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# Using Power Ultrasound to Accelerate Food Freezing Processes: Effects on Freezing Efficiency and Food Microstructure

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**Abstract**

Freezing is an effective way of food preservation. However, traditional freezing methods have the disadvantages of low freezing efficiency and generation of large ice crystals, leading to possible damage of food quality. Power ultrasound assisted freezing as a novel technique can effectively reduce the adverse effects during freezing process. This paper gives an overview on recent researches of power ultrasound technique to accelerate the food freezing processes and illustrates the main principles of power ultrasound assisted freezing. The effects of power ultrasound on liquid food, model solid food as well as fruit and vegetables are discussed, respectively, from the aspects of increasing freezing rate and improving microstructure. It is shown that ultrasound assisted freezing can effectively improve the freezing efficiency and promote the formation of small and evenly distributed ice crystals, resulting in better food quality. Different inherent properties of food samples affect the effectiveness of ultrasound application and optimum ultrasound parameters depend on the nature of the samples. The application of ultrasound to the food industry is more likely on certain types of food products and more efforts are still needed to realize the industrial translation of laboratory results.

**Keywords:** freezing, power ultrasound, texture, ice crystals, microstructure

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## 1. Introduction

Freezing, as an effective way of food preservation, is widely used in the modern food industry (Dalvi-Isfahan et al., 2017). Freezing process can effectively increase the shelf life of food products by reducing the water activity and enzyme activity of food. However, if slow freezing occurs during crystallization and temperature fluctuation happens during storage, large ice crystals are formed, thus causing damage to cell structure of food products and resulting in serious drip loss of thawed food with poor food quality. Generally speaking, the freezing rate of conventional methods such as air blast freezing (Boonsumrej et al., 2007), contact freezing (Robertson et al., 1976) and immersion freezing (Liang et al., 2015) remain relatively low, which could lead to the formation of the large ice crystals. Therefore, novel techniques such as high-pressure freezing (Norton and Sun, 2008), electrically and magnetically disturbed freezing (Cheng et al., 2017), microwave-assisted freezing (Xanthakis et al., 2014) and ultrasound-assisted freezing (Zheng and Sun, 2006) have been investigated for possible improvement in frozen food quality by generating small and evenly distributed ice crystals. Among them, ultrasound-assisted freezing has been extensively studied in the past decade.

Ultrasound, as an effective way for enhancing food processes, has attracted much interest among researchers (Chemat and Khan, 2011; Rastogi, 2011). Generally speaking, according to the intensity and frequency, the applied range of ultrasound can be divided into two categories (Tao and Sun, 2015). The first is low-intensity diagnostic ultrasound with high frequency ranging from 5 to 10 MHz (Zheng and Sun, 2006). Because of the high frequency and low intensity, the ultrasound propagation medium only has little effect in the propagation process (Zhang et al., 2015). As a result, this type of ultrasound is usually used as an analytical technique in non-destructive inspection, process analysis and quality control (Awad et al., 2012), for example, it can be used to monitor the formation of nuclei and the growth of ice crystals due to the difference in ultrasound transmission speed between solid and liquid (Xu et al., 2017). Sigfusson et al. (2004) measured the flight time of ultrasound pulse moving parallel to heat flux in blocks of gelatin, chicken and beef and found that ultrasound could be used to reasonably estimate the degree of freezing and total freezing time. The other is the high intensity power ultrasound with low frequency approximately in the range of 20–100 kHz, which could generate physical and chemical interactions during the transmission. As this type of ultrasound has significant effects on food processes, it has been widely used for enhancing food processing, such as freezing, extraction, drying, thawing, meat tenderization and so on (Tao and Sun, 2015; Dolatowski et al., 2007; Vilkhu et al., 2008; Garcia-Perez et al., 2012; Cheng et al., 2014b; Lee and Feng, 2011). In particular, it is proved that power ultrasound is an effective technology for preserving food microstructure during freezing due to the promotion of the formation of nuclei and the control of the size and distribution of ice crystals (Zheng and Sun, 2006), in addition, power ultrasound shows its great benefits in improving heat and mass transfer, thus significantly reducing the freezing time.

Ultrasound-assisted freezing as a novel and effective technology is developed rapidly and many studies are published and progresses are made about the effects of power ultrasound on liquid food, model solid food as well as fruit and vegetables during freezing processes. Although there are some review papers illustrating the principle of ultrasound assisted freezing and the effect of ultrasound on the freezing rate, the size and shape of ice crystals, and food quality, there is no review available to summarize research progresses on liquid food, model solid food as well as fruit and vegetables from two key aspects of freezing efficiency and food microstructure. Therefore, in the current review, an overview on recent studies concerning power ultrasound on accelerating the freezing processes is provided, and its principles and mechanisms are elucidated. In addition, effects of power ultrasound on liquid food, model solid food as well as fruit and vegetables are discussed respectively from the aspects of increasing freezing rate and improving microstructure, and future trends of this technology are also proposed.

## 2. Principles of Power Ultrasound for Freezing Acceleration

### 2.1 Effects of acoustic cavitation

Power ultrasound is a mechanical wave, which induces a series of compression and rarefaction cycles during the propagation through a medium (Fig.1). When the ultrasonic power is high enough, the negative pressure induced by the rarefaction may exceed the attractive forces during the ultrasound transmission, resulting in the formation of bubbles or cavities (Cheng et al., 2015). Cavitation effects can be divided into two categories: stable cavitation and transient cavitation (Zheng and Sun, 2006). Stable cavitation usually occurs at low acoustic pressure, in which the cavitation bubbles gradually grow up without collapse during the compression and rarefaction cycles of ultrasound, as long as these bubbles do not reach the critical size for collapsing. On the contrary, transient cavitation takes place when the cavitation bubbles reach a critical size and bubble collapse occurs violently, resulting in extreme high temperature (up to 5000 K) and pressure(up to 100 MPa) (Cheng et al., 2015). In addition, water molecules can break down into highly reactive free radicals at extremely high temperatures and pressures, and these free radicals are able to affect other molecules and facilitate chemical reactions (Riesz and Kondo, 1992).

Besides, the cavitation effect induced by power ultrasound is able to promote the formation of nucleation. It is proved that cavitation bubbles can act as nuclei when these bubbles reach the critical size for nucleation (Mason et al., 1996). Therefore, ultrasound-assisted freezing can promote primary nucleation in solutions without pre-existing crystals as shown during the nucleation process in supercooled aqueous solutions (Chow et al., 2003; Chow et al., 2004; Chow et al., 2005).

