Visualization of Temperature and Velocity Fields during Phase Change of Water under High Hydrostatic Pressure

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Abstract

In this study, a special method is used to visualize velocity fields when phase change of ice-water occurs under high pressure. Formation of different ice structures under high pressure affects also convective transport phenomena and creates mutually heterogeneous velocity fields. Especially Ice I-water and Ice III-water pressure assisted thawing, and Ice I-water pressure shift thawing processes are investigated and results showing velocity distribution of processes are analysed by High Pressure Particle Image Velocimetry (HP-DPIV). With increase of pressure, the density anomaly of water vanishes, therefore different flow patterns are generated for liquid-solid transition. Ice I has a lower density than water; and Ice III, differently, has a higher density than water and Ice I, and this creates different velocity distributions. It is found that velocity of ice during thawing of Ice III (0.35 mm/s) is relatively higher than that of Ice I (0.16 mm/s). Pressure assisted and shifted thawing are also compared and it is concluded that pressure shift thawing is occurring faster than pressure assisted thawing, due to appearance of forced convection during pressure shift thawing.

1. Introduction

High hydrostatic pressure (HHP) processing has become subject of interest in food industry in recent years. This newly emerged technique provides methods of avoiding off-flavor and deterioration of food components and nutrients, producing unique texture on food, and saving total amounts of energy required for food processing [1]. The major advantage over classical thermal processes is that high pressure only slightly affects nutritional and sensorial quality. It also offers opportunities in food processing because it influences the functionality, structure and texture of biological systems. Freezing as well as thawing can be considerably accelerated by use of HHP conditions and cellular tissue remains almost undamaged, which again contributes to a higher quality retention in food.

Therefore, HHP phase change is one of the processes attributed with high potential of application in food industry. The quality of freezing matter is closely related to its freezing and thawing processes. Temperature-pressure relation during phase change can be seen in phase diagram of water, in Figure 1. The major problem associated with classical freezing and thawing at atmospheric pressure is due to the formation of large ice crystals, which causes mechanical damage, and cracking upon fast freezing as a consequence of the stress-inducing front [2]. When water is frozen at atmospheric pressure, there will be a volume increase causing tissue damage in the food sample. Whereas density of several kinds of ices formed under HHP -except Ice I- are greater than that of water therefore tissue damage can be reduced [3]. This vanishing density anomaly also produces different flow patterns during the phase change. Moreover ice formation is instantaneous when super-cooled, so intracellular water does not destroy the tissue structure.

Several processes of high pressure freezing and thawing can be carried out as can be seen in the phase diagram of water (Figure 1). The pressure assisted freezing consists in cooling a sample under pressure up to its phase change temperature at the applied pressure. In this way, the freezing takes place under a constant pressure. Reciprocally, pressure assisted thawing corresponds to a thawing under a constant pressure. In pressure assisted thawing the temperature difference between the walls and the medium is greater. This difference brings a driving force for phase change. In case of pressure shift thawing this driving force is provided by pressure and phase transition occurs during pressure change.

Distributed transport effects have already been investigated under HHP treatment [4]. A detailed insight into these processes has been achieved with in-situ measuring technique for visualizing temperature and velocity fields as well as with numerical simulation models [5]. The measuring system is now further developed to investigate the transient spatial phase change processes, which are pressure assisted/shift freezing and thawing processes (Figure 1). Such a system has not been previously used in this field of application.

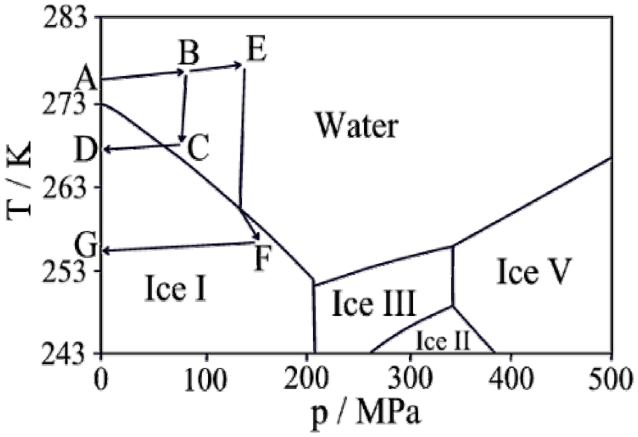

Figure 1. ABCD/DCBA pressure shift freezing/thawing, ABEFG/GFEBA pressure assisted freezing/thawing.

2. Materials and Methods

The main experimental setup consists of a tempered high pressure optical cell having a volume of 2 ml, which is equipped with sapphire windows of 6 mm optical width. This high pressure cell is designed to bear pressures up to 700 MPa. System is illuminated by a sheet of white light from a xenon lamp. The field is recorded by a fixed 3-chip RGB (Red-Green-Blue), CCD camera which is located at a right angle to the incident light sheet. Detailed description and schemes for the experimental set up can be found in [7].

