ELSEVIER

Journal of Food Engineering 54 (2002) 175–182

JOURNAL OF FOOD ENGINEERING

www.elsevier.com/locate/jfoodeng

# Novel methods for rapid freezing and thawing of foods – a review

Bing Li, Da-Wen Sun *

*FRCFT Group, Department of Agricultural and Food Engineering, University College Dublin, National University of Ireland, Earlsfort Terrace, Dublin 2, Ireland*

Received 10 August 2001; accepted 19 October 2001

**Abstract**

This paper reviews new developments in methods of freezing (high-pressure freezing, dehydrofreezing and applications of antifreeze protein and ice nucleation protein) and thawing (high-pressure and microwave thawing, ohmic thawing and acoustic thawing) for foods. With a good understanding of the solid–liquid phase diagram of water, the effects of pressure on food freezing–thawing cycles are highlighted. High-pressure freezing promotes uniform and rapid ice nucleation and growth through the whole sample. Dehydrofreezing has been successfully used in freezing of vegetables and fruits with the advantage of less damage to plant texture because of partial water removal before freezing. Recently, studies have been carried out for the biotechnological use of antifreeze and ice nucleation proteins because of their uniqueness in directly improving freezing processes. Thawing under pressure can be achieved at lower temperature than that at atmospheric pressures. Finally microwave, ohmic and acoustic thawing are described. It is hoped that this paper will attract more research in novel freezing and thawing processes and methods. 

*Keywords:* Acoustic; Antifreeze protein; Dehydrofreezing; Freezing; Freezing time; Foods; High pressure; Ice crystal; Ice nucleation protein; Microwave; Ohmic; Thawing

## 1. Introduction

Freezing preservation of food has been used for thousands of years because of high product quality (Persson & Londahl, 1993). Generally speaking, the quality of frozen food is closely related to freezing and thawing processes. The rate of freezing and the formation of small ice crystals in freezing are critical to minimise tissue damage and drip loss in thawing. Thawing generally occurs more slowly than freezing. During thawing foods are subject to damage by chemical and physical changes and microorganism. Therefore, optimum thawing procedures should be of concern to food technologists (Fennema, Powrie, & Marth, 1973; Kalichevsky, Knorr, & Lillford, 1995). Quick thawing at low temperature to avoid notably rising in temperature and excessive dehydration of food is desirable to assure food quality.

Currently, chemical and physical aids to freezing and thawing are developed with the consideration of energy saving and/or quality improvement. The aim of this paper is to present new developments in methods of freezing and thawing, and to discuss their potential applications in frozen food technology.

## 2. High-pressure freezing

When water is frozen at atmospheric pressure, its volume increases. This increase in volume is contributed to the ice I formed, which uniquely has a lower density than that of liquid water, resulting in a volume increase of about 9% on freezing at 0 °C, about 13% at −20 °C (Kalichevsky et al., 1995). This causes tissue damage in freezing. However, under high pressure, several kinds of ices (ice II–IX) are formed, their densities being greater than that of water. During phase transition, high-pressure ice (ice II–IX) does not expand in volume, which may reduce tissue damage. The frozen preservation of food would take advantage of the phase diagram of water. As shown in Fig. 1, changing the physical state of food can be achieved using external manipulation of temperature or pressure (Knorr, Schlueter, & Heinz, 1998). There is a water non-freezing region (liquid state) below 0 °C under high pressure. When pressure is

* Corresponding author. Tel.: +353-1-716-5528; fax: +353-1-4752119.
*E-mail address:* dawen.sun@ucd.ie (D.-W. Sun).
*Website:* www.ucd.ie/~refrig (D.-W. Sun).

0260-8774/02/$ - see front matter 
PII: S0260-8774(01)00209-6

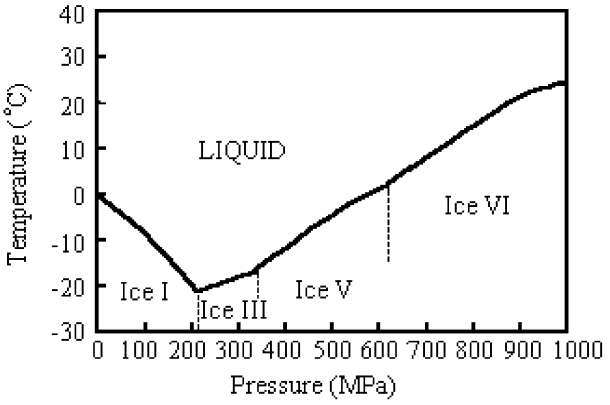


Fig. 1. Phase diagram of water (Kalichevsky et al., 1995; Zhao, Fores, & Olson, 1998).

released, a high supercooling can be obtained, as a result the ice-nucleation rate is greatly increased. Ice VI having a density of $1.31 \times 10^3$ kg/m$^3$ may be formed at room temperature at a pressure of 900 MPa. In other words, food materials can be frozen without any form of cooling. However, few experiments have been carried out in this area, owing to the high pressure required (Kalichevsky et al., 1995). It is noted that during reduction of pressure, water state would change, for example, ice VI $\rightarrow$ ice V $\rightarrow$ ice III $\rightarrow$ liquid $\rightarrow$ ice I, at $-20$ °C, as pressure is reduced from 600 MPa to atmospheric pressure.