Saclier et al. (2010b) illustrated that power ultrasound could be used in the industry to initiate the nucleation of organic molecules while Xu et al. (2014) demonstrated that the application of power ultrasound was able to induce nucleation during the freezing process of radish cylinders, and it is normally considered that the nucleation occurs immediately after the collapse of cavitation bubbles. However, some studies indicated a period of delay between the collapse of cavitation bubbles and the occurrence of nucleation (Inada et al., 2001; Chow et al., 2005; Hu et al., 2013). On the other hand, the pressure gradient and high supercooling degrees created by the collapse of cavitation bubbles can also result in the formation of ice nucleation (Dodds et al., 2007; Grossier et al., 2007).

### 2.2 Effects of microstreaming

Microstreaming is a phenomenon closely associated with cavitation, which produces continuous turbulence in the medium and promote physical and chemical reactions during processing (Simal et al., 1998; Zheng and Sun, 2006). As shown in Fig. 2, the motion of stable cavitation bubbles can cause microstreaming, which occurs during the propagation of acoustic oscillations (Kiani et al., 2015). These bubbles are stable and isolated without the occurrence of collapse phenomenon (Ashokkumar, 2011) and the surrounding air diffuses into or out of the bubbles constantly with the assistance of flow streams, contributing to the occurrence of mixing effects during the oscillation of air bubbles in liquid medium (Chow et al., 2003; Kiani et al., 2011). Moreover, the turbulence generated by microstreaming is able to improve heat and mass transfer (Zhang et al., 2015).

Some studies also show that microstreaming induced by stable cavitation appears to promote the nucleation process. Zhang et al. (2003) observed two kinds of water containing bubbles of different size distributions during the ultrasound-assisted freezing process and found that there was a time lag of about 0.5 s between the application of ultrasound and occurrence of nucleation when the water was supersaturated with air bubbles. However, their results are different from Hickling's theory (Hickling, 1965), in which the occurrence of ice nucleation is induced by the high degree of supercooling when bubbles collapse, namely, nucleation occurs immediately after the collapse of cavitation bubbles. It is suggested that microstreaming is likely to promote the occurrence of nucleation, which was also confirmed by Chow et al. (2005), who suggested that secondary nucleation was probably induced by the microstreaming effect based on microscopic observation.

## 2.3 Enhancement of heat and mass transfer

Generally speaking, improving heat and mass transfer rate, which is closely associated with the freezing rate, can significantly accelerate the freezing process (Zheng and Sun, 2006). Application of power ultrasound can effectively improve heat and mass transfer during freezing (Li and Sun, 2002b) due to the violent turbulence induced by cavitation and microstreaming. Cavitation bubbles are generated inside liquid medium and mass transfer is improved when the bubbles escape from the surface of the liquid, which contributes to the enhancement of heat transfer at the surface (Gao et al., 2017). On the other hand, if cavitation bubbles are broken near solid-liquid interface, the violent agitation generated by the collapse breaks the boundary layers, thus reducing the heat and mass transfer resistance close to the interface and improving the freezing efficiency (Li and Sun, 2002a; Zheng and Sun, 2006). The improvement of heat and mass transfer efficiency in turn facilitates the generation of ice nucleation and the process of ice crystal growth (Cheng et al., 2017).

The positive effects of ultrasound on the improvement of heat transfer have been confirmed by experiments. Kiani et al. (2012b) studied the heat transfer phenomenon by applying power ultrasound on a stationary copper sphere during the cooling process. Their experimental observation demonstrated that acoustic streaming and the cavitation clouds at the sphere surface led to a high heat transfer rate and the intensity of power ultrasound was closely associated with the cooling rate. However, high intensity of ultrasound could lead to the generation of thermal effect at the sphere surface, which might lower the cooling rate and limit the final temperature achieved. Kiani et al. (2013a) also studied the effect of power ultrasound on the enhancement of heat transfer between cooling medium and a stationary copper sphere at different Reynolds (Re) and Prandtl (Pr) numbers. The results indicated that ultrasound could effectively enhance the heat transfer rate between the submerged object and the cooling medium, and cooling medium with low flowrates and high viscosities could consult in high heat transfer rate. It was also proved that the application of ultrasound during convective drying process could increase mass transfer and effective moisture diffusion (Fan et al., 2017). Ozuna et al. (2011) found that ultrasound with 37 $kW/m^3$ intensity and at 40 °C could effectively increase the effective moisture diffusivity by 64 % and mass transfer coefficient by 58 % during convective drying process of potato. Su et al. (2018a, b) studied the combined effects of ultrasound and microwave on water removal and the quality of purple-fleshed potato during vacuum frying and found that the ultrasound and microwave-assisted vacuum frying could effectively increase the effective moisture diffusivity from $0.693 \times 10^{-8}$ $m/s^2$ to $1.099 \times 10^{-8}$ $m/s^2$ at the frying temperature of 90 °C.

## 3. Effects on Freezing Efficiency

Power ultrasound can be applied during the freezing processes of liquid food, model solid food and solid food. As shown in Table 1, a number of studies show that the application of power ultrasound can effectively enhance the freezing rate. The effects of ultrasound on facilitating the freezing process can be attributed to the following aspects. Firstly, the cavitation and microstreaming effects generated by ultrasound irradiation can effectively enhance the heat transfer and mass transfer rate between the freezing medium and food, resulting in the improvement of freezing rate. Secondly, the application of ultrasound can increase the nucleation temperature, which contributes to the occurrence of nucleation at higher temperatures and promote the nucleation process, and thus reducing the freezing time. Thirdly, gas bubbles induced by the cavitation can act as nuclei and promote the generation of multiple nucleation sites, leading to the enhancement of nucleation rate. Finally, large ice crystals could be broken into small ones under the application of ultrasound, which can also increase the nucleation sites.

### 3.1 Liquid foods

Water is the main component in foods, which involves lots of chemical reactions during processing and has a significant impact on the quality attributes of food products, such as viscosity, texture, flavour and so on. Studying the behaviour of water during ultrasound-assisted freezing contributes to the understanding of similar processes in other systems (Zhang et al., 2015). Chow et al. (2005) investigated the effects of different intensity levels of ultrasound on freezing of sucrose solutions and showed that increasing power intensity from 1 to 7 a.u. was able to increase the nucleation temperature from about -4.3 to -2.9 ◦C, thus promoting early occurrence of nucleation and accelerating the freezing process.

