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Modelling the freezing of butter

Amsha Nahid[a,*], *John E. Bronlund*[a], *Donald J. Cleland*[a], *Bruce Philpott*[b]

[a]*Institute of Technology and Engineering, Massey University, Private Bag 11222, Palmerston North 5103, New Zealand*
[b]*Fonterra Research Centre, Private Bag 11029, Palmerston North 5103, New Zealand*

ARTICLE INFO

Article history:
Received 10 February 2006
Received in revised form 27 June 2007
Accepted 8 July 2007
Published online 6 August 2007

Keywords:
Butter
Freezing
Modelling
Simulation
Freezing time
Temperature
Nucleation
Crystallization

ABSTRACT

Butter is a water-in-oil emulsion so its behaviour during freezing is very different from that of most food products, for which water forms a continuous phase. The release of latent heat during freezing is controlled as much by the rate of crystallization of water in each of the water droplets as by the rate of heat transfer. Measurements of the freezing of butter show that the release of latent heat from the freezing water depends on the degree of supercooling, which, in turn, depends on the cooling medium temperature, the size of the butter item, the packaging and the type of butter. Four modelling approaches were tested against the experimental data collected for a 25 kg block of butter. A "sensible heat only model" accurately predicted the butter temperature until temperatures at which water freezing becomes significant were reached. An "equilibrium thermal properties model" predicted a temperature plateau near the initial freezing point of the butter in a manner that was inconsistent with the measured data. A third model used a stochastic approach to ice nucleation based on supercooling using classical homogeneous nucleation theory. The predicted temperatures showed that supercooling-driven nucleation alone is not sufficient to predict the freezing behaviour of butter. A fourth approach took account of time-dependent nucleation and ice crystal growth kinetics using classical Avrami crystallization theory. The relationship between the ice crystal growth rate and the supersaturation was assumed to be linear. The model predicted the experimental data accurately, particularly by predicting the slow rebound in the temperature following supercooling that is found when freezing butter under some conditions.

Modélisation de la congélation de beurre

Mots clés : Beurre ; Congélation ; Modélisation ; Simulation ; Temps de congélation ; Température ; Nucléation ; Cristallisation

1. Introduction

Butter is a water-in-oil emulsion. Approximately 16% of water in butter exists in the form of tiny spherical or oval droplets embedded in the continuous fat phase. There are approximately 10^{10}–3×10^{10} droplets per millimeter in butter (Precht, 1988; Walstra, 2003; Mulder et al., 1956).

Butter is commonly frozen and stored in bulk before thawing and further processing into consumer packs or use by the food processing industry. Accurate predictions of the rates of

* *Corresponding author*. Tel.: +64 6 350 5799x7439; fax: +64 6 350 5604.
E-mail address: a.nahid@massey.ac.nz (A. Nahid).
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doi:10.1016/j.ijrefrig.2007.07.012

Nomenclature

C	volumetric specific heat capacity ($J\,m^{-3}\,K^{-1}$)
c	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
L_{if}	latent heat of freezing at T_{if} ($J\,kg^{-1}$)
F	fraction frozen
G	linear growth rate ($m\,s^{-1}$)
H	enthalpy ($J\,kg^{-1}$)
H_{if}	enthalpy at initial freezing point ($J\,kg^{-1}$)
J	nucleation rate ($s^{-1}\,m^{-3}$)
K	Avrami constant (S^{-n})
L	latent heat of freezing at T ($J\,kg^{-1}$)
T	temperature (°C)
T_{if}	initial freezing point (°C)
U	crystallization constant ($m\,s^{-1}\,K^{-1}$)
V	volume fraction
X	length of the butter block (m)
Y	height of the butter block (m)
Z	width of the butter block (m)
a	constant for nucleation rate (s^{-1})
d	thickness (m)
g	growth constant ($m\,s^{-1}\,K^{-1}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
n	Avrami index
r	nucleation rate constant
t	time (s)
V	volume of water droplet (m^3)
v	velocity (ms^{-1})
x	distance in x direction (m)
y	distance in y direction (m)
z	distance in z direction (m)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
λ_{eff}	effective thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
φ	Volume fraction
θ	normalized temperature, $T+273.15/T_{if}+273.15$
τ_θ	reduced temperature $(\theta^3(1-\theta)^2)^{-1}$
ρ^*	relative density

Subscripts

a	air
c	continuous
d	discrete
f	fully frozen
i	initial
if	initial freezing
m	equilibrium freezing
p	polythene liner
s	surface
u	unfrozen

freezing and thawing would assist in the design of equipment and in optimizing thawing and freezing operations to avoid any quality-related problems.

A conduction-only model with convective heat transfer at the surfaces using enthalpy transformation of Eyres et al. (1946) and equilibrium thermal properties was developed by Nahid et al. (2004) and used to predict heat transfer in bulk palletized butter. The effective thermal conductivity of the pallet was calculated by considering the butter as a continuous phase and the packaging and air as a dispersed phase, using the Maxwell Eucken model:

$$\lambda_{eff} = \lambda_c\left[\frac{\lambda_d + 2\lambda_c - 2\varphi_d(\lambda_c - \lambda_d)}{\lambda_d + 2\lambda_c + \varphi_d(\lambda_c - \lambda_d)}\right] \quad (1)$$

The butter enthalpy data used were measured as a function of temperature under equilibrium conditions for thawing in a differential scanning calorimeter. The enthalpy data for the combined butter plus packaging were calculated on a pro rata weighted average basis.

The thawing process was accurately predicted by the model, as shown in Fig. 1. The freezing behaviour of butter was not accurately modelled using this approach (Fig. 2). The experimental results showed the release of latent heat over a very long period of time when freezing a pallet of butter at −11 °C (starting about 500 h after the start of cooling).

A number of experiments were conducted by Nahid (2007) on small 0.5 kg butter blocks to observe the behaviour of butter on a small scale. Release of latent heat was observed over a long period of time consistent with the pallet experiments.

It was postulated that nucleation of the water droplets was a rate-limiting process because they were present in the form of many tiny water droplets (e.g. with a radius from 1.3 to 7.6 μm Lu, 1999), which supercooled below the initial freezing point of water in the bulk form. The nucleation in each water droplet would not necessarily trigger nucleation and ice crystal growth throughout the rest of the butter because droplets nucleate and freeze independently of each other. Walstra (2003) confirmed that significant supercooling can occur in water-in-oil emulsions because of the division of the water phase into such small droplets that nucleation sites (e.g. impurities) are not present in most of the particles.

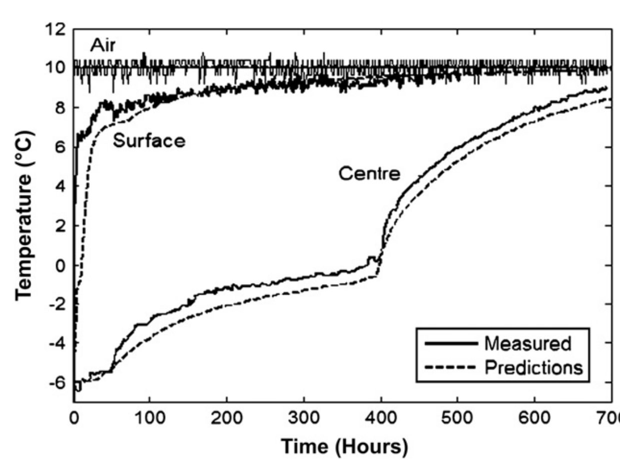

Fig. 1 – Comparison of model predictions (enthalpy transformation with equilibrium thermal properties) with thawing experimental data for a pallet of butter (taken from Nahid et al., 2004).