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Modeling of Food Freezing

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4.1 Introduction

Modeling of the freezing process is accomplished in many ways. Computation of refrigeration requirements to achieve the desired temperature reductions and requirements involved in removal of both sensible and latent heats from the product are one component of modeling. In addition, the design of processes for food freezing requires knowledge of time needed to reduce product temperature to desired levels. Ultimately, design of frozen-food storage requires knowledge of changes occurring within the food product as it is exposed to the environmental conditions existing within the storage system. The design of systems requires insight into the changes occurring within the product structure during freezing, the influence of these changes on product properties along with the accepted approaches to computation of freezing times, and the use of these computed times in design calculations.

This chapter will review the following components of modeling as applied to food freezing: (1) the thermodynamics of food freezing and illustration of changes occurring within the product during freezing and the influence of changes to frozen food properties; (2) the impact of temperature-dependent properties on the solution of unsteady-state heat transfer equations; and (3) calculations for freezing time for food and capacity selection of food freezing systems.

4.2 Thermodynamics of Phase Change in Foods

The thermodynamics of food freezing describes the changes in water within a food product as the freezing process proceeds. As illustrated in figure 4.1, the change in product temperature during freezing decreases gradually as the latent heat of fusion is removed from water within the product. The freezing process has two unique characteristics when compared to the freezing of pure water. First, the product temperature at which initial ice-crystals are formed is depressed below the temperature of initial ice crystal formation in pure water. The second difference
between the food product system and pure water is the gradual removal of latent heat of fusion as the product temperature decreases. The actual shape of the temperature-time curve will vary with product composition and with the location within the product structure.

The relationship between product composition and temperature is most often explained in terms of the freezing temperature depression equation for an ideal solution. This equation is derived by Heldman and Singh (1981) and can be presented as follows:

$$\frac{\lambda}{R} \left[ \frac{1}{T_{Ao}} - \frac{1}{T_A} \right] = \ln X_A$$  \hspace{1cm} (4.1)

Equation 4.1 illustrates the relationship between the mole fraction ($X_A$) of water within the product and the absolute temperature ($T_A$) at which ice-crystal formation occurs as a function of molar latent heat of fusion ($\lambda$) and the universal gas constant ($R$). The mole fraction of water within the product can be defined as follows:

$$X_A = \frac{m_A / M_A}{m_A / M_A + m_s / M_s}$$ \hspace{1cm} (4.2)

In equation 4.2, the mole fraction of water in the product is defined in terms of product moisture content expressed as a moisture fraction ($m_A$), the molecular weight of water ($M_A$), the mass fraction of product solids ($m_s$), and the molecular weight of product solids ($M_s$). The applications of equations 4.1 and 4.2 can be direct in the case of some food products but may be more indirect when product compositions are not well defined. In addition to a complete composition analysis of the food product, knowledge of the product components causing depression of the initial temperature of freezing is needed. More detailed discussion on the thermodynamics of freezing can be found in chapter 2.