Effects of air bubbles on nucleation during ultrasound assisted freezing process in liquid samples such as sucrose solution and water have been also studied. Hu et al. (2013) investigated the effect of power ultrasound on the nucleation temperature and the delay between the application of power ultrasound and the occurrence of nucleation, and showed that the delay time in samples containing bubbles was the shortest, probably because the bubbles could act as cavitation bubbles and nuclei, thus enhancing the occurrence of the nucleation process. Yu et al. (2012) studied the nucleation process of degassed water and pure water by applying ultrasound on supercooled samples. The nucleation temperatures of both pure water and degassed water were increased after applying ultrasound from 0.0 to 0.49 $W/cm^2$, especially the supercooling of pure water on promoting nucleation was less than that of degassed water. These studies indicate that air bubbles, either pre-existed or generated by power ultrasound, could effectively promote the initiation of nucleation and facilitate the freezing process.

Although power ultrasound has the above advantages, it also has some inherent limitations. For example, generation of undesirable flavour and the destruction of nutrients would occur during the application of power ultrasound on oil (Chemat et al., 2004). In addition, the instantaneous high temperature and pressure generated by the collapse of cavitation bubbles may contribute to the formation of free radicals and the dissociation of molecules (Goskonda et al., 2002). The free radicals generated by cavitation can initiate free radical chain reactions and accelerate some physicochemical reactions and oxidation processes. Therefore, the mechanisms of these adverse reactions should be further understood in order to overcome these adverse effects.

## 3.2 Model solid foods

Besides liquid foods, freezing of model solid foods assisted by ultrasound has also been studied. The nucleation and crystallization process of model solid foods is easy to observe, which can provide a reference for solid foods, such as meat, fruit and vegetables. The improvement of nucleation rate and the generation of multiple nucleation sites can effectively enhance the freezing efficiency. Kiani et al. (2012a) investigated the effect of ultrasound irradiation temperature, intensity and exposure time on the nucleation process of ice crystals in agar gel samples, and showed that the ultrasound irradiation time of 1 s was not enough to induce nucleation but 3 s could repeatedly induce the nucleation, however longer exposure time led to the generation of thermal effect, thus delaying nucleation. Therefore, choosing suitable irradiation duration is important for inducing and promoting the nucleation process. In addition, pre-existing bubbles and infusion of $CO_2$ can also have an effect on the efficiency of freezing process. Xu et al. (2016) researched the effect of injection of $CO_2$ in gelatin gel during ultrasound-assisted freezing and indicated that the combined effect of $CO_2$ infusion and power ultrasound had positive effects on freezing time, ice crystal size and distribution and water mobility of gelatin gel samples. Compared to immersion freezing, the infusion of $CO_2$ and ultrasound combined treatment could decrease the freezing time by about 20 % during the freezing process.

In the food industry, ultrasound is also employed for manufacturing ice cream and its application could significantly enhance the freezing rate and sensory property of ice cream. Cavitation can not only contribute to the generation of air bubbles in ice cream, which can act as nuclei for crystallization, but can also lead to micro-streaming and enhanced heat and mass transfer as shown by Mortazavi and Tabatabaie (2008), who experimented the application of 20 kHz frequency ultrasound on ice cream manufacture process. Their results indicated that the application of power ultrasound could accelerate the freezing process of ice cream and improve the sensory quality of ice cream. Compared to conventional freezing methods, the freezing time was shortened by 65 % when applying ultrasound for 20 min (Mortazavi and Tabatabaie, 2008).

### 3.3 Fruit and vegetables

Fruit and vegetables are prone to the occurrence of deterioration reaction, which causes damage to the sensory values such as texture, flavour and taste (Lespinard et al., 2015). Freezing as a conventional preservation method can effectively reduce food quality deterioration caused by the determination reaction but traditional freezing methods cannot meet the need of preserving better food quality. Power ultrasound has been applied to assist food freezing process for promoting the formation of small and evenly distributed ice crystals, lead to better microstructure and food quality (Sun and Li, 2003, Lili et al., 2013). Apple is often chosen as a typical fruit because of its uniform structure and stability during storage in order to investigate the underlying freezing mechanism (Sterling, 1968). Since apple is mechanically anisotropic, Delgado et al. (2009) researched the effect of power ultrasound on tangential or radial orientated apple samples and showed that by applying ultrasound of 40 kHz at 0 °C or -1 °C for a total time of 120 s with interval of 30 s, the freezing time was significantly reduced by 8 % ($p < 0.05$), and radial and tangential samples showed no significant differences. On the other hand, application of power ultrasound can effectively improve mass transfer for apple samples in sucrose solution. Cárcel et al. (2007) investigated the effect of ultrasonic intensity on the transport rate of water and dry matter in apple juice in sucrose solution and showed that ultrasound treatment at 11.5 W/cm$^2$ increased the water diffusivity by 117 % and the dry matter diffusivity by 137 % as compared to the control group.

Similarly, potato is also commonly used in studying ultrasound-assisted freezing. Li and Sun (2002) evaluated the effect of power ultrasound on the freezing rate of potatoes during immersion freezing process. As shown in Fig. 3, the increase of ultrasound intensity could significantly improve the freezing efficiency, but at the same time the increase of power level led to more thermal effects. It was indicated that the best freezing rate was achieved when power ultrasound of 15.85 W was applied on the samples for 2 min. In addition, the effect of ultrasonic parameters on the freezing process of potatoes was also studied, Sun and Li (2003) studied the effect of exposure time and intensity level of ultrasound on the immersion freezing of potatoes and indicated that increasing ultrasound power level and exposure time could significantly improve the freezing rate, but simultaneously, the thermal effects generated during the ultrasound wave propagation through the medium reduced the freezing rate. Moreover, the temperature at which ultrasound is applied can affect the freezing process. Comandini et al. (2013) applied ultrasound of 35 kHz frequency to freeze potato cube samples when the sample central temperature was between -0.1 and -3.0 °C and found that the application of ultrasound could lead to the expected nucleation when sample was below -0.1 °C. When the applying temperature was -2.0 °C, the freezing time was 53.39 min compared to 62.44 min for control sample, namely the freezing rate was increased by about 14.4 %. Similarly, Cheng et al. (2014a) applied power ultrasound at different temperatures during freeze drying of strawberry and found that the characteristic freezing time was reduced by approximately 16 % when ultrasound was applied at -2.0 °C, compared to 6 % when ultrasound was applied at 0 °C. The duty cycle (DC) of ultrasound application can also affect the freezing time. Kiani et al. (2015) evaluated the effect of ultrasound on freezing potato samples by experiments and numerical analysis and indicated that applying ultrasound could significantly reduce the characteristic freezing time and the shortest freezing time was in the range of 30-70 % DC.

