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Simulation of high pressure freezing processes by enthalpy method

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ABSTRACT

High pressure freezing processes such as pressure assisted freezing (PAF) and high pressure shift freezing (HPSF) are novel technologies that can be used to improve the quality of frozen foods. A one dimensional finite difference numerical model based on the enthalpy formulation was developed to simulate high pressure freezing of tylose, agar gel and potatoes. The Schwartzberg equation was used in the prediction of both the initial freezing point and the temperature evolution below freezing. Results showed that the model can satisfactorily describe the PAF and HPSF processes. When compared under similar heat transfer conditions, the phase transition times for HPSF were shorter than those at atmospheric pressure. The amount of ice instantaneously formed upon pressure release and the total freezing times were also determined by the developed model and were in reasonable agreement with the experimental data in the literature.

1. Introduction

Freezing has long been established as a food preservation technology that can ensure a high food quality with long storage duration. Despite the benefits of this technique, one of its main drawbacks is the risk of damage to the food caused by the formation of ice crystals (Fuchigami et al., 1997; Otero et al., 2000). The size and location of ice crystals formed during freezing depend on the rate and final temperature of the process, and affect important quality parameters such as exudate, texture and colour of the frozen products. Large ice crystals, formed by slow freezing, can cause deleterious damages in food, particularly in muscle or vegetable tissues by puncturing cell walls. Rapid freezing is thus preferred, for it promotes intensive nucleation and the formation of small ice crystals (Otero et al., 2000).

Under high pressure, water remains in a liquid state below 0 °C, with a reduction in its freezing point to a minimum of −22 °C at 207.5 MPa (Bridgman, 1912). Therefore, by observing the influence of pressure on the phase diagram of water various pathways of changing the physical state of food can be followed by manipulating ambient temperature and/or pressure. In fact, as shown in Fig. 1, two types of high pressure freezing processes can be distinguished, namely high pressure assisted freezing (PAF) and high pressure shift freezing (HPSF) (Otero and Sanz, 2000). In the former process phase transitions occur under constant pressure, higher than atmospheric pressure, and as the latent heat of crystallisation is reduced when pressure increases, reductions in phase transition times can be achieved. On the other hand, releasing the pressure once the temperature of the food reduces to the modified freezing point results in a high supercooling effect and the ice nucleation rate is greatly increased. This process is called HPSF, and its main advantage is that the initial formation of ice is instantaneous and homogeneous throughout the whole volume of the product. Therefore, high pressure shift freezing can be especially useful to freeze foods with large dimensions where the effects of freeze cracking caused by thermal gradients can become pronounced (Martino et al., 1998).

Applications of HPSF for foods are still under development and the amount of data available is increasing accordingly. Most of the studies carried out to date focus on the advantageous effects that HPSF has on the texture and structure of various products. Koch et al. (1996) observed that HPSF of potato cubes resulted in less damage to the cell structure, less drip loss on thawing and less enzymatic browning than conventionally frozen potato cubes. In the work of Otero et al. (1998), who compared the processes of conventional air freezing and HPSF, high pressure shift frozen samples had the appearance of fresh samples, and no differences between the centre and surface cell structure were observed, indicating that uniform ice nucleation had been achieved.

High pressure shift freezing has also been applied in the processing of fruits, pork, lobster, and tofu. Otero et al. (2000) confirmed the beneficial effects of HPSF on whole peaches and mangoes as compared to air-blast frozen samples. Martino et al.

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Nomenclature

A,B	Schwartzberg constants
c	specific heat (kJ kg^{-1}K^{-1})
h	enthalpy (kJ kg^{-1})
h_o	enthalpy at 0 °C (kJ kg^{-1})
h_c	surface heat transfer coefficient W (m^{-2}K^{-1})
h_f	enthalpy of the sample at the initial freezing point (kJ kg^{-1})
h_{T_f}	enthalpy of the sample at the freezing point (kJ kg^{-1})
i	ith node
k	thermal conductivity W (m^{-1}K^{-1})
L	latent heat (kJ kg^{-1})
m	slope °C (MPa^{-1})
m_i	fraction of frozen ice in the sample
P	pressure (MPa)
q	heat flow rate W (s^{-1})
R	characteristic dimension (m)
r	distance from centre along radius (m)
s	number of space steps in the finite difference grid
T	temperature (°C)
T_0	centre temperature (Eq. (14)) (°C)
T_1	temperature at node 1 (Eq. (14)) (°C)
T_o	initial freezing point of water (°C)
T_f	freezing temperature (°C)
T_i	initial temperature of food (°C)
T_r	reference temperature (°C)
T_s	surface temperature (°C)
T_∞	temperature of surrounding freezing fluid (°C)
V	specific volume (m^3/kg)
α	thermal diffusivity (m^{2}s^{-1})
β	thermal expansion coefficient (K^{-1})
Δh	enthalpy increment (kJ kg^{-1})
Δr	distance increment (m)
Δt	time increment (s)
ρ	density (kg m^{-3})

