Food Research International 76 (2015) 595–604

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Effect of temperature abuse on frozen army rations. Part 1: Developing a heat transfer numerical model based on thermo-physical properties of food

J.S. Karthikeyan [a], Kiran M. Desai [a], Deepti Salvi [a], Rieks Bruins [b], Mukund V. Karwe [a,*]

[a] Department of Food Science, Rutgers University, 65 Dudley Road, New Brunswick, NJ 08901, USA
[b] Rutgers Food Innovation Center — North, 120 New England Avenue, Piscataway, NJ 08854, USA

ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form 2 July 2015
Accepted 2 July 2015
Available online 7 July 2015

Keywords:
Numerical simulation
Frozen food
Differential scanning calorimeter
Apparent heat capacity

ABSTRACT

Numerical simulation was carried out to predict the effect of external temperature conditions on thermal behavior of frozen US military rations, during storage and transportation. An army breakfast menu box containing beefsteaks, concentrated orange juice, peppers & onions, French toast, and Danishes, was selected for conducting this study. Thermo-physical properties of each food item were characterized using their composition and differential scanning calorimeter (DSC). Apparent heat capacity method was used to account for the latent heat of phase change during simulation of thawing and freezing. Numerically simulated results were experimentally validated using a gel-based model food system and the food items in the menu box. The average deviation between numerically predicted temperature and experimentally measured temperature for the model food system was approximately 1 °C and for the targeted food items the deviation ranged from 2 °C to 5 °C, depending on the food item.

1. Introduction

Most of the U.S. military operational rations consist of shelf-stable food items. The united group ration-A (UGR-A) is the only U.S. army ration that consists of perishable food items, which requires cold chain storage (Natick PAM 30–25, 2012). These rations are manufactured in the U.S. by different vendors and are frozen before shipping to army bases in various countries. According to the Combat Rations Network for Technology Implementation (The United States Department of Defense), cold chain transportation of these frozen army rations, via road and via sea, can take anywhere between 3 and 5 months. Different modes of transportation with loading, unloading, and storage in between, increase the possibility of temperature abuse on these frozen army rations, which might compromise their microbial safety and chemical quality (Blond & Le Meste, 2004; Moureh & Derens, 2000). It is imperative to have a technological solution for such frozen food items that would alert the end user, about the freeze–thaw cycles experienced by the food items due to possible temperature abuse and its overall impact on the safety and quality of food items, before they are consumed.

Temperature variation with time within a food item during freezing/thawing can be determined experimentally. However, experimental procedures are often too expensive and time consuming. In order to accurately predict the temperature variation from the numerical solutions of mathematical models, the physical changes that a food item undergoes during phase change have to be well understood. Since freezing or thawing is a heat transfer process with phase change, the Fourier equation for heat conduction (Eq. (1)) can be used to predict temperature distribution in a solid material.

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + S \tag{1}$$

where ρ is density (kg/m^3), C_p is heat capacity (J/(kg·K)), T is temperature (K), t is time (s), k is thermal conductivity (W/(m^2·K)) and S is a source term (W/m^3) referring to distributed heat source or heat sink depending upon whether the product is being frozen or thawed, respectively (Ayasoufi, Keith, ASME fellow, & Rahmani, 2005). The simplest approach for solving Eq. (1) for a food system is to consider the food system as a bulk of material in which water and ice experience phase transition during a freeze–thaw process (Watzke, Deyber, & Limbach, 2010). For a multi-component substance such as food, freezing or thawing does not occur at a fixed temperature. The latent heat will be released (during freezing) or absorbed (during thawing) over a range of temperature due to the changes in the concentration of solutes (Franke, 2000). The phase transition temperature range that separates the completely thawed and the completely frozen food is termed as the 'mushy' zone, which generally is characterized as the region with solid ice suspended

---

* Corresponding author.
E-mail address: karwe@aesop.rutgers.edu (M.V. Karwe).

http://dx.doi.org/10.1016/j.foodres.2015.07.007
0963-9969/© 2015 Elsevier Ltd. All rights reserved.

in liquid water (Bhattacharya, Tanmay, & Ayappa, 2002). In the mushy zone, the major thermo-physical properties: density, thermal conductivity and heat capacity, vary with temperature due to the changes in unfrozen water fraction and ice fraction. These thermo-physical properties can be assumed to be constant in completely thawed and completely frozen regions (Voller, 1997). Density and thermal conductivity of food items can be expressed as a function of temperature, based on the combination of the major constituents of individual food items (Hamdami, Jean-Yves, & Alain, 2004a; Watzke et al., 2010). The challenge in solving Eq. (1) is the inclusion of sensible heat and latent heat of phase change in the mushy zone. For a food system, a method based on latent heat has to be developed, such that, a single energy balance equation is required for the entire domain consisting of coexisting solid, liquid, and mushy zone. The most commonly used and reliable method is the apparent heat capacity (AHC) method (Kumar & Subhendu, 2009; Pham, 2006). In this method, latent heat is included in the sensible heat to produce a heat capacity curve with a large peak around the mushy zone, which lies between the temperatures T_1 (thawed side) and T_2 (frozen side), as depicted in Fig. 1. The original heat transfer equation (Eq. (1)) is modified as Eq. (2), in which $C_{p(app)}$ is the apparent heat capacity (AHC) expressed in J/(kg·K).

$$\rho C_{p(app)} \frac{\partial T}{\partial t} = \nabla(k \nabla T) \tag{2}$$

To determine AHC, a differential scanning calorimeter (DSC) is usually used. A DSC generated thermogram, in which the rate of heat transfer is plotted versus temperature for a small amount of sample, provides information on the energy released or absorbed in the form of latent heat during phase transition of that sample (Hamdami et al., 2004a; Le Reverend, Fryer, & Bakalis, 2009; Sebnam, Seher, & Volker, 2007).