The effects of ultrasonic waves on freezing different fruit and vegetables are different due to the variation in their inherent characteristics. Xu et al. (2015b) compared the effects of immersion freezing, slow freezing and ultrasound-assisted freezing on physical and chemical properties of red radish and indicated that power ultrasound could significantly shorten the freezing time. The freezing rate was increased by 14 % and 90 % under ultrasound treatment at the intensity of 0.26 W/cm$^2$, as compared to slow freezing and immersion freezing, respectively. Ying et al. (2014b) evaluated the effect of ultrasound on freezing time during immersion freezing of broccoli samples and showed that with ultrasonic intensity in the range of 0.250-0.412 W/cm$^2$, the total freezing time including precooling, phase change and subcooling stages was significantly reduced. Islam et al. (2014) examined the effect of ultrasound on physical and chemical properties of three mushroom varieties during immersion freezing and indicated that applying the ultrasound of 0.39 W/cm$^2$ and 20 kHz could significantly ($p < 0.05$) decrease the freezing time by about 40 % on mushroom samples. Xin-feng et al. (2014) investigated the effects of ultrasound intensity and temperature on freezing strawberries and illustrated that applying ultrasound at −1.6 °C could significantly ($p < 0.05$) reduce the characteristic freezing time by about 21 % and increasing ultrasound intensity could shorten the characteristic freezing time by reducing the time at supercooling stage. Jing et al. (2015a) studied the effects of initial physical-chemical properties of lotus roots on their suitability for ultrasound assisted freezing, and showed that the initial physical and chemical properties such as moisture content, liquid viscosity and gas content could directly affect the freezing characteristics of lotus root, such as transition phase time, initial freezing temperature and total freezing time.

In addition, Xu et al. (2014b) reported that osmotic dehydration pretreatment before freezing could reduce the freezing time. They studied the effect of ultrasound-assisted osmotic dehydration and then freezing on the freezing characteristics of radish (*Raphanus sativus L.*) and found that ultrasound-assisted osmotic dehydration and then freezing for radish samples with water content of 75 % (w/w) could reduce the freezing time by approximately 18 % as compared to osmotic dehydration and then freezing for samples with the same water content.

The above experimental results show that during ultrasound assisted freezing, heat transfer rate and freezing rate can be significantly improved with the increase in power intensity and exposure time. However, thermal effects caused by ultrasound are also increased. Therefore, optimisation of the freezing parameters should be performed to maximize the improvement of freezing rate and minimize the generation of thermal effect.

## 4. Effects on Food Microstructure

Food microstructure is closely associated with food quality, sensory and nutritional values and crystallization process is an important process that affects the microstructure of food products. Power ultrasound can be used to control and improve the crystallization process as it can enhance both the nucleation rate and crystal growth rate (Delgado and Sun, 2011). As shown in Table 2, application of ultrasound can improve the microstructure and quality of frozen foods during freezing process. Sun and Li (2003) studied the effect of ultrasound-assisted freezing on the freezing process of potato tissue and the potato samples with ultrasound treatment showed better cell structure with less cell rupture and extracellular void than those without applying ultrasound (Fig. 4). In addition, other quality parameters such as texture, colour and total calcium content can also be improved with the assistance of ultrasound.

## 4.1 Liquid foods

Crystallization is closely related to nucleation process, and both have significant impacts on food microstructure. It is proved that ultrasound can be an effective way to control the nucleation process and lowering nucleation temperatures can lead to the generation of smaller and even distributed ice crystals. Kiani et al. (2011) studied the effect of power ultrasound on inducing dynamic nucleation and controlling the crystallization process in deionized water, agar gel sample and sucrose solution, and indicated that ultrasound application could induce ice nucleation at different temperatures close to the ultrasound irradiation temperatures with high repeatability and thus ultrasound could be used to control the initiation of nucleation process. Saclier et al. (2010a) researched the effect of power ultrasound on the shape and size of ice crystals during freezing mannitol aqueous solution samples in vials and demonstrated that increasing both supercooling and intensity level of ultrasound could cause a decrease in average size and an increase in the average circularity of the ice crystals.

The rupture of ice dendrite crystals and secondary nucleation of ice crystals can also contribute to the formation of multiple nucleation sites and small and uniform ice crystals. Chow et al. (2003) observed the nucleation and crystallization process in sucrose solution by a novel microscope and found that ice crystals could break into smaller sizes, which could act as new nucleation sites, and dendritic structures of ice crystal could be observed. Chow et al. (2005) studied the primary and secondary nucleation process of ice crystals under the application of power ultrasound and found that cavitation bubbles could induce nucleation and pre-existing ice crystals could be fragmented into small fragments during the secondary nucleation process (Fig. 5).

## 4.2 Model solid foods

Model solid foods provide a convenient way to observe the effect of ultrasound on nucleation and crystallization process, which can provide a reference for studying the nucleation and crystallization of solid foods. Kiani et al. (2012a) evaluated the effect of different irradiation temperature, duration and intensity of ultrasound on the nucleation behaviour of ice crystals in agar gel samples. The results showed that power ultrasound could effectively induce nucleation at different supercooled temperatures in agar gel samples. During the nucleation process, higher ultrasound intensity was effective when irrigation time was short and the ultrasound intensity required was lowered when the ultrasound irrigation time was prolonged. Kiani et al. (2013b) also observed ice crystals size and distribution in agar gel samples, indicating that the particle size and distribution of ice crystals were affected by nucleation temperature and lower nucleation temperature could lead to finer ice crystals. Compared with the samples without ultrasound irradiation, smaller ice crystals were observed in the agar gel sample with ultrasound application and duty cycle of 30 %, irradiation duration of 180 s and intensity level of 0.42 W/cm$^2$ could effectively decrease ice crystals size.

In addition, the infusion of $CO_2$ can affect the size of ice crystals in model solid food system. Xu et al. (2016) evaluated the effect of infusion of $CO_2$ in gelatin gel during ultrasound assisted immersion freezing and showed that the combined treatment of infusion of $CO_2$ and low–frequency ultrasound generated the smallest size of ice crystals with 47 μm in diameter, compared to the diameter of 235 μm for slow freezing with infused $CO_2$ treatment and the diameter of 75 μm for immersion freezing with infused $CO_2$ treatment.