Subscripts

atm	atmospheric
f	frozen
N	nucleation
p	effect of pressure
u	unfrozen

(1998) observed that a uniform and instantaneous ice nucleation within the whole volume of a pork sample was achieved only by high pressure shift freezing when compared to classical freezing methods.

Some modelling studies of high pressure freezing processes have been published to date, most notably those of Denys et al. (2000) and Schlüter (2003) for PAF, and Denys et al. (1997) and Otero and Sanz (2000, 2006) for HPSF. Sanz and Otero (2000) developed a model for the HPSF process of a finite cylinder using equations based on the product solution of the corresponding transient heat transfer equations for infinite cylinders and infinite slabs. The time needed to complete the phase change was calculated by a modified Plank equation and reasonably good agreement with experimental data was achieved (Sanz and Otero, 2000). Denys et al. (2000) used a finite difference scheme to model the high pressure shift freezing process of a food analogue (tylose), and found good agreement with experimental data. In their study, Denys et al. (2000) considered the adiabatic heat generation or heat reduction during pressure build-up and release, respectively; and the temperature dependence of the apparent specific heat and thermal conductivity.

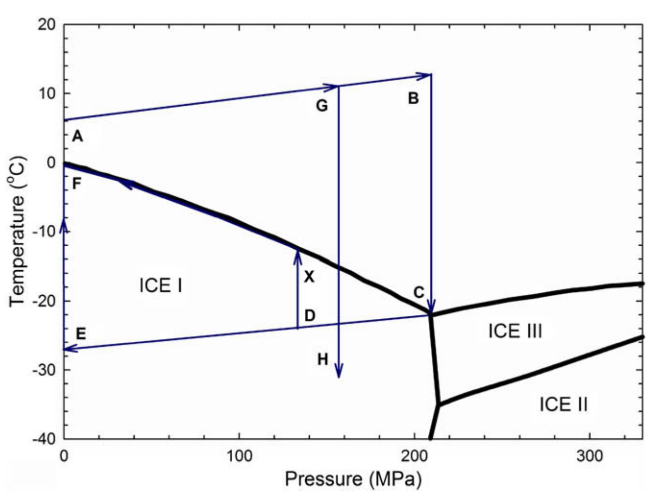

Fig. 1. Phase diagram of water, with pathways followed during HPSF and PAF freezing processes. ABCEF: rapid release HPSF; ABCDXF: slow release HPSF; AGH: PAF.

Based on the difficulties in the handling of latent heat under pressure and the shortcomings of the apparent specific heat approach, Pham (2006) suggested that a simpler and more efficient way to model the high pressure freezing process is to use the enthalpy formulation. By observing this suggestion and in order to avoid the problem of strong discontinuity experienced when the apparent specific heat formulation is used to predict temperatures for situations involving phase change, the enthalpy formulation was used in the current study.

The objectives of this work were to develop a computer model to simulate high pressure freezing processes, to provide an insight into what occurs during these processes, to predict freezing times and the amount of ice instantaneously formed during HPSF, and to validate the model with experimental data available in the literature.

2. Theoretical considerations

An explicit one dimensional finite difference model was developed in the present study to simulate both PAF and HPSF processes for cylindrical food samples using the C programming language. The model is based on the enthalpy formulation and predicts temperature profiles, freezing times and instantaneous ice formation.

When pressure is applied during the high pressure freezing process, it is uniformly distributed at all points within a high pressure chamber. As a food sample is pressurised, the compression results in a reduction of the initial freezing point, as observed in Fig. 1, where the different pathways followed by PAF and HPSF processes are illustrated. The present simulation describes the PAF and HPSF processes by considering the shifting effect of pressure on the enthalpy curve, initial freezing temperature and thermophysical properties. Since during the HPSF process pressure can be released slowly, over several minutes, or quickly, in seconds, the present simulation also considers these cases. Fig. 2 shows the shifting effect of pressure on the enthalpy-temperature curve.