Prediction of the Thermal Conductivity of Porous Foods

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Abstract

A review of the food engineering literature exposed a paucity of information in the area of effective thermal conductivity prediction for porous foods. No useful guidelines were found that could advise a food engineer on the selection of appropriate effective thermal conductivity models for this application. The aims of this study were to increase the understanding in this area and to produce a general procedure for effective thermal conductivity prediction.

The specific focus of this study was the influence of porosity on thermal conduction and so the porous foods under consideration were assumed to contain small (<5mm), uniformly distributed void spaces filled with stagnant gas (either air or carbon dioxide), in order that convection and radiation effects could be neglected. It was also assumed that only bound water was present within foods so that moisture migration and its associated heat effects would not be an issue. Two basic classes of porous foods were identified: foods in which void spaces existed in the interstices of particulate foods were referred to as having "external porosity" and foods in which bubbles existed within a solid or liquid matrix were referred to as having "internal porosity".

Using a comparative method, thermal conductivity measurements were performed on food analogues comprised of expanded polystyrene (EPS) beads suspended in guar gel. Thermal conductivity data were produced that revealed a basic dependence of the relative effective thermal conductivity (k_e/k_1) on the porosity (v_2). The mean volume of the individual EPS beads used to simulate the air bubbles was varied between 10^{-6} and $4\text{x}10^{-3}$ of the total sample volume, but no significant dependence of k_e/k_1 on bead diameter was observed. Thermal conductivity measurements were also performed on samples containing squat aluminium cylinders suspended in guar gel. The results from these samples highlighted the significant influence of the component thermal conductivity on the uncertainties involved in effective thermal conductivity prediction.

Using a finite element software package, two-dimensional numerical models were constructed to simulate the measurement of effective thermal conductivity for theoretical material samples having different basic structures. These models allowed the relative significance of several structure-related variables to be examined. The results indicated that the status of the gaseous and solid/liquid components of porous foods, whether continuous or dispersed, and the degree to which pores (in the case of internal porosity) or particles (in the case of external porosity) were in contact with neighbouring pores or particles had a significant influence on the effective thermal conductivity. The sizes and shapes of the individual pores or particles were found to have only minor or negligible influence.

The predictions from two basic types of models were compared to the results from the physical experiments: those models that were functions of component thermal conductivity and volume fractions only (referred to as Type A models), and those that were functions of these two variables as well a third variable (referred to as Type B models). None of the Type A models provided accurate predictions for all the experimental data considered and it was concluded that, apart from certain scenarios, the use of Type B models was preferable. Of the Type B models considered, those that were based on isotropic physical models such as the Maxwell and Effective Medium Theory (EMT) based models, provided better predictions on average than those based on anisotropic physical models, such as the Krischer and Chaudhary-Bhandari models.

The analysis of the experiments and the results of the model evaluation exercise highlighted an important issue regarding the selection of appropriate effective thermal conductivity models: the effective thermal conductivity of the materials had a strong dependence on the optimum heat conduction pathway for a given structure. Hence an assessment of a material's structure should be performed in order to determine the optimum heat conduction pathway within that material.

Two basic optimal heat conduction pathways were identified. In the first scenario the continuous phase of the material has a higher thermal conductivity than the dispersed phase, as is the case with materials having internal porosity, and the optimum heat conduction pathway avoids the gas bubbles that comprise the dispersed phase. In the second scenario, the continuous phase has a lower thermal conductivity than the dispersed phase, as is the case with materials having external porosity, and the optimum heat conduction pathway passes through as many of the solid particles that comprise the dispersed phase as possible.

Previous workers have shown that the two forms of the Maxwell-Eucken model provided theoretical upper and lower limits of the effective thermal conductivity of isotropic materials. In this work, it was proposed that the effective thermal conductivities of materials having internal porosity are bounded by the Landauer-EMT model and the form of the Maxwell-Eucken model in which the continuous phase has a higher thermal conductivity than the dispersed phase. Similarly, it was proposed that the effective thermal conductivities of materials having external porosity are bounded by the Landauer-EMT model and the form of the Maxwell-Eucken model in which the continuous phase has a lower thermal conductivity than the dispersed phase.

The degree of contact between the pores or particles of the dispersed phase, which was related to the optimum conduction pathway, was identified as the variable having the most significant influence on a material's thermal conductivity, in terms of its position relative to thermal conductivity bounds. For this reason, effective thermal conductivity models for general applications should incorporate some measure of this variable. For isotropic, non-frozen foods, two new models based on the Maxwell and EMT structural models with structure-related parameters were proposed. An advantage of these models was that the values of the structure-related parameters had linear variation between the thermal conductivity bounds, unlike other models in the literature.

A simple, general procedure for predicting the effective thermal conductivity of isotropic non-frozen foods was proposed and tested on two types of cake. The predictions from the models recommended by the procedure for the cakes agreed with the experimental data to within ±10%, which would be sufficient for many food industry purposes.

It was recommended that further testing of the proposed thermal conductivity prediction procedure be performed to assess its accuracy and practicality. A need to improve the understanding of the relationship between the structure-related model parameter and the extent of contact between pores or particles was also identified.

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"It is certain that there is nothing more dangerous,
in philosophical investigations, than to take any thing for granted,
however unquestionable it may appear, till it has been proved by
direct and decisive experiment."

—Count Rumford (Benjamin Thompson)

"The heart of the discerning acquires knowledge;
the ears of the wise seek it out."

—Proverbs 18:15 (NIV)

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