In addition, the samples frozen by the assistance of ultrasound with infused $CO_2$ treatment had the lowest water loss of 10.53 %, higher gel strength of 188.96 g, and better TPA parameters including hardness, springiness, cohesiveness and chewiness.

For manufacturing ice cream, ultrasound can be used to improve its sensory properties by generating fine and uniformly distributed ice crystals, as a number of studies have indicated that applying power ultrasound during ice cream production can effectively promote the nucleation and improve the heat and mass transfer (Donhowe and Hartel, 1996, Russell et al., 1999). In addition, Zheng and Sun (2006) pointed out that ultrasound irradiation could reduce the generation of crusted and hard surface during ice cream production, as cavitation effect caused by ultrasound can lead to the improvement of heat transfer rate and the generation of small and uniform ice crystals. Moreover, as fat and gas content are essential for the flavour and taste of the ice cream, increasing the cavitation bubbles could significantly enhance the sensory properties of ice cream, such as flavour, texture and taste.

### 4.3 Fruit and vegetables

Ultrasound can be used to maintain better cell structure and the original quality of food products by producing small and uniform distributed ice crystals. Sun and Li (2003) studied the effect of power ultrasound on the quality of potatoes during freezing process. When the power level was 15.85 W and the exposure time was 2 min, the freezing rate was the fastest and at the same time less cell void and cell disruption were observed in plant tissues. This is due to the formation of small and even distributed ice crystals caused by the rapid freezing rate at optimum ultrasound intensity and exposure time. Islam et al. (2015) applied contact ultrasound with 300 W intensity and 20 kHz frequency on mushroom (*Agaricus bisporus*) during freezing and found that ultrasound was able to induce the nucleation of ice crystals and decreased the average size of ice crystals, and thus the mushroom samples showed better cell structure and quality compared to control samples.

It is proved that ultrasound-assisted freezing can significantly reduce the drip loss and the loss of nutrients and maintain high calcium content during freezing fruit and vegetables. Xu et al. (2015a) studied the effect of ultrasound-assisted immersion freezing on the microstructures and quality attributes including firmness, drip loss and sensory evaluation of red radish. Their results indicated that samples with ultrasound treatment showed smaller ice crystal pores in the scan electron microscopy image and had the firmness approximately 17 % higher than immersion freezing (IF) samples. The ultrasound treated products also exhibited less drip loss and better appearance, aroma and texture compared to IF products. Ying et al. (2014a) investigated the effect of power ultrasound on quality attributes of broccoli including drip loss, hardness and microstructure during immersion freezing, and showed that the drip loss of samples with ultrasound treatment was about 8 % compared to about 10 % in normal freezing samples and the firmness of ultrasound treatment samples was about 50 N compared to about 40 N in normal freezing samples. Jing et al. (2015b) evaluated the effects of immersion freezing, air blast freezing and ultrasound assisted freezing on the microstructure and quality attributes including firmness, colour and drip loss of lotus roots, and found that the drip loss in ultrasound treatment samples was about 8 % compared to about 13 % in immersion freezing samples and about 18 % in air blast freezing samples, and the firmness was about 1500 g in ultrasound treatment samples compared to about 1200 g in immersion freezing samples and 1100 g in air blast freezing samples. It is thus shown that ultrasound assisted freezing maintained better quality attributes and microstructure of lotus roots while air blast freezing caused most serious damage to the plant tissues.

In addition, it was reported that the osmotic dehydration pretreatment can effectively reduce the damage of freezing process on the sensory and nutritional value of food products. Xin et al. (2014) investigated the effect of ultrasound-assisted osmodehydrofreezing treatment on the quality parameters of broccoli and results indicated that ultrasound-assisted osmodehydrofreezing treatments could effectively reduce the degradation of drip loss and $_{L}$-ascorbic acid content and better preserve the firmness and colour when the broccoli was stored at -25 °C for 6 months. Xu et al. (2014b) also studied the effect of ultrasound-assisted osmodehydrofreezing on the cell structure and quality of radish and found that the drip loss of ultrasound treated products with 80 % water content was decreased by 72 % compared to the control frozen products and ultrasound-assisted osmodehydrofreezing products showed better preservation of microstructure and firmness compared to products with osmodehydrofreezing.

**5. Conclusions and Future Trends**

Power ultrasound plays a significant role in accelerating freezing processes. The cavitation and the microstreaming cause strong oscillation in liquid, thus increasing the heat transfer and mass transfer efficiency. In the meantime, cavitation bubbles can act as nuclei, further promoting the occurrence of nucleation and increase the nucleation rate. In addition, fragmentation of ice crystals are conducive to the formation of small and evenly distributed ice crystals, which cause less damage to food microstructure and better preserve food quality.

Ultrasonic parameters affect the freezing efficiency. Generally, the higher the intensity of ultrasound is, the higher the freezing efficiency is. However, with the increase in ultrasonic intensity, thermal effect induced by power ultrasound is also increased, which negatively affect the freezing efficiency. Therefore, future work should consider process optimisation in order to strike a balance between the ultrasonic intensity and the generated thermal effect.

Different inherent characteristics of food samples affect the effectiveness of ultrasound application. Optimum ultrasound parameters such as frequency, intensity, exposure time and duty cycle depend on the nature of the samples. In particular, most studies available focus on liquid, model food, or plant tissues such as fruit and vegetables, little information on ultrasound-assisted freezing of samples with animal origin is available, thus more studies should be conducted on this aspect. On the other hand, food microstructure is closely associated with the crystallization process. Application of ultrasound can cause small and uniformly distributed ice crystals, leading to less damage to the cell structure and minimal loss of nutritional values such as calcium and phenol contents, thus resulting in better food quality. This aspect has been confirmed by numerous experimental results, however, few studies are focused on theoretical investigation such as dynamic modelling of ice crystal formation and growth under the influence of ultrasound. Such studies should be able to shed more light on relevant freezing mechanisms, leading to better understanding and control of the freezing process, which should be conducted in future.

Although ultrasound assisted freezing has shown positive effects in accelerating food freezing processes, the adoption of this novel technology by the industry is slow. Considering different effects on different food samples, the application of ultrasound-assisted freezing to the food industry is more likely on certain types of food products, and therefore future investigations can concentrate on design and optimisation of the freezing process and equipment for these food products for the early adoption of the technology to the industry.