With a good understanding of the water phase change, the use of high pressure can greatly aid freezing process and improve product quality. The main advantage of high-pressure freezing is that the initial formation of ice is instantaneous and homogeneous throughout the whole volume of the product because of the high supercooling reached on pressure release (Martino, Otero, Sanz, & Zaritzky, 1998; Sanz, Otero, Elvira, & Carrasco, 1997; Otero, Martino, Zaritzky, Solas, & Sanz, 2000). Therefore, this technology can be especially useful to freeze foods with large dimensions in which a uniform ice crystal distribution is required and where thermal gradients are pronounced and damage of freeze-cracking would be possible when applying classical freezing methods, including cryogenic freezing (Martino et al., 1998; Otero et al., 2000). The use of high pressure facilitates supercooling, promotes uniform and rapid ice nucleation and growth, and produces smaller crystals (Kalichevsky et al., 1995). From the microstructural point of view, damage to cells is minimised because of the small size of ice crystal, resulting in a significant improvement of product quality (Chevalier, Sentissi, Havet, & Le Bail, 2000; Fuchigami & Teramoto, 1997; Fuchigami, Kato, & Teramoto, 1998a,b; Martino et al., 1998).

These advantages have recently attracted a number of research activities dealt with high-pressure freezing. Martino et al. (1998) compared the size and location of ice crystal in large meat pieces obtained by high-pressure freezing with that by air-blast and liquid $N_2$, and found that high-pressure frozen samples showed uniform, small-sized ice crystals both at the surface and at the central zones whereas air-blast and cryogenic fluid freezing, having thermal gradients, showed non-uniform ice crystal distribution. Chevalier et al. (2000) reported that high-pressure freezing resulted in a reduction in the size of ice crystal and in a much preserved microstructure in comparison with air-blast frozen samples. However, they also pointed out that the operation of high-pressure freezing should adopt lower pressure levels to minimise pressure effects on proteins.

Fuchigami, Kato, and Teramoto (1997a,b) reported on textural and histological changes in high-pressure-frozen carrots. High-pressure freezing at 200, 340 and 400 MPa would be effective in improving both the texture and histological structure of frozen carrots. This result was in agreement with the findings on high-pressure-frozen Chinese cabbage and tofu (Fuchigami & Teramoto, 1997; Fuchigami et al., 1998a,b). Peach and mango were also cooled under pressure (200 MPa) to $-20$ °C without ice formation, then the pressure is released to 0.1 MPa. By scanning electron microscopy (SEM), it was observed that the cells were arranged adjacently without clear breakage, suggesting that this is the freezing method that best preserves vegetal microstructure (Otero et al., 2000).

However, Teramoto and Fuchigami (2000) reported that the textural and structure of konnyaku frozen at 0.1–700 MPa then thawed at atmospheric pressure changed greatly, and high-pressure freezing was ineffective in improving the texture of the frozen konnyaku.

Sanz et al. (1997) studied the relationship among pressure, temperature and specific volume in the liquid water region, ice I region and the boundary between both regions, and predicted the amount of ice appearing instantaneously in high-pressure freezing by mathematical modelling.

Japan has been at the forefront of high-pressure food processing – both in research and commercial developments, and the USA and European industries are exploring this technology (Swientek, 1992). Nowadays, the biggest obstacle to high-pressure processing is high capital costs (Mertens & Deplace, 1993). In the operation of high-pressure equipment at subzero temperature, the use of special steel for vessel design and suitable pressure-transmitting fluids is needed (Knorr et al., 1998). In order to improve quality and stability of operation, precise monitoring is also necessary.

## 3. Dehydrofreezing

Dehydrofreezing is a variant of freezing in which a food is dehydrated to a desirable moisture and then

frozen (Robbers, Singh, & Cunha, 1997; Spiazzi, Raggio, Bignone, & Mascheroni, 1998). Fresh fruits and vegetables contain more water than meat, and their cellular structure of cell wall, which is less elastic than cell membrane, could be susceptible to large ice crystal formed in freezing. Although increasing freezing rate can reduce the possibilities of the formation of large ice crystal, the tissue damage is still inevitable due to the presence of large amount of water. Dehydrofreezing provides a promising way to preserve fruits and vegetables by removing part of water from food materials prior to freezing (Biswal, Bozorgmehr, Tompkins, & Liu, 1991; Garrote & Bertone, 1989; Robbers et al., 1997). A reduction in moisture content would reduce the amount of water to be frozen, thus lowering refrigeration load during freezing. In addition, dehydrofrozen products could lower cost of packaging, distribution and storage, and maintain product quality comparable to conventional products (Biswal et al., 1991).

Successful applications of dehydrofreezing on fruits and vegetables have been reported (Garrote & Bertone, 1989; Spiazzi et al., 1998). Samples of fresh kiwi were immersed in 68% (w/w) aqueous sucrose solution to dehydrate for 3 h, then frozen in an air-blast freezer with an air velocity of 3 m/s at about −3 °C (Spiazzi et al., 1998). It was clearly observed that freezing starts at a lower temperature in the dehydrated product and the temperatures of dehydrated samples went down to −18 °C in 19–20 min, 20–30% faster as compared with untreated kiwi which required the freezing time of 23–24 min. It was suggested that the lower water content of dehydrated food always induces a lower freezing point and a shorter freezing time possibly because there is less water to freeze and consequently less heat to remove (Spiazzi et al., 1998). Garrote and Bertone (1989) found that strawberry halves osmotically treated in the presence of solution of glycerol, glucose and sucrose varying with different concentration, sustained a significantly smaller exudate loss ($p < 0.05$), while untreated fresh strawberry halves produced a larger amount of exudate. Similarly, melon samples which were dehydrated longer produced less exudate. This is in agreement with the lower water content and the presumably lower extent of structural damage caused by freezing (Spiazzi et al., 1998).