For visualization of velocity and temperature fields microencapsulated thermochromic liquid crystals are used. For the velocity field, after proper image enhancement techniques images are analysed by the help of self developed methods: High Pressure Particle Image Velocimetry and High Pressure Particle Image Thermography (HP-DPIV and HP-DPIT, respectively). Temperature field is determined by using selective light reflecting property of liquid crystals. This reflected light is first expressed as RGB values and then related with temperature values by digital post-processing. In this contribution, results obtained for velocity field calculation will be discussed.

Acquired images are first enhanced by using image processing, a stop motion filter and mask with a diameter of the sight are applied. Former prevents irregular random movements in the image. The latter avoids disturbances that can occur from the particles that are located outside of the observation area. Those enhanced images are further processed with a PIV procedure created by Gui [6].

For this particular Particle Image Velocimetry application , MQD (the minimum quadratic difference) algorithm is used combined with FFT. The MQD is selected because it is more reliable and accurate to evaluate PIV recordings with LS (Laser Speckle PIV mode) and high image density mode [6]. Moreover, when compared to other correlation algorithms, it does not depend directly on the determined particle shift. In order to have more accurate results and to minimise evaluation time window size should be selected according to characteristics of the image as well as of the method. Normally with MQD method due to high amount of tracer particles computation window should be large. As optimum window size 36 x 36 pixels was used, with grid size of 18 x 18. For identification of evaluation errors the median filter and reversibility are applied.

3. Results and Discussion

The case of pressure assisted thawing of Ice I is represented with GFEBA line in the Figure 1. For this process the cell is first cooled down to 263 K and then pressurized to 120 MPa. Then the temperature of the temper bath is set to a temperature around 278 K. Melting of ice starts from the walls where the temperature is maximum. After it starts to melt, in near wall region the ice detaches from the inner wall of the cell and it starts to move as a solid body. Ice I moves up because of it's density is lower than that of water. Movement of the ice block forms two counter rotating vortices in the water layer below it. This vortices have accelerative effect on heat convection, the liquid from near wall region is carried near to the solid-liquid surface and phase transition develops. Corresponding image and also velocity fields can be seen in Figure 2. In PIV image solid body motion can be differentiated with the area located in the upper part of the figure. And here convective field can also be visualized. Calculated velocity values show that ice is moving as a solid body with a velocity of 0.16 mm/s, in the liquid region and there is an average velocity of 0.37 mm/s, having a maximum of 1 mm/s approximately.

The case of pressure assisted thawing of Ice III can be seen in Figure 3. This time the cell is again cooled down to a temperature between 253 K and 248 K and then pressurized up to 300 MPa. Thawing starts when the solidification line is crossed at this pressure. Density difference of Ice III leads to a different flow characteristics during the process and this time solid body starts to move down. Thawing of Ice III and velocity field during this process can be seen in Figure 3. It has been observed that structure of Ice III is visually different from Ice I. Some disturbances occur during PIV evaluations, and those are mainly caused by the solid body motion of Ice III during melting. The motion is not unidirectional like in the case of Ice I but it also moves to side areas in the cell. In velocity distribution, there can not be seen a dominant vortex in case of Ice III. The average velocity throughout the cell is approximately 0,35 mm/s.

Pressure shift thawing which is represented with the DCBA line in Figure 1 is also investigated. In this application, first the temperature of the cell is arranged to a temperature between 263 and 253 K and it is waited until a completely solid structure is achieved. Then pressure is increased till the solidification line is crossed. Here, unlike in previous cases, solidification occurs during pressure increase. Compared to pressure assisted thawing relatively high velocities were observed. The average velocity occurring as 0.37 mm/s for pressure assisted thawing is observed as 0.63 mm/s for pressure shift thawing. As already discussed in case of pressure shift thawing we have pressure change as driving force for phase change. This is achieved by compression inducing forced convection, whereas previous cases are governed by free convection. First signs of melting can be seen in the centre of the cell rather than at the walls because temperature of the temper bath is kept constant at the start temperature during compression.

