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Freezing time prediction for partially dried papaya puree with infinite cylinder geometry

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ABSTRACT

Dehydrofreezing which is the drying of foods to intermediate moisture content and subsequent freezing has the advantages of lowering the transportation costs due to reduced weight and improved texture. The available empirical equations for freezing time prediction and the experimental data on thermo-physical properties are for fresh produce. Some of these empirical equations were used to predict the freezing times of papaya puree infinite cylinders with initial moisture contents ~52% to ~91%. The accuracies of these methods to predict the freezing times for final center temperatures of −10 °C and −18 °C were discussed. The most accurate methods for fresh and partially dries papaya puree were suggested.

1. Introduction

Freezing as an important means of food preservation has attracted the attention of many researchers. The design of a freezer is an important task to be fulfilled by the process engineer. Establishment of general, dependable and, if possible, simple models for the prediction of freezing times of foods is essential for the design of freezers. Models which have been proposed in the past for the prediction of freezing times have been reviewed by numerous researchers (Delgado and Sun, 2001; Hung, 1990; Ramaswamy and Tung, 1984). These models may be classified as empirical or numerical models. The majority of empirical models are modifications and extensions of the Plank equation (1941). Lopez-Leiva and Hallström (2003) published a thorough survey on the Plank equation, its modifications and extensions. The Plank equation is

$$t_f = \frac{\rho \Delta H_f}{(T_f - T_a)} \left(P\frac{D}{h} + R\frac{D^2}{k_f} \right) \quad (1)$$

Using $P = \frac{V}{AD}$ and $R = \frac{P}{4}$ and defining Biot number, one may obtain

$$t_f = \frac{\rho \Delta H_f \left(\frac{V}{A}\right)}{(T_f - T_a)h} \left(1 + \frac{Bi_f}{4} \right) \quad (2)$$

This equation only predicts the freezing time for a food at its freezing point. Subcooling is also not considered.

Foods like fruits or vegetables are of cellular structure. During freezing, the ice crystals formed can cause physical rupture and separation of cells. Dehydrofreezing which involves the drying of foods to an intermediate content and subsequent freezing improves texture due to reduction in ice crystal formation. Furthermore, dehydrofreezing reduces the shipping costs due to reduced weight. Ohnishi and Mitawaki (2005) reported that osmotic dehydrofreezing protects the cell structure, in particular the cell plasma membrane, against freezing injury to give reduced softening after freezing–thawing.

Dehydrofreezing has been applied as a tool in kiwifruit preservation mainly due to reduction in the freezable water content (Chiralt et al. 2001; Moraga et al. 2006; Robbers et al., 1997). Dermesonlouoglou et al. (2007) have shown that the quality of frozen tomato can significantly be improved by osmotic dehydration as a prefreezing treatment. Bunger et al. (2004) have considered osmotic dehydration of apple cubes prior to freezing. Dehydrofrozen apple cubes obtained high scores from potential customers. They have also observed that fast freezing was the best process to preserve texture and color.

Papaya is an important tropical fruit. However, its fragility limits its transportation to countries in temperate regions. Significant post harvest loss makes the preservation of papayas an interesting field of study (Fernandes et al., 2006).

The majority of the existing empirical and numerical models and the experimental data in literature are based on or has been obtained from test materials which had not undergone partial drying. For partially dried foods the estimation of the physical properties becomes a challenging task. Ilıcalı and Icier (2002) reported