For frozen fruits and vegetables, except freezing rate and exudate, sensory characteristics and textures would be the important factors influencing their acceptability by consumers. Hardness, taste and overall acceptability were evaluated for dehydrofrozen green beans which were dehydrated by soaking in NaCl–water solution (Biswal et al., 1991). Based on the scores given by a taste panel, it was suggested that osmotically dehydrated frozen green beans were as good and equally acceptable as conventionally frozen green beans. Apples, melon, potato, carrot and peas after dehydrofreezing were used for suitable food preparation such as apple pie and melon ice cream. In all cases, these products showed good or better final consistency as conventionally frozen products (Spiazzi et al., 1998). Hence, dehydrofrozen products make their future market possible.

Partial dehydration constitutes the first stage of dehydrofreezing, whereas it influences the freezing process and quality of final products. Air drying and osmotic dehydration have been long used to remove part of water. Dehydration process efficiency has been evaluated in terms of rate and extent of water removal (Lazarides & Mavroudis, 1995). Therefore, presently more attention was paid to osmotic dehydration, which has advantages over air drying, such as adaptability to a wider variety of products and less-energy requirement. However, care should be taken when choosing the aqueous solution of high osmotic pressure since solute uptake often leads to substantial modification of the product composition with a negative impact on sensory characteristics (Dixon & Jen, 1977). Sucrose, which is used for osmotic dehydration of fruits, is not suitable for vegetables because of excessive sweetness from sucrose uptake. For vegetables, sodium chloride is commonly used. Other osmotic agents include glucose, fructose, lactose, maltodextrin, corn syrup, etc. (Biswal et al., 1991; Hawkes & Flink, 1978).

## 4. Antifreeze protein and ice nucleation protein

Controlling the growth of ice crystals in frozen foods is a primary concern to food technologists (Feeney & Yeh, 1998). Antifreeze protein and ice-nucleation protein (INP) can be directly added to food and interact with ice, therefore influencing ice crystal size and crystal structure within the food, which are two functionally distinct and opposite classes of proteins (Hew & Yang, 1992). Antifreeze proteins can lower the freezing temperature and retard recrystallisation on frozen storage, while ice-nucleation proteins raise the temperatures of ice nucleation and reduce the degree of supercooling (Feeney & Yeh, 1993; Li & Lee, 1998). Although these two proteins show opposite effects on ice crystals, they are potentially added in food, attracting more attention of food technologists.

### 4.1. Antifreeze protein

The early interest in antifreeze protein was caused by the observation of fishes that inhabit in polar and northern coastal waters whose freezing point is close to −1.9 °C or about 1 °C below the plasma freezing point of the fishes (Wen & Laursen, 1993). Antifreeze proteins found in the blood and tissues of the fishes were revealed to prevent fishes from freezing (Davies & Hew, 1990; Feeney & Yeh, 1993). Moreover, antifreeze proteins

have been reported to be present in many invertebrates including mostly insects and in higher plants as well as in fungi and bacteria (Griffith & Ewart, 1995).

Nowadays, the most studied proteins with antifreeze activity are from fish. Based on the presence or absence of carbohydrates, they are classified into two main types: glycoproteins and non-glycoproteins (Hew & Yang, 1992). Antifreeze glycoproteins (AFGP) are primarily composed of repeating units of two amino acid, one of them glycosylated (Feeney & Yeh, 1993). Non-glycoproteins called antifreeze proteins (AFP) for convenience can be further subdivided into three distinct antifreeze protein subtypes: the alanine-rich, α-helical ATP of right eye flounders and sculpins (type I), the cystine-rich AFP of the sea raven (type II), and an AFP (type III) found in eel pouts (Davies & Hew, 1990).

The function of the antifreeze proteins is to lower the freezing temperature and suppress the growth of ice nuclei, thus inhibiting ice formation and altering the ice habit and growth rate (Hew & Yang, 1992). It is generally accepted that antifreeze proteins function by binding to ice and interfering with water molecule propagation to crystal surface. Wen and Laursen (1993) proposed that the binding of AFPs to ice surface is a two-step process and suggested a model for the inhibition of ice crystal growth. In this model, patches or aggregates of AFP molecules bind tightly to the ice surface, allowing the ice lattice to grow only in the spaces between AFP molecules, hence decreasing the stability of the surface at the ice water interface. The addition of water to ice surface is unfavourable, then crystal growth is inhibited. Moreover, when antifreeze proteins are absorbed to ice faces, they tend to bind to ice prism faces. The dipole nature of the AFP might account for their preferential binding (Yang, Sax, Chakrabartty, & Hew, 1988). It is postulated that the dipole field of the α-helix would align dipole moments of individual water molecules in the ice crystal, thus inducing a dipole–dipole interaction between the protein molecule and the ice crystal. These interactions lead to specific absorption on the prismatic facets of ice, thus alter ice habit. Harrison et al. (1987) also presented the selective growth facet action of AFGP.