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**Table 1. Effects of power ultrasound on freezing efficiency**

| Specimen | Treatments | Effects | References |
|---|---|---|---|
| Water and sucrose solution | 20 kHz, 0.21W/cm$^2$, 3–5 s | Pre-existing bubbles shortened the delay between the occurrence of nucleation and the initiation of irradiation and improved the effectiveness of ultrasound irradiation on the initiation of nucleation. | (Hu et al., 2013) |
| Sucrose solution | 20 kHz, 67 kHz | Ultrasound increased the nucleation temperature and reduced the supercooling degree. | (Chow et al., 2005) |
| Pure water and degassed water | 40 kHz, 0.0, 0.26, 0.32, 0.37, 0.42 and 0.49 W/cm$^2$ | Ultrasound increased the nucleation temperature and promoted the nucleation. | (Yu et al., 2012) |
| Gelatin gel | 20 kHz, 0-300 W, 0.2 MPa ($CO_2$ infused) | The presence of $CO_2$ promoted the freezing process and decreased the freezing time. | (Xu et al., 2016) |
| Agar gel | 25 kHz, , 0.07, 0.14, 0.25, 0.35 and 0.42 W/cm$^2$, 0 s, 1 s, 3 s, 5 s, 10 s or 15 s<br><br>Irradiation temperature: −2 °C, −3 °C, −4 °C and −5 °C | Exposure time of 3 s induced the nucleation repeatedly and increasing the intensity of ultrasound could decrease the delay between irradiation and nucleation. | (Kiani et al., 2012a) |
| Ice cream | 20 kHz, 1, 5, 20, 40, 60 min | Ultrasound at pulse time of 20, 40 and 60 min shortened the freezing time and samples with 20 min pulse time had the best sensory value. | (Mortazavi and Tabatab |

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| | | | aie, 2008) |
| Potato | 25 kHz, 0-300 W, 270 s;<br><br>Duty cycle: 0-100 %, 1 s on / 9 s off (10 % DC), 3 s on / 7 s off (30 % DC), 5 s on / 5 s off (50 % DC), and 7 s on / 3 s off (70 % DC) | Ultrasound at DC of 30–70 % decreased the freezing time. | (Kiani et al., 2015) |
| Lotus roots | 30 kHz, 0-300 W, 6 min<br><br>Duty cycle: 30 s on / 30 s off, 15 s on / 45 s off, 45 s on / 15 s off | Ultrasound at intensity of 150 W and duty cycle of 30 s on / 30 s off decreased the freezing time by approximately 16.4 % and 52.2 % as compared to immersion freezing and air blast freezing, respectively. | (Jing et al., 2015b) |
| Broccoli | 20 or 30 kHz, 125–190 W, 0.250–0.412 $W/cm^2$;<br><br>Duty cycle: 60 s on / 60 s off | Ultrasound at intensity of 0.412 $W/cm^2$ significantly decreased the freezing time ($p < 0.05$). | (Ying et al., 2014b) |
| Radishes | 20 kHz, 0.09, 0.17, 0.26 and 0.37 $W/cm^2$, 0 s, 3 s, 7 s, 10 s or 15 s; Irradiation temperature: −0.5, −1, −1.5 and −2 °C | Ultrasound at irradiation temperature of −0.5 °C, duration of 7 s and intensity of 0.26 $W/cm^2$ increased the nucleation temperature and induce nucleation. | (Xu et al., 2014a) |
| Strawberries | 30 kHz, 0.09, 0.17, 0.28, 0.42 and 0.51 $W/cm^2$, 30 s<br><br>Irradiation temperature: −0.1, −0.6, −1.1, −1.6 and −2.1 °C | Ultrasound at irradiation temperature of −1.6°C and the intensity of 0.51 $W/cm^2$ decreased the characteristic freezing time | (Xin-feng et al., 2014) |
| Mushrooms | 20 and 30 kHz, 0.39 $W/cm^2$, 300 W | Ultrasound at 0.39 W $cm^{-2}$ (20 kHz) reduced freezing time by approximately 4 %. | (Islam et al., 2014) |

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| Dough | 25 kHz, 175, 224, 288, 360, and 418 W;<br><br>Duty cycle: 30 s on / 30 s off | Ultrasound at intensity of 288 or 360 W decreased the total freezing time by more than 11 % ($p < 0.05$). | (Song-Qing et al., 2013) |
| Potato | 35 kHz, 300 W, 8 s;<br><br>Irradiation temperature: −0.5 °C, −2.0 °C and −3.0 °C | The shortest freezing time was achieved at irradiation temperature of −2 °C. | (Comandini et al., 2013) |
| Apple | 40 kHz, 131.3 W (0.23W / cm$^2$), 120 s<br><br>Duty cycle: 30 s on / 30 s off<br><br>Irradiation temperature: 0 °C or −1 °C | Improved the freezing rate by approximately 8 % ($p < 0.05$). | (Delgado et al., 2009) |
| Potato | 25 kHz, 0-300 W, 15.85 W, 1, 1.5, 2 and 2.5 min | Ultrasound at intensity of 15.85 W and exposure time of 2 min increased the freezing rate. | (Li and Sun, 2002a) |

**Table 2. Effects of power ultrasound on food microstructure**

| Specimen | Treatments | Effects | References |
|---|---|---|---|
| Sucrose solutions | 20 kHz, 67 kHz | Ultrasound at high output level and duty cycle increased nucleation temperature and promoted primary and secondary nucleation. | (Chow et al., 2003) |
| Water, sucrose solution, and agar gel samples | 25 kHz, 0.25 W/cm$^2$, 0, 1, 3, 5, 10 or 15 s | Ultrasound induced ice nucleation with high repeatability at different temperatures close to the irradiation temperatures and exposure time of 3 s was the optimal condition to induce nucleation. | (Kiani et al., 2011) |
| Mannitol aqueous solution | 35 kHz, 1 s | Ultrasound increased supercooling, decreased ice crystals' mean sizes and increased their mean circularity. | (Saclier et al., 2010a) |
| Agar gel | 25 kHz, , 0.07, 0.14, 0.25, 0.35 and 0.42 W/cm$^2$, 0 s, 1 s, 3 s, 5 s, 10 s or 15 s<br>Irradiation temperature: −2 °C, −3 °C, −4 °C and −5 °C | Initiated nucleation at different supercooled temperatures and exposure time of 3 s induced the nucleation repeatedly. | (Kiani et al., 2012a) |
| Agar gel | 25 kHz, 0.07, 0.25 and 0.42 W/cm$^2$, 3 s, 90, 180 and 270 s<br>Duty cycle: 30, 50 and 70 % | Ultrasound at intensity of 0.25 and 0.42 W/cm$^2$ and exposure time of 90 s significantly decreased the size of ice crystals. | (Kiani et al., 2013b) |
| Gelatin gel | 20 kHz, 0-300 W, 0.2 MPa ($CO_2$ infused) | The presence of $CO_2$ decreased ice crystal size and water loss. | (Xu et al., |

