contact way, both using external high-frequency electromagnetic frames, and by using radio antennas. Many authors studied the food products with various thermo-physical properties, at various values of field induction and field frequencies, which makes it difficult to reproduce the results, to scale them and to compare. It is advisable to keep on researches in a wider range of the field induction values and it would be useful to introduce the additional unifying requirements for the researchers to test their own research results in certain standard modes, including the samples of comparable geometric shape, weight and size, with the same freezing conditions and the same control methods.

Conclusion

The declared efficiency of the freezers with a magnetic CAS system, proposed by Japanese scientists, used for freezing food products and based on the food exposure to the weak static magnetic fields and alternating magnetic fields in the vast majority of tests received no experimental confirmation and no proper scientific justification. To a large extent, the positive effects in some cases were obtained not due to the use of magnetic fields, but due to the use of rational freezing modes and subsequent storage of products at the lower temperatures compared to the stage of their freezing. These techniques make it possible to slow down the processes of moisture recrystallization, compared with technologies when the food is stored at higher air temperatures than the temperature used during the freezing.

The presented results of studies were obtained from the experiments run on the specialized test benches. The results confirm that weak static magnetic fields provide practically no effect on the kinetics of the process of freezing the real sizes samples. Fields with high induction values can have an effect, but there are not enough databases of these processes.

It is shown that AMFs of low intensity also provide very little effect on the freezing processes, however at the high field induction values the effect manifests itself, and it is probably associated with the generating of the alternating magnetic field of the alternating electric field, which affects the inner kinetics of the freezing process.

The application of strong electric field and microwave field during freezing of food media decreases the degree of water super chilling so that it's easier to achieve, it accelerates the beginning of the water crystallization, decreases the ice crystals size, and reduces the losses during thawing of the food product. For a number of reasons, these methods will require a lot of effort when scaling up in the food processing industry.

REFERENCES

1. Evans, J.A. (2008). Frozen Food Science and Technology. Blackwell Publishing Ltd., 2008. https://doi.org/10.1002/9781444302325
2. Steele, R. (2004). Understanding and measuring the shelf-life of food. Woodhead Publishing Ltd., 2004.
3. Ugraitskaya, S.V., Shishova, N.V., Valeeva, E.R., Kaurova, S.A., Shvirst, N.E., Fesenko, E.E. (2021).Cryopreservation of hela cells at a high hydrostatic pressure of 1.0–1.5 kBar. *Biophysics,* 66(1), 98–106. https://doi.org/10.1134/S0006350921010140
4. Martino, M.N., Otero, L., Sanz, P.D., Zaritzky, N.E. (1998). Size and location of ice crystals in pork frozen by high-pressure-assisted freezing as compared to classical methods. *Meat Science*, 50(3), 303–313. https://doi.org/10.1016/S0309-1740(98)00038-2
5. Sun, D.-W., Li, B. (2003). Microstructural change of potato tissues frozen by ultrasound-assisted immersion freezing. *Journal of Food Engineering,* 57(4), 337–345. https://doi.org/10.1016/S0260-8774(02)00354-0