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Nomenclature

A	heat transfer area, m^2
Bi	Biot number
Cp	specific heat capacity, J/kgK
CE	the method given in Cleland and Earle (1984) [Eq. (4)]
D	characteristic length, m
$EHTD$	equivalent heat transfer dimension, 2 for an infinite cylinder
FD	the finite difference numerical method given in Ilıcalı et al. (2009) [Eqs. (22) and (23)]
H	enthalpy, J/kg
HT	the method given in Hung and Thompson (1983) [Eq. (7)]
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	latent heat of water, J/kg
P	shape factor in Plank equation
P1	the method given in Pham (1984), Eq. (15)
P2	the method given in Pham (1986) [Eq. (16)], where $T_{fm} = T_f - 1.5$ °C (P2) in Eq. (20)
P3	the method given in Pham (1986) [Eq. (16)], where $T_{fm} = T_f - 2.5$ °C (P3) in Eq. (20)
Pk	Plank number, $Cp_l\,(T_{ini} - T_f)/\Delta H$
r	radial position (m)
R	shape factor in Plank equation
R_c	radius of infinite cylinder, m
Rj	Rjutov coefficient, 1/K
RJ	The method given in Rjutov (1936) [Eq. (3)]
Ste	Stefan number, $Cp_f\,(T_f - T_a)/\Delta H$
t	time, s
T	temperature, °C
U	term defined in Eq. (10)
V	volume of foodstuff, m^3

Greek letters

α	thermal diffusivity, m^2/s
ϕ	water mass fraction
ρ	density, kg/m^3
ω	ice mass fraction
Δ	difference

Subscripts

a	ambient
c	center
d	dry solid
e	end
exp	experimental
f	frozen or freezing point for temperature or freezing period in Eq. (15)
i	ice
ini	initial
l	unfrozen
m	logaritmic mean
num	numerical
pre	precooling
sub	subcooling
tot	total
un	moisture content dependent unfrozen property
w	water
−10	between the initial freezing point and −10 °C
−18	between the initial freezing point and −18 °C

numerical data for the freezing time prediction of partially dried papaya infinite slabs with moisture contents 61–87%. No experimental data was reported in their work. Ilıcalı et al. (2007) have developed a numerical model for the freezing time prediction of papaya infinite slabs and tested the model against experimental data. Good agreement was observed between experimental and numerical temperature histories. Ilıcalı et al. (2009) extended their numerical model to predicting the temperature histories of papaya puree with infinite cylinder shape. Satisfactory agreement was observed between experimental and numerical profiles. Numerical models, if they are formulated and implemented correctly, are generally considered to be the most accurate, reliable and versatile freezing and thawing time prediction methods (Cleland et al., 1987). However, it will be more practical to develop simple, accurate empirical models which can be used for freezing time prediction of partially dried products. Therefore, it was considered worthwhile to assess the suitability of some of the existing empirical models in literature in predicting the freezing times of partially dried papaya infinite cylinders by comparing their predictions with experimental data (Ilıcalı et al., 2009). Best performing model was recommended.

2. Materials and methods

2.1. Experimental data used and empirical models

Ilıcalı et al. (2009) recently presented experimental data for the freezing time of partially dried papaya infinite cylinders. Papayas purchased locally were peeled and the seeds were removed. The remaining flesh was turned into puree form using an ordinary blender. Only the infinite cylinder shape was considered. Infinite cylinder geometry was realized by insulating the two flat ends of a copper sample holder. The purees obtained were partially dried by using a SHARP Microwave Oven R9H11. The papaya purees to be tested were categorized into three groups according to their moisture contents: ~90% (fresh), ~70% and ~50%. K-type thermocouples Model TP-K01 wire probes were inserted into the papaya puree for temperature measurement. The moisture contents of the test samples were determined by an OHAUS moisture analyzer MB45. Papaya cylinders were frozen in an air blast freezer (Armfield FT36C). Temperature histories at two positions on the symmetry axis were measured and recorded by a Monarch 309 data logger until the thermal center temperature reached −18 °C. No significant difference between the two thermocouple readings were observed, indicating unidirectional heat transfer. For each test condition experiments were repeated two or three times. The mean of the recorded temperatures at a specific time were taken as the experimental temperature at that time.

The heat transfer coefficients were obtained from the cooling data of an aluminum cylinder having the same dimension with the papaya puree. The cooling data were obtained under the same conditions with the freezing experiments. The lumped heat capacity method was used.

The initial freezing points for the papaya puree were determined experimentally. Temperature histories of the papaya purees under identical conditions with the experimental ones were calculated by a fully implicit finite difference numerical model. Numerical freezing times for final center temperatures −10 and −18 °C