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| | | | 2016) |
| Red radishes | 20 kHz, 0-300 W, 0.09, 0.17, 0.26, and 0.37 $W/cm^2$;<br>Duty cycle: 30 s on / 30 s off | Decreased drip loss and phytonutrients loss and sample with showed better cellular structures, less cell separation and disruption and higher calcium content. | (Xu et al., 2015a) |
| Lotus roots | 30 kHz, 0-300 W, 6 min<br>Duty cycle: 30 s on / 30 s off, 15 s on / 45 s off, 45 s on / 15 s off | Ultrasound improved relative firmness and reduced drip loss. | (Jing et al., 2015b) |
| Mushroms | 20 and 30 kHz, 0.39 $W/cm^2$, 300 W | Ultrasound reduced the ice crystal size and caused more uniform structure of samples. | (Islam et al., 2015) |
| Broccoli | 20 and 30 kHz, 125–190 W, 0.250–0.412 $W/cm^2$;<br>Duty cycle: 60 s on / 60 s off | Ultrasound promoted the formation of small ice crystals inside and outside the cells and decreased the calcium content loss, better preserved the textural properties, colour and L-ascorbic acid content and reduced the drip loss. | (Ying et al., 2014b) |
| Strawberries | 30 kHz, 0.09, 0.17, 0.28, 0.42 and 0.51 $W/cm^2$, 30 s<br>Irradiation temperature: −0.1, −0.6, −1.1, −1.6 and −2.1 °C | Ultrasound could induced nucleation at lower supercooling degree. | (Xin-feng et al., 2014) |
| Mushroms | 20 and 30 kHz, 0.39 $W/cm^2$, 300 W | The application of ultrasound decreased drip loss, polyphenol oxidase and peroxidase enzyme activities and increased whiteness index, chroma value and textural hardness value. | (Islam et al., 2014) |
| Dough | 25 kHz, 175, 224, 288, | Ultrasound induced the formation of a large number of tiny ice crystals | (Song- |

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| | 360, and 418 W; Duty cycle: 30 s on / 30 s off | and improved the quality of frozen dough. | Qing et al., 2013) |
| Potato | 35 kHz, 300 W, 8 s; Irradiation temperature: −0.5 °C, −2.0 °C and −3.0 °C | The application of ultrasound promoted the nucleation process. | (Comandini et al., 2013) |
| Potato | 25 kHz, 7.34, 15.85 and 25.89 W, 1, 1.5, 2 and 2.5 min | Ultrasound at intensity of 15.85 W and exposure time of 2 min significantly improved the microstructure. | (Sun and Li, 2003) |

**List of Figures**

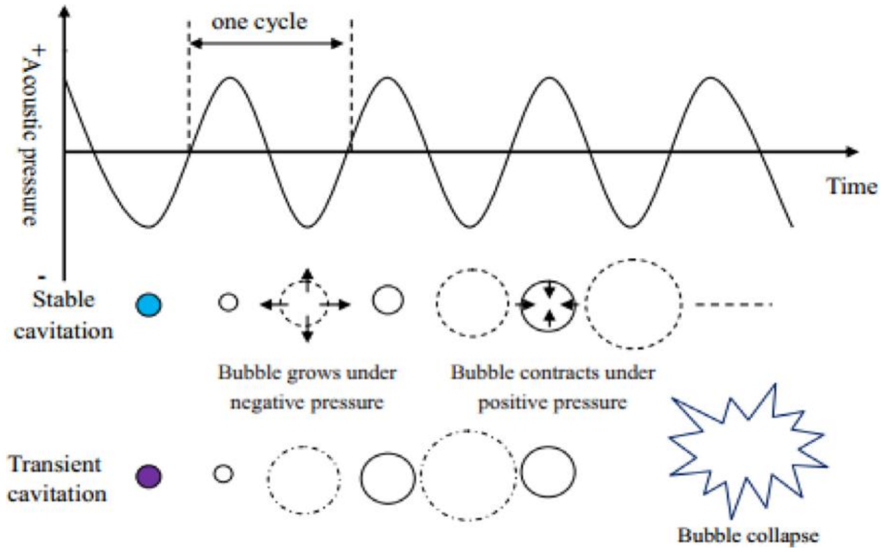


**Fig. 1.** Acoustic cavitation induced by power ultrasound (Cheng et al., 2015).

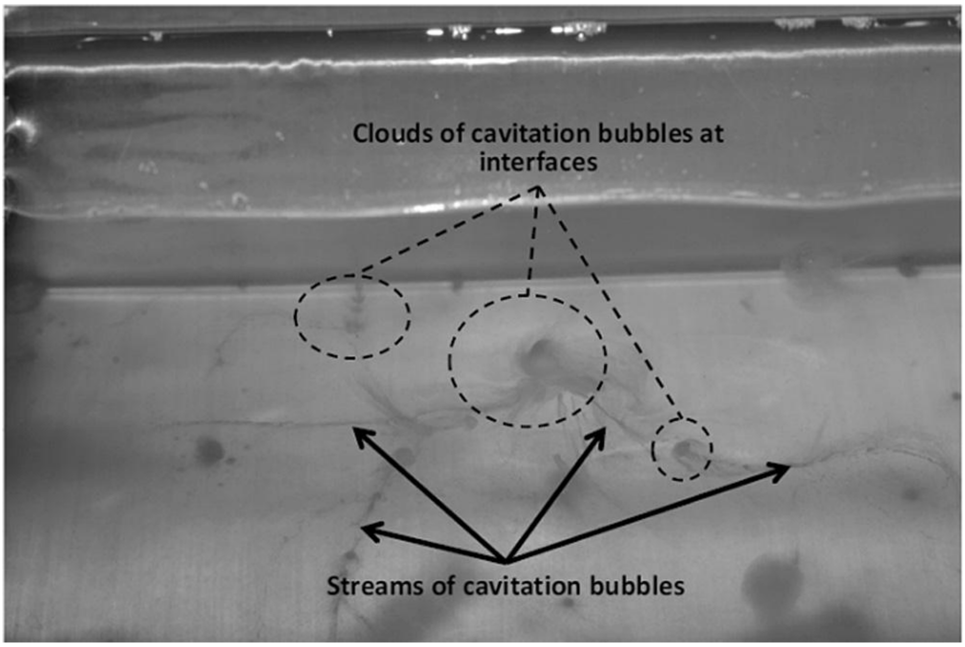


**Fig. 2.** Cavitation and acoustic streaming phenomena inside the ultrasonic bath operated at 25 kHz and 2800 W m $^{-2}$ pictured by a camera (Kiani et al., 2015).

