Prediction of Chilling Times of Foods

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ABSTRACT

Chilling is one of the most important branches of food preservation under low temperature as it retains, more closely than any other means, the "fresh" quality and appearance of the food. No simple method to predict chilling times for a wide range of geometric shapes without major disadvantages was found in the literature. Investigation via a set of test problems showed that for each available method, there were ranges of conditions under which accuracy of prediction reduced significantly. This justified development and testing of a new method. A theoretical and experimental study of methods for predicting the chilling times of both regularly and irregularly shaped foods was carried out.

Using the sphere as a reference shape and based on the first term of the series analytical solution, empirical mathematical expressions for extending the existing concept of equivalent heat transfer dimensionality E to take account of the effect of geometry on unsteady state heat conduction processes, which has been successfully applied in freezing time prediction, were derived. These cover a wide range of heat transfer environmental conditions and multi-dimensional regular and irregular geometries. Empirical formulae for the lag factor, L, as a function of object geometric shape were also developed for the thermal centre and mass-average temperatures.

Guidelines to define object geometry for irregular shapes were established. The recommended dimensional measurement approach uses actual measurements of the three dimensions of an irregular geometry to define the dimensional ratios for an equivalent ellipsoid. The neglect of sharp protrusions and of hollows in taking measurements is recommended.

Experimental chilling data for foods found in the literature, were limited in usefulness for model testing because the experimental conditions were usually not sufficiently accurately measured, described or controlled. Therefore, a comprehensive set of 3879 analytical solution simulations, 351 finite element method procedures and 165 experiments of chilling processes were made over a wide range of conditions. The chilling experiments were carried out using sixteen different two- and three-dimensional irregularly shaped objects made of Tylose, a food analogue, or of Cheddar cheese. Experiments for bricks of Cheddar cheese with uniformly distributed voids were also conducted because of the scarcity of published experimental data for chilling of products with voids.

For regular geometries (short cylinder, squat cylinder, infinite rectangular rod, rectangular brick, oblate and prolate spheroids), and across a wide range of conditions and product shape ratios the methodology predicted chilling times to within -7.6 to 5.6% of the theoretical solutions for the thermal centre position and ±9.4% for the mass-average condition. For many commonly encountered conditions the lack of fit was considered acceptably low when likely data uncertainties are taken into account.

When the guidelines for defining an equivalent ellipsoid and the simple method were tested, the 95% confidence interval of the percentage difference comparing predictions with the experimentally measured chilling times for thermal centre temperatures of two-dimensional irregular geometries was -3.1 to 14.4%. For three-dimensional irregular geometries, the equivalent interval was -6.4 to 11.6%. No experimental testing of predicted mass-average temperatures was carried out. The simple prediction method failed to match the experimental data in a similar manner to the finite element method. Lack of fit was probably more due to experimental error than errors in the form of geometric approximation and the prediction method itself.

In situations where the product contains significant uniformly distributed voids, either the simple empirical prediction method or any relevant analytical solution can be applied if an "equivalent thermal conductivity" is defined. Keey's method, with a distribution factor dependent on voidage fraction, is recommended for calculating the equivalent thermal conductivity on the basis of best fit to experimental data but ranges of applicability require further investigation. It could not be established whether natural convection in the voids was a significant enhancer of the cooling rate.

In many industrial applications, data such as heat transfer coefficients and thermal properties are difficult to estimate, and non-uniformity of chilling conditions is difficult to avoid. The overall accuracy of predictions in such applications is unlikely to be significantly increased through further reduction in the inherent inaccuracy of the proposed methodologies. The methodologies are therefore suitable for routine industrial use.

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