

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

# PREDICTION OF CHILLING TIMES OF FOODS

A thesis presented in partial fulfilment of the requirement  
for the degree of Doctor of Philosophy in Process  
and Environmental Technology at  
Massey University

ZHANG LIN, B.E. (Tsinghua)

### 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  $\pm 9.4\%$  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<sup>but ranges of applicability require further investigation.</sup> 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.

### ACKNOWLEDGEMENTS

The author would like to acknowledge the following persons for advice and assistance during the course of this project:

Professor Andrew C. Cleland, Department of Food Technology, Massey University, Chief Supervisor;

Associate Professor Donald J. Cleland, Department of Process and Environmental Technology, Massey University, Supervisor;

Dr. George F. Serrallach, Department of Process and Environmental Technology, Massey University, Supervisor.

The author would like to acknowledge the following persons for technical assistance during the experimental phase of the project:

Mr. John Alger, Mr. Wayne Mallett, Mr. Don McLean and Mr. Bruce Collins, Department of Process and Environmental Technology, Massey University;

Mr. Byron McKillop, Department of Food Technology, Massey University.

The author would like to thank family and friends for their continual support and helpfulness.

The author would also like to thank Huiting for her moral support and for proof reading.

**TABLE OF CONTENTS**

<b>ABSTRACT</b> .....	<b>ii</b>
<b>ACKNOWLEDGEMENTS</b> .....	<b>iv</b>
<b>TABLE OF CONTENTS</b> .....	<b>v</b>
<b>LIST OF FIGURES</b> .....	<b>ix</b>
<b>LIST OF TABLES</b> .....	<b>xiv</b>
<b>1 INTRODUCTION</b> .....	<b>1</b>
<b>2. LITERATURE REVIEW</b> .....	<b>2</b>
2.1 Problem Definition and Formulation .....	2
2.1.1 Unsteady State Heat Conduction .....	2
2.1.2 Boundary Conditions .....	4
2.1.3 Initial Conditions .....	6
2.2 Solutions for Problems Involving Chilling Time Prediction .....	7
2.2.1 Solutions for Problems with a Convection-Only Heat Transfer Environment	7
2.2.1.1 Analytical Solutions .....	7
2.2.1.2 Numerical Solutions .....	10
2.2.1.3 Empirical Solutions .....	15
2.2.1.4 Solutions for Problems in a Time-Varying, Convection only Heat Transfer Environment .....	22
2.2.2 Solutions for Problems with Simultaneous Convection and Evaporation ..	23
2.2.2.1 Numerical Solutions .....	23
2.2.2.2 Empirical Solutions .....	26
2.3 Published Data Suitable for Testing Methodologies .....	28
2.3.1 Thermal Properties .....	30
2.3.2 Heat Transfer Coefficients .....	30

<b>3. PRELIMINARY CONSIDERATIONS</b> .....	<b>31</b>
<b>4. DEVELOPMENT OF A NEW GENERAL EMPIRICAL METHOD</b> .....	<b>33</b>
4.1 Introduction .....	33
4.2 Proposed Form of the New Method .....	33
4.3 Geometric Definitions .....	36
4.4 Creation of Database for the Regular Geometries .....	38
4.5 Formulation of the Equivalent Heat Transfer Dimensionality, and the Lag Factors for the Thermal Centre and the Mass-Average Temperatures .....	40
4.5.1 Formulation of the Equivalent Heat Transfer Dimensionality, Denoted $E$ ..	40
4.5.1.1 Formulation of the Equivalent Heat Transfer Dimensionality at $Bi = 0$ .....	40
4.5.1.2 Formulation of the Equivalent Heat Transfer Dimensionality for $Bi \rightarrow \infty$ .....	41
4.5.1.3 Formulation of the Equivalent Heat Transfer Dimensionality at any Biot number .....	45
4.5.2 Formulation of the Lag Factor for the Thermal Centre, Denoted $L_c$ .....	46
4.5.2.1 Formulation of the Lag Factor at $Bi = 0$ , Denoted $L_0$ .....	47
4.5.2.2 Formulation of the Lag Factor at $Bi \rightarrow \infty$ , Denoted $L_\infty$ .....	47
4.5.2.3 Formulation of the Lag Factor at any Biot Number .....	47
4.5.3 Formulation of the Lag Factor for the Mass-Average Temperature, Denoted $L_m$ .....	48
4.6 Testing the New Formulae for Regular Shapes .....	49
4.7 Comparison with Existing Chilling Time Prediction Methods .....	49
4.8 Summary of the Proposed Method .....	51
<b>5. EXPERIMENTAL PROCEDURE AND DATA COLLECTION</b> .....	<b>55</b>
5.1 The Equipment .....	55
5.2 Experimental Error .....	56
5.3 Choice of Chilling Material .....	57
5.4 Temperature Measurement and Control .....	59
5.5 Chilling of Two-Dimensional Irregular Shapes .....	60