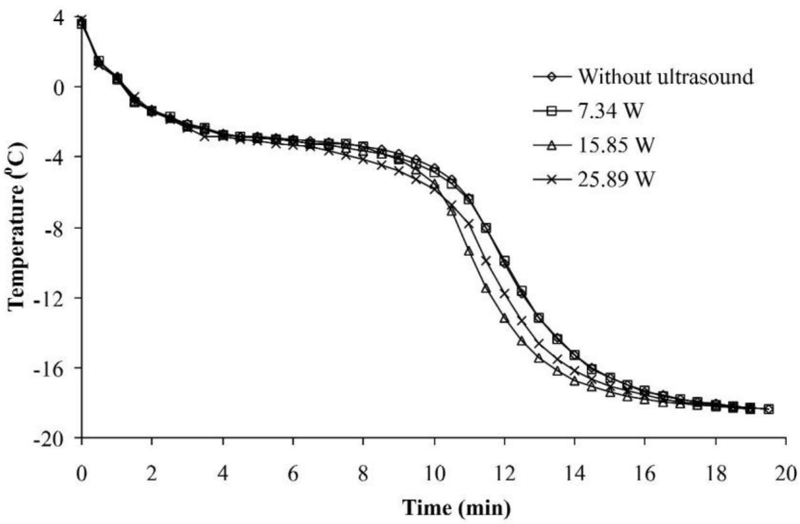


**Fig. 3.** Temperature versus time curves for potato samples under different ultrasonic power levels applied totally for 2 min at the coolant temperature of -18 °C (Li and Sun, 2002a).

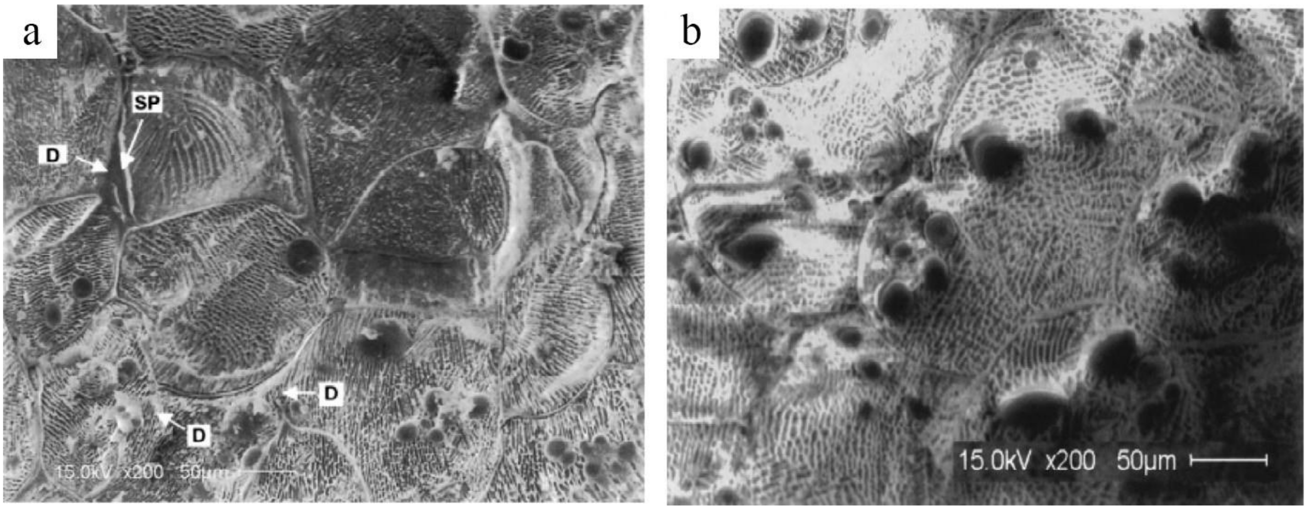


**Fig. 4.** Cryo-SEM micrograph for potato tissue by immersion freezing showing disruption of cells and separation of cells (a), as compared with Cryo-SEM micrograph for potato tissue by ultrasonically assisted immersion freezing under power of 15.85 W showing much better preserved microstructure (b) (D: disruption of cells; SP: separation of cells) (Sun and Li, 2003).

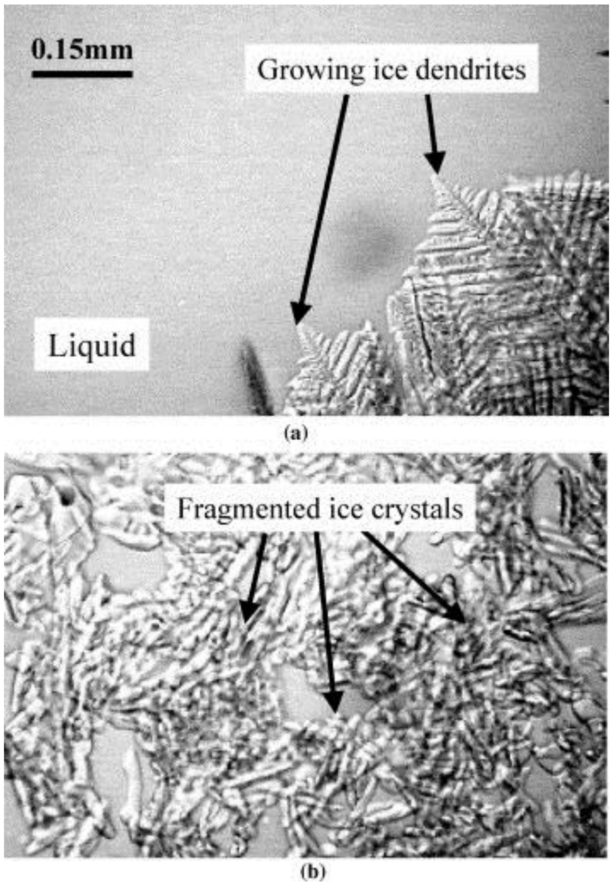


**Fig. 5.** Secondary nucleation of ice in a 15 wt% sucrose solution with ultrasound (a) ice dendrite (no ultrasound) and (b) fragments of crystals remaining after ultrasound treatment of 4 s. Image width=0.92 mm (Chow et al., 2005).