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Effective thermal conductivity prediction of foods using composition and temperature data

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A B S T R A C T

Thermal conductivity data are important for food process modelling and design. Where reliable thermal conductivity data are not available, they need to be predicted. The most accurate 'first approximation' methodology for predicting the isotropic thermal conductivity of foods based only on data for composition, initial freezing temperature and temperature dependent thermal conductivity of the major food components was sought. A key feature of the methodology was that no experimental measurements were to be required. A multi-step prediction procedure employing the Parallel, Levy and Effective Medium Theory models sequentially for the components other than ice and air, ice and then air respectively is recommended. It was found to provide the most accurate predictions over the range of foods considered (both frozen and unfrozen, porous and non-porous). The Co-Continuous model applied in a single step also provided prediction accuracy within ±20% (on average), except for the porous frozen foods considered. For greater accuracy more rigorous modelling approaches based on knowledge of the foods structure would be required.

1. Introduction

Thermal property data are needed for modelling and design of food processing operations. Datta (2007) argued that the implementation of advanced thermal processing models of food is now limited more by the accuracy and availability of input parameters (which includes thermal conductivity) than by computing power or modelling expertise.

A large number of thermal conductivity data may be found in the literature (Houska et al., 1994; Houska et al., 1997; Rahman, 2009; ASHRAE, 2010) and online (e.g. *Nelfood.com*, Nesvadba et al., 2004) but most of these data are for minimally processed foods. In the event that thermal property data for the food of interest are not available, to predict them with similar precision to thermal conductivity measurement using relatively simple thermal conductivity models would be highly desirable.

The literature describes a large number of thermal conductivity models (Murakami and Okos, 1989; Maroulis et al., 2002; Carson et al., 2006; Carson, 2006; Wang et al., 2006; Rahman, 2009; ASHRAE, 2010). Many of them are simply empirical data-reduction models, and hence have a limited range of applicability. A large number have theoretical bases, although many of them include one or more parameters the values of which must be determined empirically, and these often perform well in model validation exercises (e.g. Murakami and Okos, 1989; Hamdami et al., 2003). However, if the numerical value of the empirical parameter is an unknown, these models are of little use if the user intends to perform a prediction without performing any measurements, particularly if very little is known about the microstructure of the food. The aim of this paper was to determine the most accurate model/method for obtaining a first approximation (preferably to within ±20%) of the thermal conductivity of any isotropic food product, by referring just to its composition data, initial freezing temperature (if applicable) and the temperature of the food, without the need to perform any measurements.

2. Thermal conductivity prediction for foods

The thermal conductivity of food products depends on three basic factors: composition, processing conditions, and structure

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(Rahman, 2009). Foods may be considered as mixtures of the following major components: water, protein, fat, carbohydrate and ash (i.e. non-combustible solids such as minerals etc). Some foods may contain a significant volume fraction of ice and/or air (porosity). Temperature is the most critical processing condition in solid and liquid phases although pressure can be significant too e.g. high pressure processing (HPP). The temperature-dependent thermal conductivities of the major food components were measured by Choi and Okos (1986) and have been reproduced in a number of other sources (e.g. Rahman, 2009; ASHRAE, 2010). In general terms, the thermal conductivities of protein, fat, carbohydrates and ash are similar; about three times lower than that of water, nine times lower than that of ice and ten times higher than that of air.

It is the dependence of the thermal conductivity of the food on structure that is accounted for by the thermal conductivity model. This study only considers models which are functions of the composition of the food and thermal conductivities of the major food components only, and do not involve any parameters which must be measured experimentally.

For first approximations, one of two approaches may be employed:

1) Predict the thermal conductivity of the food of concern in a single step by using a single model equation
2) Use an algorithm consisting of a number of steps in which more than one model may be used to predict the thermal conductivity

2.1. Single-step approach

Such an approach is desirable because of its simplicity and relative ease of implementation. In addition to the requirement that they must only require the volumetric fractions and thermal conductivities of the components as inputs, suitable models for first approximations will need to be able to be applied to multi-component mixtures and they should treat each component equally, and hence require no knowledge of the food structure.