5.5.1	The Test Samples	60
5.5.2	Dimension Measurement and Control	61
5.5.3	Measurement and Control of Surface Heat Transfer Coefficients	62
5.5.4	Analysis of Heat Transfer in Two-Dimensional Irregular Shapes	64
5.6	Chilling of Three-Dimensional Irregular Shapes	66
5.6.1	The Test Samples	66
5.6.2	Dimension Measurement and Control	68
5.6.3	Measurement and Control of Surface Heat Transfer Coefficients	68
5.6.4	Analysis of Heat Transfer in Three-Dimensional Irregular Shapes	69
5.6.5	Summary	70
<b>6.</b>	<b>EXPERIMENTAL DESIGN AND RESULTS</b>	<b>83</b>
6.1	Treatment of the Effect of Geometry	84
6.2	Chilling of Two-Dimensional Irregular Shapes	87
6.3	Chilling of Three-Dimensional Irregular Shapes	91
6.4	Prediction of Chilling Times for Two-Dimensional Irregular Shapes by the Proposed Method	93
6.5	Prediction of Chilling Times for Three-Dimensional Irregular Shapes by the Proposed Method	94
6.6	Discussion and Conclusions	95
<b>7.</b>	<b>CHILLING OF OBJECTS WITH UNIFORMLY DISTRIBUTED VOIDS</b>	<b>116</b>
7.1	Introduction	116
7.2	Variables Considered Important	116
7.3	Approach Undertaken	116
7.4	Experimental Methods	117
7.4.1	The Test Samples	117
7.4.2	Dimension Measurement and Control	118
7.4.3	Measurement and Control of Surface Heat Transfer Coefficients	118
7.4.4	Analysis of Heat Transfer in Rectangular Bricks with Uniformly Distributed Voids	119
7.5	Experimental Design	120

**8. PREDICTION METHODS TO ACCOUNT FOR UNIFORMLY DISTRIBUTED VOIDS . . . . . 127**

8.1 Introduction . . . . . 127

8.2 Determination of the Equivalent Thermal Conductivity from the Experimental Data . . . . . 127

8.3 Existing Equivalent Thermal Conductivity Models . . . . . 129

8.4 Results from Application . . . . . 133

8.5 Summary . . . . . 137

**9 CONCLUSIONS . . . . . 152**

**NOMENCLATURE . . . . . 154**

**REFERENCES . . . . . 155**

**APPENDIX A: MANUAL OF A GENERALLY APPLICABLE METHOD FOR CHILLING TIME PREDICTION . . . . . A-1**

**APPENDIX B: CHILLING TIME PREDICTION PROGRAMME . . . . . DISKETTE I & II**

**APPENDIX C: CHILLING TIME ANALYTICAL SOLUTION PROGRAMME . . . . . DISKETTE II**

LIST OF FIGURES

Figure 4.1	Plot of $\ln Y$ vs $Fo$ during a chilling process	34
Figure 4.2	Plot of error arising from use of eqn. (4.30) vs $\log(\beta_1)$ for an infinite rectangular rod	44
Figure 4.3.	Plot of $L_c$ vs $\log(\beta_1)$ for an infinite rectangular rod	46
Figure 5.1	Schematic diagram of the air environmental tunnel	75
Figure 5.2	Schematic diagram of the brine immersion tank	75
Figure 5.3	The sample rotator used in the brine immersion tank	76
Figure 5.4	The sample oscillator and the two-dimensional irregularly shaped sample $I_c$ used in the air environmental tunnel	76
Figure 5.5	The sample oscillator and the three-dimensional irregularly shaped sample $I_t$ used in the air tunnel	77
Figure 5.6	Cross-section and finite element method grid for the two-dimensional irregularly shaped sample $E_a$	77
Figure 5.7	Cross-section and finite element method grid for the two-dimensional irregularly shaped sample $E_b$	78
Figure 5.8	Cross-section and finite element method grid for the two-dimensional irregularly shaped sample $E_c$	78
Figure 5.9	Cross-section and finite element method grid for the two-dimensional irregularly shaped sample $E_d$	79