There is great promise of application of antifreeze proteins in foods with their abilities of depressing solution freezing temperature and inhibiting recrystallisation in freezing. However, practical applications are seldom reported. One potentially direct application is to inhibit recrystallisation of ice in dairy products such as ice cream and de-icing agents. The fine ice crystal in ice cream is very important to preserve its smooth and creamy texture. But recrystallisation occurs inevitably when temperature fluctuates in storage or in transit, resulting in coarse texture of ice cream and damage in quality. Warren, Mueller, and Mckown (1992) patented the addition of antifreeze protein to commercially available food products. The sample was a composite of a root beet shell with a heart of vanilla ice cream. After adding small quantities of antifreeze proteins, the sample was frozen at approximately −80 °C, then stored at −6 to −8 °C. After 1 h storage, very little ice crystal growth was observed in the sample with antifreeze protein, whereas the control sample showed a definite increase in ice crystal size.

The inhibition of recrystallisation of antifreeze protein may also be very useful in chilled and frozen meat, where large ice crystals may form intracellularly resulting in drip and loss of nutrition during thawing. Meat (bovine and ovine muscle) soaked in solutions of up to 1 mg/ml type I AFP or AFGP prior to freezing at −20 °C showed evidence of reduced ice crystal size (Payne, Sandford, Harris, & Young, 1994). Antifreeze protein can be incorporated into meat prior to freezing and still makes effects on meat quality of freezing and thawing. In the study of Payne and Young (1995), AFGP isolated from Antarctic Cod were injected intravenously into lambs at various times prior to slaughter. Samples of meat were vacuum packed and stored at −20 °C for 2–16 weeks. It was reported that the injection of AFGP at either 1 or 24 h before slaughter reduced drip loss and ice crystal size. Crystals were smallest in the lambs injected to a final concentration of 0.01 μg/kg AFGP, particularly when injected 24 h before slaughter.

The use of antifreeze protein in foods most likely will depend on the cost (Feeney & Yeh, 1998). At present, although commercial products of AFP or AFGP are sold, they are only suitable for research or special uses because of their high price. Chemical synthesis and genetic engineering may be a solution with the better understanding of the structure-function relationships.

### 4.2. Ice nucleation protein

Bacteria-induced ice nucleation has been recognised as a major contributing factor to frost injury in plants (Lindow, 1983; Lindow, Arny, & Upper, 1978). Bacterial ice nucleation activators can reduce the degree of supercooling and catalyse ice formation in and on frost sensitive plants between −1 and −5 °C, causing frost damage to many plants. The common species of ice nucleation active (INA) bacteria found to produce ice nucleation activator belong to genera *Pseudomonas, Erwinia* and *Xanthomonas*. However, because not all natural strains exhibit ice nucleating activity, those which produce INA substance are called $Ina^+$, and those which do not are $Ina^-$. The work of Phelps, Giddings, Prochoda, and Fall (1986) on isolation of cell-free ice nuclei from *E. herbicola MI* followed by a series of treatments supported that cell-free INA substance is associated with outer membrane vesicles. The bacterial ice nucleation phenotype is very susceptible to proteases and sulfhydryl-modifying chemicals indicating that a

protein is required for ice nucleating activity (Kozloff, Schofield, & Lute, 1983; Lindow, 1983). Phospholipid is also a requirement for expression of ice nucleating activity in *P. syringae* and in vitro (Govindarajan & Lindow, 1988). Li and Lee (1995) summarised that each protein consists of three distinguishable domain structures: a hydrophobic N-terminal domain, a hydrophilic C-terminal domain and a central repeating domain which is hydrophilic and particularly rich in alanine, glycine, serine and threonine.

$Ina^+$ bacterial cells and/or their products such as INP are great potential in the freezing of foods. They elevate the temperature of ice nucleation, shorten freezing time and change the texture of frozen foods, thus decreasing energy cost and improving the quality. For example, samples of egg white when freezing at −10 °C underwent supercooling lower than −6 °C, but when INA bacterial cells (*Erwinia ananas*) were added, the samples showed only a slight degree of supercooling (Arai & Watanabe, 1986). Similar results were also found in the case of using INA bacterial cells entrapped in calcium alginate gel (Watanabe, Watanabe, Kumeno, Nakahama, & Arai, 1989). Li and Lee (1998) reported that bacterial extracellular ice nucleators (ECINs) from *Erwinia ananas* were used for efficient freezing and texture modification. Different food systems such as liquid (milk, juice), semi-solid (ice cream) and solid (ground beef) were investigated. The degrees of supercooling were significantly reduced when 700 units of ECINs (70 g protein) were added to 10 ml samples freezing at −6 °C. In other words, the samples could achieve to −6 °C in a shorter time. However, ECINs did not apparently affect nucleation temperatures for solid foods such as ground beef (Li & Lee, 1998).