A mathematical model for a freeze–thaw process consists of partial differential equations governing the heat transfer in all three regions: unfrozen, frozen, and mushy. Analytical solution for these governing equations during phase change is impossible due to their complexity. Therefore, numerical methods based on a fundamentally sound theory, have to be used (Huan, He, & Ma, 2003). The challenging step in simulating phase change of a food system is the description of non-linear thermal properties in time and space. In such cases, it has been shown that the finite element method (FEM) is the most suitable numerical method for obtaining converged solutions (Kumar & Subhendu, 2009).

Although prior research has been done to predict the thermal behavior of frozen foods and its influence on overall safety/quality, researchers have mainly focused on simpler geometries (Elvira, Sanz, & Carrasco, 1996; Scott & Heldman, 1990; Zuritz & Singh, 1985). A detailed study involving multiple food products in a complex geometry, including the effects of phase change on the overall thermal response and safety/quality, has not been carried out. Therefore, this research was focused on quantifying the effect of external time-varying temperature conditions on the thermal behavior of five different frozen food products inside a typical army menu box, taking into account the changes in their thermo-physical properties during phase change. The specific objectives were 1) to determine the apparent heat capacity and other thermo-physical properties of five different food items using their component data and a differential scanning calorimeter, and 2) to develop and validate a numerical model of the frozen army menu box containing those food items, to predict the heat transfer within the menu box with respect to external temperature conditions. Extension of this research which focused on predicting food safety during real-time temperature abuse scenarios by correlating the numerically simulated thermal behavior of food items to microbial growth kinetics is presented in a subsequent manuscript.

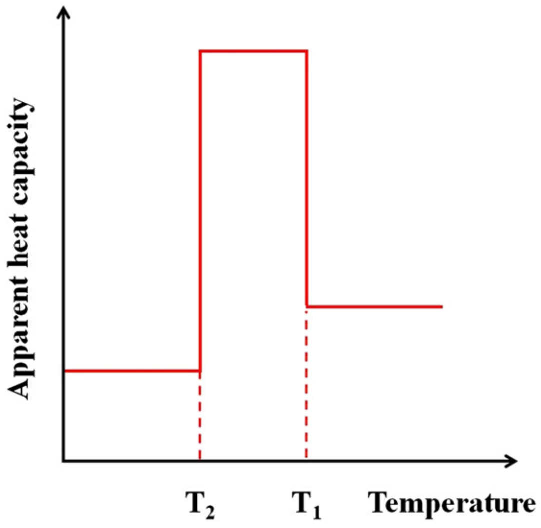

Fig. 1. Theoretical apparent heat capacity curve.

2. Materials and methods

2.1. Food description

Numerical model was developed for an army breakfast menu box, which contained beefsteaks, concentrated orange juice, peppers & onions, French toast, and Danishes (Fig. 2A). The composition of each food item, i.e., proteins, carbohydrates, fat, fiber was obtained from

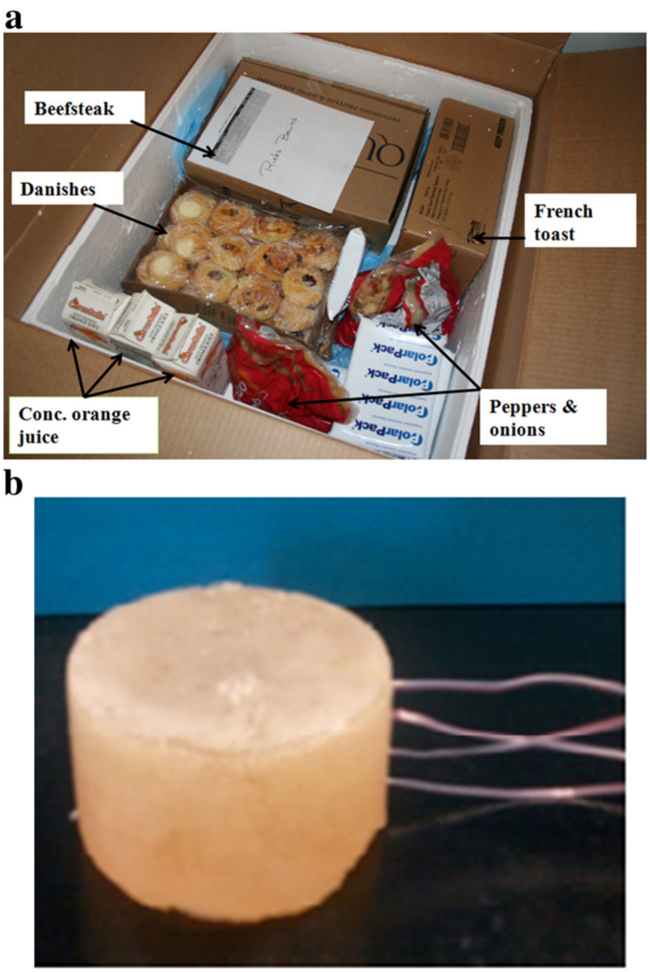

Fig. 2. (A) Five food items displayed in their respective packages. This figure does not depict the orientation of the food products inside the menu box; (B) model food system – 25% (w.b.) gelatin gel – with four 'T' type thermocouples inserted into it along the axis.