6. Shi, Z., Zhong, S., Yan, W., Liu, M., Yang, Z., Qiao, X. (2019). The effects of ultrasonic treatment on the freezing rate, physicochemical quality, and microstructure of the back muscle of grass carp (*Ctenopharyngodon idella*). *LWT,* 111, 301–308. https://doi.org/10.1016/j.lwt.2019.04.071
7. Owada N. Kurita S. Super-quick freezing method and apparatus therefor. Patent US, no. 6250087B1, 2001.
8. Owada N. Highly-efficient freezing apparatus and highly-efficient freezing method. Patent US, no. 7237400B2, 2007.
9. Otero L., Pérez-Mateos, M., Rodríguez, A.C., Sanz, P.D. (2017). Electromagnetic freezing: Effects of weak oscillating magnetic fields on crab sticks. *Journal of Food Engineering,* 200, 87–94. https://doi.org/10.1016/j.jfoodeng.2016.12.018
10. James, C., Reitz, B.G., James, S. J. (2015). The freezing characteristics of garlic bulbs (Allium sativum L.) frozen conventionally or with the assistance of an oscillating weak magnetic field. *Food and Bioprocess Technology*, 8(3), 702–708. https://doi.org/10.1007/s11947-014-1438-z
11. Purnell, G., James, C., James, S.J. (2017). The effects of applying oscillating magnetic fields during the freezing of apple and potato. *Food and Bioprocess Technology*, 10, 2113–2122. https://doi.org/10.1007/s11947-017-1983-3
12. Yamamoto, N., Tamura, S., Matsushita, J., Ishimura, K. (2005). Fracture characteristics and tissue structure of chicken breast frozen by the dielectric freezing method. *Journal of Home Economics of Japan,* 56(3), 141–151. https://doi.org/10.11428/jhej1987.56.141
13. Rodríguez, A.C., James, C., James, S.J., (2017). Effects of weak oscillating magnetic fields on the freezing of pork loin. *Food and Bioprocess Technology,* 10, 1615–1621. https://doi.org/10.1007/s11947-017-1931-2
14. Fernández-Martín, F., Pérez-Mateos, M., Dadashi, S., Gómez-Guillén, C.M., Sanz, P.D. (2017). Impact of magnetic assisted freezing in the physicochemical and functional properties of egg components. Part 1: Egg white. *Innovative Food Science and Emerging Technologies,* 44, 131–138. https://doi.org/10.1016/j.ifset.2017.07.004
15. Fernández-Martín, F., Pérez-Mateos, M., Dadashi, S., Gómez-Guillén, C.M., Sanz, P.D. (2017). Impact of magnetic assisted freezing in the physicochemical and functional properties of egg components. Part 2: Egg yolk. *Innovative Food Science and Emerging Technologies*, 49, 176–183, https://doi.org/10.1016/j.ifset.2017.11.006
16. Suzuki, T., Takeuchi, Y., Masuda, K., Watanabe, M., Shirakashi, R., Fukuda, Y. et al. (2009). Experimental investigation of effectiveness of magnetic field on food freezing process. *Transactions of the Japan Society of Refrigerating and Air Conditioning Engineers*, 26(4), 371–386. https://doi.org/10.11322/tjsrae.26.371
17. Watanabe, M., Kanesaka, N., Masuda, K., Suzuki, T. (August 21–26, 2011). *Effect of oscillating magnetic field on supercooling in food freezing.* Proceedings of the 23rd IIR International Congress of Refrigeration. Prague, Czech Republic, 2011.
18. Okuda, K., Kawauchi, A., Yomogida, K. (2020). Quality improvements to mackerel (Scomber japonicus) muscle tissue frozen using a rapid freezer with the weak oscillating magnetic field. *Cryobiology*, 95, 130–137. https://doi.org/10.1016/j.cryobiol.2020.05.005
19. Tang, J., Shao, S., Tian, C., (2020). Effects of the magnetic field on the freezing process of blueberry. *International Journal of Refrigeration*, 113, 288–295, https://doi.org/10.1016/j.ijrefrig.2019.12.022
20. Tang, J., Zang, H., Tian, C., Shao, S. (2020). Effects of different magnetic fields on the freezing parameters of cherry. *Journal of Food Engineering,* 278, Article 109949. https://doi.org/10.1016/j.jfoodeng.2020.109949
21. Chen, A., Liu, Y., El Achkar, G., Li, E., Zhou, Q., Liu, B. (2021). Effects of magnetic field on freezing characters of carrot, potato and broccoli. *The European Physical Journal Applied Physics,* 93(1), 10201. https://doi.org/10.1051/epjap/2020200188
22. Tang, J., Shao, S., Tian, C. (2019). Effects of the magnetic field on the freezing parameters of the pork. *International Journal of Refrigeration*, 107, 31–38, https://doi.org/10.1016/j.ijrefrig.2019.07.019
23. Leng, D., Zhang, H., Tian, C., Xu, H., Li, P. (2022). The effect of magnetic field on the quality of channel catfish under two different freezing temperatures. *International Journal of Refrigeration,* 140, 49–56. https://doi.org/10.1016/j.ijrefrig.2022.05.008
24. Otero, L., Pozo, A. (2022). Effects of the application of static magnetic fields during potato freezing. *Journal of Food Engineering,* 316, Article 110838. https://doi.org/10.1016/j.jfoodeng.2021.110838
25. Baryshev, M.G., Lisitsyn, A.B., Polovodov Y. A., Polovodova, A.Y. (2019). Influence of a low–frequency magnetic field on process of formation of monocrystals of ice in the cooled muscular tissue. *Vsyo o Myase*, 2, 32–35. https://doi.org/10.21323/2071-2499-2019-3-32-35
26. Panayampadan, A.S., Alam, M.S., Aslam, R., Gupta, S.K., Sidhu, G.K. (2022). Effects of alternating magnetic field on freezing of minimally processed guava. *LWT,* 163, Article 113544. https://doi.org/10.1016/j.lwt.2022.113544
27. Mccabria, J. Generator auxiliary mode lubrication system and method. Patent CN, no.1054860, 1991.
28. Dongmei I., Huiming Z., Hainan Z., Changqing T. Magnetic field-assisted freezing-based instant freezer. Patent CN, no.113819701, 2021.
29. W. Wuliang, W., Jiatian, M., Lina, H., Chang, I., Peng, H. Supercooling freezing method and freezing device. Patent CN, no.111520948, 2020.
30. Zhao, H., Zhang, F., Liu, H., Han, J. (2017). Experimental study on freezing of liquids under static magnetic field. *Chinese Journal of Chemical Engineering*, 25(9), 1288–1293, https://doi.org/10.1016/j.cjche.2016.10.026
31. Cai, R., Yang, H., He, J., Zhu, W. (2009). The effects of magnetic fields on water molecular hydrogen bonds. *Journal of Molecular Structure,* 938(1–3), 15–19. https://doi.org/10.1016/j.molstruc.2009.08.037
32. Otero, L., Rodríguez, A.C., Sanz, P.D. (2018). Effects of static magnetic fields on supercooling and freezing kinetics of pure water and 0.9% NaCl solutions. *Journal of Food Engineering,* 217, 34–42. https://doi.org/10.1016/j.jfoodeng.2017.08.007
33. Zhang, L., Yang, Z., Deng, Q. (2021). Effects of pulsed magnetic field on freezing kinetics and physical properties of water and cucumber tissue fluid. *Journal of Food Engineering*, 288(9), Article 110149. https://doi.org/10.1016/j.jfoodeng.2020.110149
34. Anisimov, M.P. (2003). Nucleation: Theory and experiment. *Russian Chemical Review,* 72(7), Article 591. https://doi.org/10.1070/RC2003v072n07ABEH000761
35. Orlowska, M., Havet, M., Le-Bail, A. (2009). Controlled ice nucleation under high voltage DC electrostatic field conditions. *Food Research International*, 42(7), 879–884. https://doi.org/10.1016/j.foodres.2009.03.015
36. Dalvi-Isfahan, M., Hamdami, N., Le-Bail, A. (2016). Effect of freezing under electrostatic field on the quality of lamb meat. *Innovative Food Science & Emerging Technologies,* 37(Part A), 68–73. https://doi.org/10.1016/j.ifset.2016.07.028
37. Fallah-Joshaqani, S., Hamdami, N., Keshavarzi, E., Keramat, J., Dalvi-Isfahan, M. (2019). Evaluation of the static electric field effects on freezing parameters of some food systems.