Figure 5.10	Cross-section and finite element method grid for the two-dimensional irregularly shaped sample I <sub>a</sub>	79
Figure 5.11	Cross-section and finite element method grid for the two-dimensional irregularly shaped sample I <sub>b</sub>	80
Figure 5.12	Cross-section and finite element method grid for the two-dimensional irregularly shaped sample I <sub>c</sub>	80
Figure 5.13	Schematic diagram showing the arrangement of the polystyrene foam caps for two-dimensional samples	81
Figure 5.14	Schematic diagram showing the method of thermocouple insertion and position within the moulded multi-dimensional samples (not to scale)	81
Figure 5.15	The three-dimensional irregularly shaped samples	82
Figure 5.16	Schematic diagram of box corner types	82
Figure 6.1	Temperature/time profile for chilling of the Tylose two-dimensional irregular shape E <sub>a</sub> during Run E <sub>a</sub> 1	97
Figure 6.2	Temperature/time profile for chilling of the Tylose two-dimensional irregular shape E <sub>b</sub> during Run E <sub>b</sub> 5	97
Figure 6.3	Temperature/time profile for chilling of the Tylose two-dimensional irregular shape E <sub>c</sub> during Run E <sub>c</sub> 1	98
Figure 6.4	Temperature/time profile for chilling of the Tylose two-dimensional irregular shape E <sub>d</sub> during Run E <sub>d</sub> 7	98

Figure 6.5	Temperature/time profile for chilling of the Tylose two-dimensional irregular shape $I_a$ during Run $I_a5$	99
Figure 6.6	Temperature/time profile for chilling of the Tylose two-dimensional irregular shape $I_b$ during Run $I_b2$	99
Figure 6.7	Temperature/time profile for chilling of the Tylose two-dimensional irregular shape $I_c$ during Run $I_c3$	100
Figure 6.8	Plot of $M_{exp}$ versus $M_{FEM}$ for Tylose two-dimensional irregular shapes	100
Figure 6.9	Plot of $L_c_{exp}$ versus $L_c_{FEM}$ for Tylose two-dimensional irregular shapes	101
Figure 6.10	Errors arising from displacement of the thermocouple from the thermal centre	101
Figure 6.11	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $I_p$ during Run $I_p3$	102
Figure 6.12	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $I_q$ during Run $I_q1$	102
Figure 6.13	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $I_r$ during Run $I_r1$	103
Figure 6.14	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $I_s$ during Run $I_s3$	103
Figure 6.15	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $I_t$ during Run $I_t1$	104

Figure 6.16	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $S_a$ during Run $S_a3$	104
Figure 6.17	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $S_b$ during Run $S_b1$	105
Figure 6.18	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $S_c$ during Run $S_c1$	105
Figure 6.19	Temperature/time profile for chilling of the Tylose three-dimensional irregular shape $S_d$ during Run $S_d1$	106
Figure 6.20	Examples of measurement of object geometry	106
Figure 8.1	Data analysis procedure used to find $k_e$ and $L_c$ model	128
Figure 8.2	Plot of $f$ , the distribution factor in Keey's method determined from experimental $k_e$ data vs $Bi$	144
Figure 8.3	Normal probability plot to determine data outliers for the approach of Keey (1)	144
Figure 8.4	Normal probability plot to determine data outliers for the approach of Keey (2)	145
Figure 8.5	Normal probability plot to determine data outliers for the approach of Keey (3)	145
Figure 8.6	Plot of mean differences between the predictions of Keey (1) and the experimental data for $k_e$ versus ratio of $(L_c$ exp / $L_c$ model)	146