Arai and Watanabe (1986) proposed to use INA bacterial cells as heterogeneous ice nuclei to improve freezing texture. Egg white samples without INA bacterial cells froze at temperature as low as −15 °C and formed small ice crystals. On the other hand, the samples with the bacterial cells froze at −3 °C or slightly lower and formed large and long ice crystals and a flake-like texture. Such directional textures were also obtained by adding INA bacterial cells to isotropic aqueous dispersions of hydrogels composed of proteins and polysaccharides, such as bovine blood, 5–15% soybean protein isolate, soybean curd, milk cured, 0.5–2% agar, 5–20% corn starch paste and 0.5–2% glucomanna. Since the mechanical and sensory properties of foods are closely related to their texture, Li and Lee (1998) further reported that addition of ECINs markedly affected ice formation patterns. Ice crystals formed at −10 °C in the absence of ECINs seemed to be smooth, with no directionality and consisted of very fine particles. In contrast, in the presence of ECINs, ice crystals formed appeared to be ordered, with a defined directionality and uneven surfaces. Rice flour pasta with ECINs freezing and then thawing showed a higher degree of hardness and was easily fractured. Fibre-like texture which are desirable for some materials such as tofu, alkali-extracted red meat or poultry proteins can be produced using INA bacterial cells and/or their products.

As mentioned above, the use of INA bacterial cells and/or their products in food products can increase nucleation temperature, this improves the cost effectiveness. However, one major concern to their applications in the food industry is that bacterial ice nucleators must be safe, non-toxic and non-pathogenic (Li & Lee, 1995). If the whole bacterial cells are added, another consideration is to make sure that inedible microorganism is killed completely before food is consumed.

## 5. High-pressure thawing

High-pressure thawing would be another new application of high pressure on food industry. Though less attention has been paid to high-pressure thawing in comparison with high-pressure freezing, recently some research revealed that high-pressure thawing can preserve food quality and reduce the necessary thawing time (Makita, 1992; Zhao, Fores, & Olson, 1996; Zhao et al., 1998), suggesting its potential for the food industry.

Makita (1992) found that high-pressure thawing at frozen meat required only one-third of the time necessary at atmospheric pressure but produced sensory qualities comparable to those of conventionally thawed products. Teramoto and Fuchigami (2000) reported the improvement on the texture of konnyaku (konjac glucomannan gel) when konnyaku was frozen – then thawed at 200–400 MPa. Also, high-pressure thawing was more effective in texture improvement in frozen tofu than was atmospheric-pressure thawing. During high-pressure thawing, the drip loss of beef was too small to detect and there were no negative effects ($p < 0.05$) on colour, penetration force or cooking loss of thawed beef (Zhao et al., 1998).

The thawing rate depends only on the conduction of heat, as pressure is transmitted uniformly through the sample (Kalichevsky et al., 1995). Zhao et al. (1998) demonstrated that pressure level and treatment time affected thawing rate and product quality, while product characteristics, such as size and initial temperature, did not affect thawing rate, indicating that it is advantageous to thaw a larger amount of product at high pressure.

Limitations on the application of high-pressure thawing are mainly high cost, the same as high-pressure freezing encounters, and pressure-induced protein denaturation and meat discoloration (Kalichevsky et al., 1995; Mertens & Deplace, 1993). Therefore, studies on fundamental data influencing high-pressure thawing

process and its optimisation is important to its commercial application.

## 6. Microwave thawing

The unique property of microwaves to penetrate and produce heat deep within food materials (Tong, Lentz, & Lund, 1993) make them potential in accelerating thawing. Microwave thawing requires shorter thawing time and smaller space for processing, and reduces drip loss, microbial problems and chemical deterioration (Meisel, 1973; Rosenberg & Bogl, 1987; Virtanen, Goedeken, & Tong, 1997; Taoukis, Davis, Davis, Gordon, & Takmon, 1987). However, localised overheating (run-away heating) has limited the application of microwave thawing to food systems. The preferential absorption of microwaves by liquid water is a major cause for run-away heating. In this case, food products take risk of excess water loss and thermally chemical deterioration (Rosenberg & Bogl, 1987; Virtanen et al., 1997). The improvement on the temperature uniformity during microwave thawing is necessary. Tong et al. (1993) designed a microwave oven with variable continuous power and a feedback temperature controller to maintain a desired temperature gradient within a model food system. Using this apparatus, thawing time was reduced by as much as a factor of seven compared to convective thawing at atmospheric temperature when appropriate conditions were used.

The thawing rates of frozen samples in microwave thawing depend on material properties and dimensions and the magnitude and frequency of the electromagnetic radiation (Pangrle, Ayappa, Davis, Davis, & Gordon, 1991). Factors such as thermal properties varying with temperature, irregular shapes and heterogeneity of the food make the thawing process more complicated (Taoukis et al., 1987). In order to optimise thawing rate and effectively use microwaves, approaches to the problem of predicting thawing rate have been developed. The numerical solutions based on finite difference or finite element methods can approximate more realistically the actual process (Taoukis et al., 1987). Basak and Ayappa (1997) analysed microwave thawing of tylose slabs using the effective heat capacity method and obtained the microwave power, temperature and liquid volume fractions by finite element. Pangrle et al. (1991) modelled microwave thawing of pure water and 0.1 M NaCl cylinders using the finite elements method and demonstrated that a two-phase mushy region may exist and an additional thawing front may appear at the centre of the cylinder. Moreover, Taoukis et al. (1987) used modified isotherm migration method which treats the problem as the propagation of a phase front to solve a mathematical model of microwave thawing of homogeneous food products, model and experimental results for thawing a lean beef cylinder heated at low power using 2450 MHz frequency were compared well.