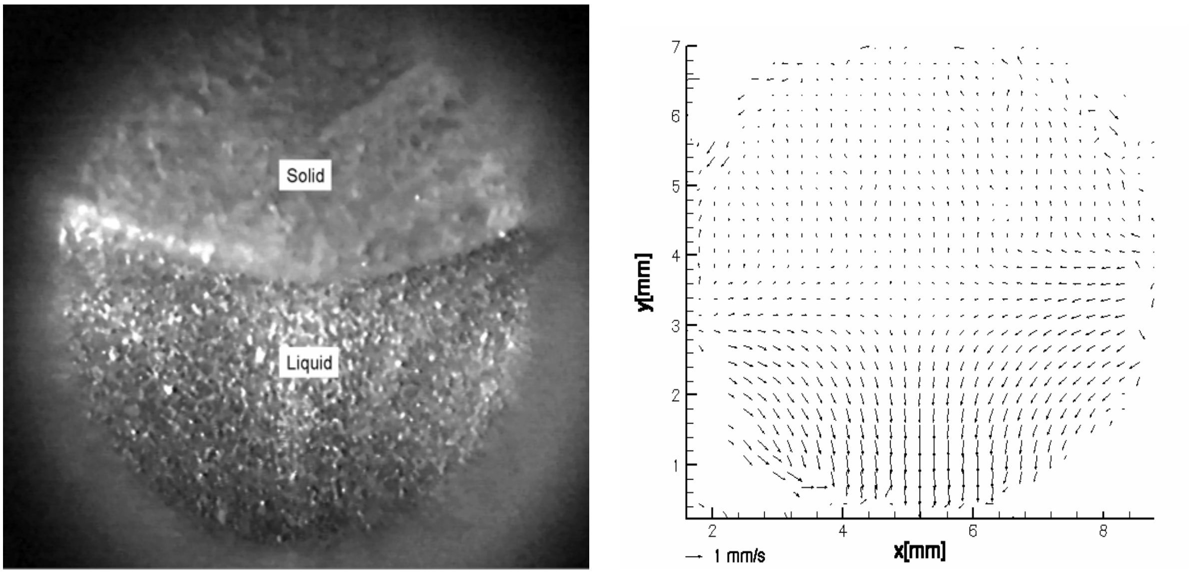

Figure 2. Pressure Assisted Thawing of Ice I.

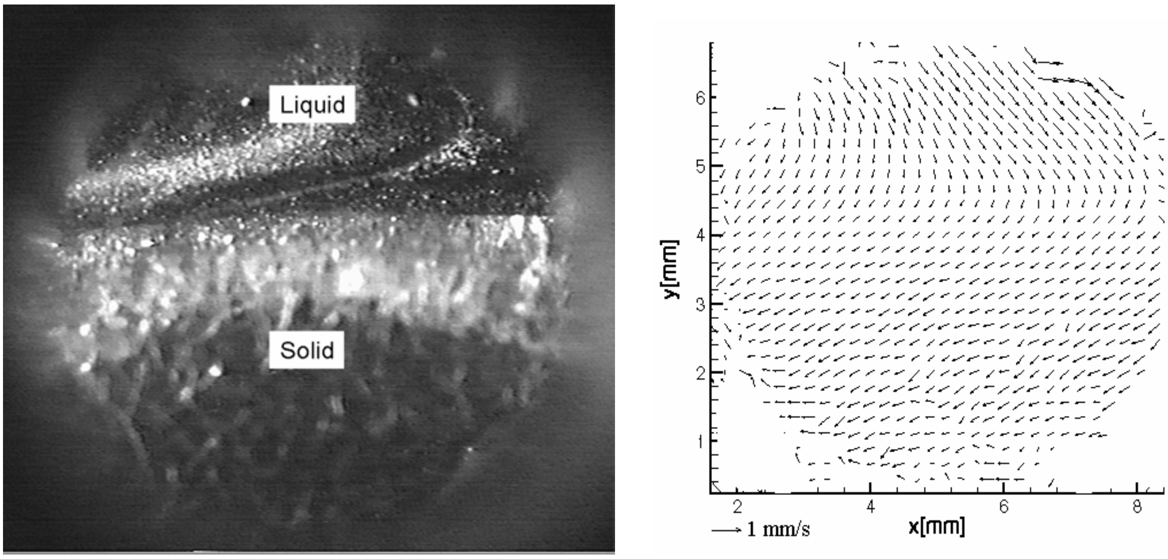

Figure 3. Pressure Assisted Thawing of Ice III.

4. Conclusions

Investigation of different types of ices that occur under the effect of high pressure, allows a better understanding of the main mechanisms. The main point of motivation is to observe different flow mechanisms during pressure assisted/shift thawing of ice as well as pressure assisted thawing of Ice III. During pressure assisted thawing of ice I, melting starts from the walls that have higher temperature than the medium inside. Water formed from melting of ice causes ice to detach from the surface and to start to move. As this solid body moves fluid part creates vortices which enhance convection in the cell. During this motion ice has a velocity of 0.16 mm/s and water has 0.37 mm/s on average. Pressure shift thawing causes relatively high velocities during melting. This can be explained by the effect of pressure increase in the cell during melting. The main motion starts from the centre of the ice body. A different ice type Ice III proves its density difference during thawing. Not likely ice I, it starts to move downwards and creates a different flow characteristics. The average velocity, in this case, is about 0.35 mm/s throughout the cell.

The interest of high pressure for freezing and thawing will continue to be the target of many researches as it has been in recent years. Pressure permits the achievement of rapid freezing and thawing at rates which are difficult to obtain under atmospheric conditions. And the other advantages like drip loss reduction and microbial inactivation appear as a motivating criterion for industry application. Nevertheless, additional studies are required for a better understanding of the biological and physical phenomenon involved in these processes. Distributed transport properties that is given with this contribution will be a necessary source of information for further studies.

5. References

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