International Journal of Refrigeration, 99, 30–36. https://doi.org/10.1016/j.ijrefrig.2018.12.011

38. Zhang, R., Ding, F., Zhang, Y., Zhou, C., Zhang, W., Shi, J. et al. (2022). Freezing characteristics and relative permittivity of rice flour gel in pulsed electric field assisted freezing. *Food Chemistry,* 373(Part A), Article 131449. https://doi.org/10.1016/j.foodchem.2021.131449
39. Li, J., Shi, J., Huang, X., Zou, X., Li, Z., Zhang, D. et al. (2020). Effects of pulsed electric field on freeze-thaw quality of Atlantic salmon. *Innovative Food Science and Emerging Technologies*, 65, Article 102454. https://doi.org/10.1016/j.ifset.2020.102454
40. Babakin, B.S., Voronin, M.I., Belozerov, G.A., Babakin, S.B. (August 24–30, 2019). *Study of freezing process and short-term storage of meat using electroconvection*. 25th IIR international congress of refrigeration "Refrigeration science and technology proceedings". Montreal, Quebec, Canada. 2019. https://doi.org/10.18462/iir.icr.2019.0215
41. Rogov, I.A., Babakin, B.S., Vygodin, V.A. (1996). Electrophysical methods in refrigeration and technology. Moscow: Kolos, 1996.
42. Vereschagin, I.P., Levitov, V.I., Mirzabekyan, G.Z., Pashin, M.M. (1974).Fundamentals of electro-gas dynamics of dispersed systems. Moscow: Energy, 1974.
43. Jha, P.K., Xanthakis, E., Jury, V., Le-Bail, A. (2017). An overview on magnetic field and electric field interactions with ice crystallisation; application in the case of frozen food. *Crystals,* 7(10), Article 299. https://doi.org/10.3390/cryst7100299
44. Xanthakis, E., Le-Bail, A., H. Ramaswamy, H. (2014). Development of an innovative microwave assisted food freezing process. *Innovative Food Science and Emerging Technologies,* 26, 176–181. https://doi.org/10.1016/j.ifset.2014.04.003
45. Roujia, Z., Shiyi L., Jiyong, S., Xiaobo, Z. Quick-freezing device with cooperating high-voltage pulse electric field and low-frequency alternating magnetic field and method for quick-freezing of instant rice through quick-freezing device. Patent CN, no. 114009660, 2022.
46. Kolodyazhnaya, V.S., Rumyantseva, O.N., Kiprushkina, E.I. (2023). The history and the prospects of food refrigeration. *Journal of International Academy of Refrigeration*, 1, 47–54. https://doi.org/10.17586/1606-4313-2023-22-1-47-54
47. Anese, M., Manzocco, L. Panozzo, A., Beraldo, P. Foschia, M., Nicoli, M.C. (2012). Effect of radiofrequency assisted freezing on meat microstructure and quality. *Food Research International,* 46(1), 50–54. https://doi.org/10.1016/j.foodres.2011.11.025

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