## 7. Ohmic thawing

When electric current passes through conducting food with high electrical resistance, heat is generated instantly inside the food, thus increasing the temperature of the food item (Fu & Hsieh, 1999). This heating technology is termed as ohmic heating or electro-heating. In the food industry, more attention has been paid to the application of ohmic heating on aseptic processing and pasteurisation of particulate foods. In comparison with microwave heating, ohmic heating is more efficient because nearly all of the energy enters the food as heat and ohmic heating has no limitation of penetration depth. Ohmic heating also has advantages over conventional heating such as high heating rate, high energy conversion efficiency, volumetric heating, etc. (Reznick, 1996; Fellows, 2000).

Using ohmic heating to thaw frozen foods is an innovative method. Ohtsuki (1991, 1993) patented an ohmic thawing process where frozen foods positioned with negative electrons were introduced into a high voltage electrostatic field. Using this method, frozen foodstuffs can be thawed rapidly in the temperature range $-3$ to 3 °C. For instance, the thawing time for frozen tuna, beef and eggs was shortened to 1/4–1/3 of that under the same temperature condition. Fuchigami, Hyakuumoto, Miyazaki, Nomura, and Sasaki (1994) investigated the effects of electrostatic thawing on texture and amount of cell damage. Light microscopy and transmission electronic microscopy for frozen carrots revealed that drip, cell damage and softening were prevented by ohmic thawing. The use of an alternating electric field would be more beneficial because an electrostatic field would cause electrolysis and thus require expensive electrodes. Yun, Lee, and Park (1998) examined ohmic thawing of frozen chucks of meat in combination with conventional water immersion thawing with 60–210 V (a.c.) at frequencies of 60 Hz–60 kHz. It was found that frequency changes did not significantly affect thawing time and ohmically thawed samples showed reduced drip loss and improved water holding capacity when lower voltages were applied.

Ohmic heating technology shows potential in supplying thawed foodstuffs of high quality. However, at present very little research on ohmic thawing has been carried out.

## 8. Acoustic thawing

The utilisation of acoustic energy to thaw frozen foodstuffs was investigated about 50 years ago, however,

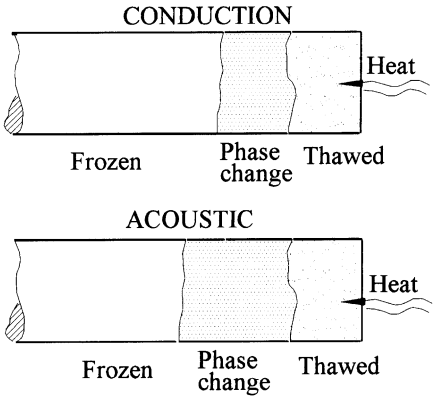


Fig. 2. Effect of ice relaxation frequency acoustic waves on the phase change region as compared to passive conduction heating.

the negative aspects of poor penetration, localised heating and high power requirement hindered the development of this method (Brody & Antenevich, 1959). Recently, work on relaxation mechanism showed more acoustic energy could be absorbed by frozen foods when a frequency in the relaxation frequency range of ice crystals in the food was applied (Kissam, Nelson, Ngao, & Hunter, 1981). Kissam et al. (1981) illustrated the thawing process under the relaxation frequency (Fig. 2). Compared with a thawing process only using conductive heating, the frozen front approaches faster, namely higher thawing rate. Experiments showed that blocks of cod required 71% less time by using acoustically assisted water immersion thawing than that with water immersion only when 1500 Hz acoustic energy at 60 watts was applied. Miles, Morley, and Rendell (1999) applied high power ultrasound to thaw meat and fish, their work indicated that acceptable ultrasonic thawing was achieved at frequencies around 500 kHz, which conformed to relaxation mechanism. Therefore, acoustic thawing still is a promising technology in the food industry if proper frequencies and acoustic power are chosen.

## 9. Conclusions

Freezing and thawing processes are complex, involving heat transfer and possibilities of a series of physical and chemical changes which may greatly affect product quality. From energy saving or quality improving point of view, new methods are necessary. The novel freezing methods of high-pressure freezing and dehydrofreezing accelerate freezing process, thus forming small and uniform ice crystals, and the use of antifreeze and ice nucleation proteins improve freezing process directly by interacting with ice crystals formed. The innovative thawing methods of high-pressure thawing, microwave thawing, ohmic thawing and acoustic thawing can shorten thawing time, thus reducing drip loss and improving product quality. It is hoped that the paper would attract more research in novel freezing and thawing processes and methods.

## References

Arai, S., & Watanabe, M. (1986). Freeze texturing of food materials by ice-nucleation with the bacterium *Erwinia ananas*. *Journal of Biological Chemistry, 50*(1), 169–175.

Basak, T., & Ayappa, K. G. (1997). Analysis of microwave thawing of slabs with effective heat capacity method. *AlChE Journal, 43*(7), 1662–1674.

Biswal, R. N., Bozorgmehr, K., Tompkins, F. D., & Liu, X. (1991). Osmotic concentration of green beans prior to freezing. *Journal of Food Science, 56*(4), 1008–1011.

Brody, A. L., & Antenevich, J. N. (1959). Ultrasonic defrosting of frozen foods. *Food Technology, 13*, 109–110.

Chevalier, D., Sentissi, M., Havet, M., & Le Bail, A. (2000). Comparison of air-blast and pressure shift freezing on Norway lobster quality. *Journal of Food Science, 65*(2), 329–333.