The simplest thermal conductivity models that meet the Single-step criteria are, respectively, the arithmetic, harmonic and geometric weighted means of the thermal conductivities of the components of the food, where the weighting coefficients being provided by the volumetric fractions of the food:

$$\text{Parallel Model (Rahman, 2009):} \quad k_e = \sum_i k_i v_i \tag{1}$$

$$\text{Series Model (Rahman, 2009):} \quad k_e = \frac{1}{\sum_i \frac{v_i}{k_i}} \tag{2}$$

$$\text{Geometric Model (Rahman, 2009):} \quad k_e = \prod_i k_i^{v_i} \tag{3}$$

The Series and Parallel models physically match structures where the components are in layers perpendicular or parallel to the heat flow direction respectively. The geometric model represents no particular physical structure but it is mathematically simple. The Series and Parallel models respectively represent the theoretical lower and upper bounds of the thermal conductivity of mixtures, provided thermal conduction is the only transport mechanism involved (Carson et al., 2005). It is therefore unlikely that they will provide the most accurate predictions; however, since they provide limits it is useful to consider their predictions in any modelling exercise. The predicted values by the Geometric model always lie between those predicted by the Series and Parallel models.

Two other models which meet the single-step criteria are the well-known Effective Medium Theory model (EMT) (Landauer, 1952):

$$\sum_i v_i \frac{k_e - k_i}{2k_i + k_e} = 0 \tag{4}$$

and Wang's Co-continuous model (CC) (Wang et al., 2008):

$$k_e = \frac{\sum_i \frac{v_i}{k_i}}{2}\left(\sqrt{1 + \frac{8\sum_i k_i v_i}{\sum_i \frac{v_i}{k_i}}} - 1\right) \tag{5}$$

The EMT model represents the physical structure where all of the components are randomly dispersed with each other (co-dispersed) i.e. no component necessarily represents a continuous phase. The Co-Continuous (CC) model represents a physical structure where all of the components are continuous but intertwined and none is dispersed. Fig. 1 shows plots of these five models (Eqs. (1)–(5)) for a food with two components in which the ratio of thermal conductivities of the components (k_1/k_2) is 20.

The well-known Maxwell-Eucken model (described below, Eqs. (8) and (9)) represents the physical structure where a component is dispersed in another one which is continuous. The above single-step criteria rule out the Maxwell-Eucken model for use in a single step, since it requires the designation of a continuous, and a dispersed phase, and is only capable of handling two components at a time. The Maxwell-Eucken model is, however, suitable for use in a multi-step approach since it does not contain any empirical parameters.

2.2. Multi-step approach

While the single-step, single model approach offers simplicity, there is the potential for greater accuracy from the same input data using a multi-step method, since more than one structural model may be employed. Also, components in foods seldom exist in a single well-defined micro-structure. Multi-step thermal conductivity prediction methods have been proposed and implemented previously (e.g. Maroulis et al., 2002; Carson, 2006; Cogné et al., 2003); however, only the method proposed by Wang et al. (2010)

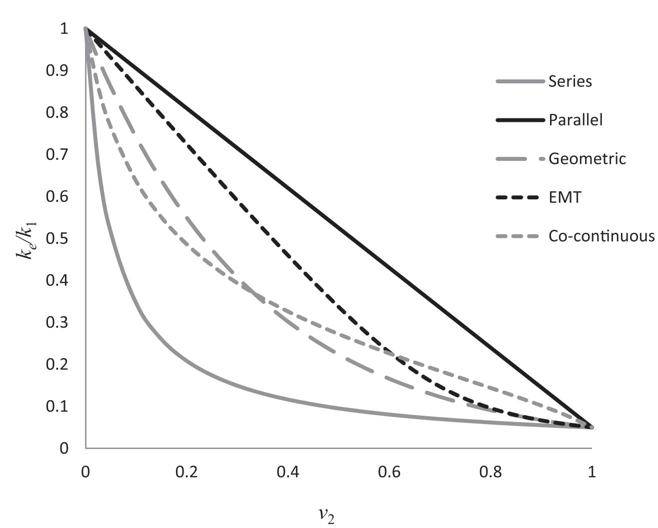

Fig. 1. Plots of the Series, Parallel, Geometric, EMT and Co-continuous models for a binary mixture in which $k_1/k_2 = 20$.