- Figure 8.7 Plot of mean differences between the predictions of Keey (2) and the experimental data for  $k_e$  versus ratio of ( $L_{c \text{ exp}} / L_{c \text{ model}}$ ) 146
- Figure 8.8 Plot of mean differences between the predictions of Keey (3) and the experimental data for  $k_e$  versus ratio of ( $L_{c \text{ exp}} / L_{c \text{ model}}$ ) 147
- Figure 8.9 Plot of differences between the predictions of  $k_e$  by the Keey (1) approach and experimental  $k_e$  values versus Biot number 147
- Figure 8.10 Plot of differences between the predictions of  $k_e$  by the Keey (2) approach and experimental  $k_e$  values versus Biot number 148
- Figure 8.11 Plot of differences between the predictions of  $k_e$  by the Keey (3) approach and experimental  $k_e$  values versus Biot number 148
- Figure 8.12 Plot of differences between the predictions of  $k_e$  by the Keey (1) approach and experimental  $k_e$  values versus voidage fraction 149
- Figure 8.13 Plot of differences between the predictions of  $k_e$  by the Keey (2) approach and experimental  $k_e$  values versus voidage fraction 149
- Figure 8.14 Plot of differences between the predictions of  $k_e$  by the Keey (3) approach and experimental  $k_e$  values versus voidage fraction 150
- Figure 8.15 Plot of differences between the predictions of  $k_e$  by the Keey (2) approach and experimental  $k_e$  values versus box size 150
- Figure 8.16 Plot of differences between the predictions of  $k_e$  by the Keey (2) approach and experimental  $k_e$  values versus particle size 151
- Figure 8.17 Plot of differences between the predictions of  $k_e$  by the Keey (2) approach and experimental  $k_e$  values versus particle size/box size 151

LIST OF TABLES

Table 4.1	Values of geometric parameters $P_1$ , $P_2$ and $P_3$	45
Table 4.2	Values of geometric parameters $\gamma_1$ , $\gamma_2$ and $\lambda$	48
Table 4.3	Percentage errors in predicted chilling times to selected thermal centre temperatures ( $1 \leq \beta \leq 4$ , $0.1 \leq Bi \leq 10$ , $0.05 \leq Y_c \leq 0.55$ )	50
Table 4.4	Percentage errors in predicted chilling times to selected mass-average temperatures. ( $1 \leq \beta \leq 4$ , $0.1 \leq Bi \leq 10$ , $Y_m$ corresponding to $0.05 \leq Y_c \leq 0.55$ )	50
Table 4.5	Percentage Differences in Predicted Times for Different Empirical Methods Against Analytical (*) or Numerical (•) Solutions	54
Table 5.1	Thermal Properties of Chilling Test Materials	59
Table 5.2	Experimental Conditions for Cylinders	71
Table 5.3	Experimental Conditions for Tylose Bricks	74
Table 5.4	Experimental Data for Cheddar Cheese Bricks	74
Table 6.1	Geometric Parameters of Two-Dimensional Samples	107
Table 6.2	Geometric Parameters of Three-Dimensional Samples	107
Table 6.3	Experimental Data and Finite Element Predictions for Chilling of Two-Dimensional Irregular Shapes	108

Table 6.4	Percentage Differences Between Experimental and Calculated Chilling Times for Two-Dimensional Irregular Shapes (Cumulative Results for $Y_c = 0.50, 0.25, 0.10$ )	110
Table 6.5	Percentage Differences Between Experimental and Calculated Chilling Times for Two-Dimensional Irregular Shapes when $Y_c = 0.50$	110
Table 6.6	Percentage Differences Between Experimental and Calculated Chilling Times for Two-Dimensional Irregular Shapes when $Y_c = 0.25$	111
Table 6.7	Percentage Differences Between Experimental and Calculated Chilling Times for Two-Dimensional Irregular Shapes when $Y_c = 0.10$	111
Table 6.8	Comparison of Percentage Errors in Predicted Times by Different Methods for Shape $I_c$ with and without Excision of Protrusions	112
Table 6.9	Correlations in Percentage Errors Between Finite Element Calculations and Other Approaches for Two-Dimensional Irregular Shapes	112
Table 6.10	Experimental Data for Chilling of Three-Dimensional Irregular Shapes	113
Table 6.11	Mean Percentage Differences in Analytically Predicted Chilling Time for the Equivalent Brick Model for Shape $I_p$ Using the Conservation of Area-Volume Approach	113
Table 6.12	Summary of Percentage Differences Between Experimental and Proposed Method Predicted Chilling Times for Two-Dimensional Irregular Shapes	114
Table 6.13	Percentage Differences Between Experimental Results and Chilling Times Predicted by the Proposed Method for Three-Dimensional Shapes	115

Table 7.1	Geometric Measurements of the Rectangular Bricks Used in Voidage Experiments	122
Table 7.2	Correlation Coefficients Between Variables Used in Voidage Experiments	122
Table 7.3	Experimental Data for the Cheddar Cheese Bricks with Uniformly Distributed Voids	123
Table 8.1	Percentage Error in Predicted Thermal Conductivities for Objects with Uniformly Distributed Voids Using Various Approaches	138
Table 8.2	Curve-fit Coefficients Used in Eqn (8.24) for the Different Versions of Key's Method	143