Davies, P. L., & Hew, C. L. (1990). Biochemistry of fish antifreeze proteins. *FASEB, 4*, 2460–2468.

Dixon, G. M., & Jen, J. J. (1977). Changes of sugars and acids of osmovacuum-dried apple slices. *Journal of Food Science, 42*, 1126–1127.

Feeney, R. E., & Yeh, Y. (1993). Antifreeze proteins: properties mechanism of action and possible applications. *Food Technology* (January), 82–88, 90.

Feeney, R. E., & Yeh, Y. (1998). Antifreeze proteins: current status and possible food uses. *Trends in Food Science and Technology, 9*, 102–106.

Fellows, P. (2000). *Food processing technology – principles and practice* (2nd ed., pp. 369–380). Chichester, UK: Ellis Horwood.

Fennema, O. R., Powrie, W. D., & Marth, E. H. (1973). *Low-temperature preservation of foods and living matter* (p. 598). New York, USA: Marcel Dekker.

Fu, W. R., & Hsieh, C. C. (1999). Simulation and verification of two-dimensional ohmic heating in static system. *Journal of Food Science, 64*(6), 946–949.

Fuchigami, M., Hyakuumoto, N., Miyazaki, K., Nomura, T., & Sasaki, J. (1994). Texture and histological structure of carrots frozen at a programmed rate and thawed in an electrostatic field. *Journal of Food Science, 59*(6), 1162–1167.

Fuchigami, M., & Teramoto, A. (1997). Structural and textural changes in kinu-tofu due to high-pressure-freezing. *Journal of Food Science, 62*(4), 828–837.

Fuchigami, M., Kato, N., & Teramoto, A. (1997a). High-pressure-freezing effects on textural quality of carrots. *Journal of Food Science, 62*(4), 804–808.

Fuchigami, M., Miyazaki, K., Kato, N., & Teramoto, A. (1997b). Histological changes in high-pressure-frozen carrots. *Journal of Food Science, 62*(4), 809–812.

Fuchigami, M., Kato, N., & Teramoto, A. (1998a). High-pressure-freezing effects on textural quality of Chinese cabbage. *Journal of Food Science, 63*(1), 122–125.

Fuchigami, M., Teramoto, A., & Ogawa, N. (1998b). Structural and textural quality of kinu-tofu frozen-then-thawed at high-pressure. *Journal of Food Science, 63*(6), 1054–1057.

Garrote, R. L., & Bertone, R. A. (1989). Osmotic concentration at low temperature of frozen strawberry halves. Effect of glycerol glucose, and sucrose solution on exudate loss during thawing. *Food Science and Technology, 22*, 264–267.

Govindarajan, A. G., & Lindow, S. E. (1988). Phospholipid requirement for expression of ice nuclei in *Pseudomonas syringae* and in vitro. *Journal of Biology Chemistry, 263*(19), 9333–9338.

Griffith, M., & Ewart, K. V. (1995). Antifreeze proteins and their potential use in frozen foods. *Biotechnology Advance, 13*(3), 373–402.

Harrison, K., Hallett, J., Burcham, T. S, Feeney, R. E., Kerr, W. L., & Yeh, Y. (1987). Ice growth in supercooled solutions of antifreeze glycoproteins. *Nature, 328*, 241–243.

Hawkes, J., & Flink, J. M. (1978). Osmotic concentration of fruit slices prior to freeze dehydration. *Journal of Food Processing and Preservation, 2*, 265–284.

Hew, C. L., & Yang, D. S. C. (1992). Protein interaction with ice. *European Journal of Biochemistry, 203*, 33–42.

Kalichevsky, M. T., Knorr, D., & Lillford, P. J. (1995). Potential food applications of high-pressure effects on ice-water transitions. *Trends in Food Science and Technology, 6*, 253–258.

Kissam, A. D., Nelson, R. W., Ngao, J., & Hunter, P. (1981). Water-thawing of fish using low frequency acoustics. *Journal of Food Science, 47*, 71–75.

Knorr, D., Schlueter, O., & Heinz, V. (1998). Impact of high hydrostatic pressure on phase transitions of foods. *Food Technology, 52*(9), 42–45.

Kozloff, L. M., Schofield, M. A., & Lute, M. (1983). Ice-nucleating activity of *Pseudomonas syringae* and *Erwinia herbicola*. *Journal of Bacteriology, 153*, 222–234.

Lazarides, H. N., & Mavroudis, N. E. (1995). Freeze/thaw effects on mass transfer rates during osmotic dehydration. *Journal of Food Science, 60*(4), 826–828, 857.

Li, J., & Lee, T. C. (1995). Bacterial ice nucleation and its potential application in the food industry. *Trends in Food Science and Technology, 6*, 259–265.

Li, J., & Lee, T. C. (1998). Bacterial extracellular ice nucleator effects on freezing of foods. *Journal of Food Science, 63*(3), 375–381.

Lindow, S. E., Arny, D. C., & Upper, C. D. (1978). *Erwinia herbicola*: an active ice nuclei incites frost damage to maize. *Phytopathology, 68*, 523–527.

Lindow, S. E. (1983). The role of bacterial ice nucleation in frost injury to plants. *Annual Review Phytopathology, 21*, 363–384.

Makita, T. (1992). Application of high pressure and thermophysical properties of water to biotechnology. *Fluid Phase Equilibrium, 76*, 87–95.

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.

Meisel, N. (1973). Microwave applications to food processing and food systems in Europe. *Journal of Microwave Power, 8*(2), 143–146.

Mertens, B., & Deplace, G. (1993). Engineering aspects of high-pressure technology in the food industry. *Food Technology, 47*(6), 164–169.

Miles, C. A., Morley, M. J., & Rendell, M. (1999). High power ultrasonic thawing of frozen foods. *Journal of Food Engineering, 39*, 151–159.

Ohtsuki, T. (1991). *Process for thawing foodstuffs*. US Patent 5,034, 236.

Ohtsuki, T. (1993). *Process for thawing foodstuffs*. European Patent 0409430.

Otero, L., Martino, M., Zaritzky, N., Solas, M., & Sanz, P. D. (2000). Preservation of microstructure in peach and mango during high-pressure-shift freezing. *Journal of Food Science, 65*(3), 466–470.

Pangrle, B. J., Ayappa, K. G., Davis, H. T., Davis, E. A., & Gordon, J. (1991). Microwave thawing of cylinders. *AlChE Journal, 37*(12), 1789–1800.

Payne, S. R., Sandford, D., Harris, A., & Young, O. A. (1994). The effects of antifreeze proteins on chilled and frozen meat. *Meat Science, 37*, 429–438.

Payne, S. R., & Young, O. A. (1995). Effect of pre-slaughter administration of antifreeze proteins on frozen meat quality. *Meat Science, 41*, 147–155.

Persson, P. O., & Londahl, G. (1993). Freezing technology. In C. P. Mallett (Ed.), *Frozen food technology* (pp. 20–58). Glasgow, UK: Blackie Academic & Professional.

Phelps, P., Giddings, T. H., Prochoda, M., & Fall, R. (1986). Release of cell-free ice nuclei by *Erwinia herbicola*. *Journal of Bacteriology, 167*(2), 496–502.

Reznick, D. (1996). Ohmic heating of fluid foods. *Food Technology* (May), 250–251.

Robbers, M., Singh, R. P., & Cunha, L. M. (1997). Osmotic-convective dehydrofreezing process for drying kiwifruit. *Journal of Food Science, 62*(5), 1039–1042, 1047.

Rosenberg, U., & Bogl, W. (1987). Microwave thawing, drying, and baking in the food industry. *Food Technology* (June), 85–91.

Sanz, P. D., Otero, L., Elvira, C. D., & Carrasco, J. A. (1997). Freezing processes in high-pressure domains. *International Journal of Refrigeration, 20*(5), 301–307.

Spiazzi, E. A., Raggio, Z. I., Bignone, K. A., & Mascheroni, R. H. (1998). Experiments on dehydrofreezing of fruits and vegetables: mass transfer and quality factors. *Advances in the Refrigeration Systems, Food Technologies and Cold Chain, IIF/IIR, 6*, 401–408.

Swientek, R. J. (1992). High hydrostatic pressure for food preservation. *Food Processing* (November), 90–91.

Taoukis, P., Davis, E. A., Davis, H. T., Gordon, J., & Takmon, Y. (1987). Mathematical modelling of microwave thawing by the modified isotherm migration method. *Journal of Food Science, 52*(2), 455–463.

Teramoto, A., & Fuchigami, M. (2000). Changes in temperature texture and structure of konnyaku (konjac glucomannan gel) during high-pressure-freezing. *Journal of Food Science, 65*(3), 491–497.

Tong, C. H., Lentz, R. R., & Lund, D. B. (1993). A microwave oven with variable continuous power and a feedback temperature controller. *Biotechnology Progress, 9*, 488–496.

Virtanen, A. J., Goedeken, D. L., & Tong, C. H. (1997). Microwave assisted thawing of model frozen foods using feed-back temperature control and surface cooling. *Journal of Food Science, 62*(1), 150–154.

Warren, C. J., Mueller, C. M., & Mckown, R. L., (1992). *Ice crystal growth suppression polypeptides and methods of preparation*. US Patent 5,118,792.

Watanabe, M., Watanabe, J., Kumeno, K., Nakahama, N., & Arai, S. (1989). Freeze concentration of some foodstuffs using ice nucleation-active bacterial cells entrapped in calcium alginate gel. *Journal of Biological Chemistry, 53*(10), 2731–2735.

Wen, D., & Laursen, R. A. (1993). Structure-function relationships in an antifreeze polypeptide. *Journal of Biological Chemistry, 268*(22), 16401–16405.

Yang, D. S. C., Sax, M., Chakrabartty, A., & Hew, C. L. (1988). Crystal structure of an antifreeze polypeptide and its mechanistic implications. *Nature, 333*, 232–237.

Yun, C. G., Lee, D. H., & Park, J. Y. (1998). Ohmic thawing of a frozen meat chunk. *Journal of Food Science and Technology (Korean), 30*(4), 842–847.

Zhao, Y. Y., Fores, R. A., & Olson, D. G. (1996). The action of high hydrostatic pressure on the thawing of frozen meat. *Annual Meeting of Institute of Food Technologist, New Orleans, LA* (June), 22–26.

Zhao, Y. Y., Fores, R. A., & Olson, D. G. (1998). High hydrostatic pressure effects on rapid thawing of frozen beef. *Journal of Food Science, 63*(2), 272–275.