HEAT TRANSFER DURING FREEZING OF FOODS AND PREDICTION OF FREEZING TIMES

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Biotechnology at Massey University.

ANDREW CHARLES CLELAND

1977

HEAT TRANSFER DURING FREEZING OF FOODS AND PREDICTION OF FREEZING TIMES

ABSTRACT

A study of methods for predicting the freezing time of foods was made. Four shapes - finite slabs, cylinders, spheres and rectangular bricks were considered.

For each shape experimental measurements of the freezing time were made over a wide range of conditions using Karlsruhe test substance, a defined analogue material. Experiments with slabs of minced lean beef and mashed potato were also conducted.

Practical food freezing problems, where the material is initially superheated above its freezing point and the third kind of boundary condition (convective cooling) is applied, have not been solved analytically because of the non-linear boundary conditions. Food materials when freezing release latent heat over a range of temperature which further complicates any attempt at solution.

The accuracy of the various solutions to the freezing problem proposed in the literature was evaluated by comparison of the various calculated freezing times with the experimentally determined values over a total of 187 freezing experiments.

For those solutions requiring numerical evaluation, the best was found to be a three-level finite difference scheme which generally gave a prediction of the freezing time to within ±9% of the experimental values with 95% confidence. With the regular geometric shapes investigated finite elements have no advantage over finite differences and were not considered.

For the existing exact and approximate analytical solutions, it is shown that these do not give accurate prediction of the freezing time for any of the four shapes,

mainly because all but two of these solutions do not take account of initial superheat in the material to be frozen, and these two solutions are for initial superheat in a semi-infinite slab, not a finite slab.

For the existing empirically modified solutions and empirical relationships, it is shown that they do not give accurate prediction of freezing time; at best the 95% confidence limits of the percentage difference between the calculated and experimental freezing times are 0% to +20% for slabs, cylinders and spheres.

All solutions for freezing of rectangular bricks with the third kind of boundary condition use the geometric factors derived by Plank. These factors are shown to be subject to error, the error increasing as the ratios of the two larger dimensions to the smallest increase.

A group of formulae is proposed which are simple to use and give accurate prediction of freezing time. They modify the geometric factors in Plank's equation, taking initial superheat into account, and in the case of rectangular bricks correct the errors inherent in these geometric factors. This group of simple formulae are shown to predict the freezing time with 95% confidence to within 5% of the experimental values for slabs, to within 7% for cylinders and spheres, and to within 10% for rectangular bricks.

The prediction accuracy of the simple formulae and the three level finite difference scheme are similar but the simple formulae can be calculated quickly without the use of a computer which is a big advantage. In addition to simplicity and accuracy the simple formulae are also versatile, and by use of suitable approximations can handle some practical problems in which conditions change with time.

ACKNOWLEDGEMENTS

I wish to acknowledge the following:-

- Professor R.L. Earle for his supervision and assistance.
- Dr. S.H. Richert and Dr. R.H. Villet for their supervision.
- Hoechst New Zealand Limited for supplying methylcellulose samples.
- Dr. I.F. Boag for valuable assistance in the statistical analysis of data.
- Mr. J.T. Alger and Mr. D.W. Couling for their assistance in building and maintaining equipment.
- Rosemary for moral support and for proof reading.

CONTENTS

ABSTRACT. 2

ACKNOWLEDGEMENTS. 4

CONTENTS. 5

LIST OF FIGURES. 10

LIST OF TABLES. 14

1 INTRODUCTION. 16

2 LITERATURE REVIEW. 18
- 2.1 Problem Definition. 18
  - 2.1.1 Definition of freezing time. 18
  - 2.1.2 Boundary conditions. 19
  - 2.1.3 Initial conditions. 20
- 2.2 Solutions Using the Assumption of a Unique Freezing Temperature. 21
  - 2.2.1 Exact solutions for slabs. 21
  - 2.2.2 Approximate solutions for slabs. 21
    - 2.2.2.1 Integral profile and variational techniques. 21
    - 2.2.2.2 Solutions for alloy solidification. 22
    - 2.2.2.3 Other analytical approaches. 23
    - 2.2.2.4 Solutions for aqueous systems. 23
  - 2.2.3 Solutions for other shapes. 23
  - 2.2.4 Empirical relationships. 24
  - 2.2.5 Use of analogues. 25
  - 2.2.6 Numerical solutions. 26
- 2.3 Solutions Using Changing Apparent Specific Heat Capacity and Varying Thermal Conductivity. 26
- 2.4 Summary. 28

3 PRELIMINARY CONSIDERATIONS 30

4 COLLECTION OF EXPERIMENTAL DATA. 32
4.1 Introduction. 32
4.2 Choice of Freezing Material. 32
4.3 One-Dimensional Heat Transfer in Slabs. 34
4.3.1 The equipment. 34
4.3.2 Dimensional measurement and control. 35
4.3.3 Temperature measurement and control. 38
4.3.4 Measurement and control of the surface heat transfer coefficient. 39
4.3.5 Analysis of heat transfer in slabs. 41
4.4 Radial Heat Transfer in Cylinders and Spheres. 45
4.4.1 The equipment. 45
4.4.2 Dimensional measurement and control. 55
4.4.3 Temperature measurement and control. 55
4.4.4 Measurement and control of the surface heat transfer coefficient. 55
4.4.5 Analysis of heat transfer in radial geometry. 58
4.5 Three-Dimensional Heat Transfer in Rectangular Bricks. 65
4.5.1 The equipment. 65
4.5.2 Dimensional measurement and control. 66
4.5.3 Temperature measurement and control. 67
4.5.4 Measurement and control of the surface heat transfer coefficient. 67
4.5.5 Analysis of heat transfer in rectangular bricks. 68

5 EXPERIMENTAL DESIGN AND RESULTS. 71
5.1 Introduction. 71
5.2 Slabs. 71
5.3 Cylinders and Spheres. 73
5.4 Rectangular Bricks. 74

6 PREDICTION OF FREEZING TIME BY NUMERICAL METHODS 93
6.1 Slabs. 93
6.1.1 Selection of numerical method. 93
6.1.2 Selection of finite difference approach. 95
6.1.3 Comparison of finite difference schemes. 96
6.2 Cylinders and Spheres. 105
6.2.1 Selection of numerical method. 105
6.2.2 Selection of finite difference approach. 106
6.2.3 Comparison of finite difference schemes. 106
6.3 Rectangular Bricks. 112
6.3.1 Selection of numerical method. 112
6.3.2 Selection of finite difference method. 112
6.3.3 Use of the finite difference scheme. 113
6.4 Summary. 119

7 PREDICTION OF FREEZING TIME BY SIMPLE FORMULAE. 121
7.1 Thermal Data. 121
7.2 Slabs. 121
7.2.1 Solutions for the first kind of boundary condition. 123
7.2.2 Solutions for the third kind of boundary condition. 123
7.2.3 Empirical modifications and formulae. 128
7.2.4 Present developments. 129
7.3 Cylinders and Spheres. 131
7.3.1 Solutions for the first kind of boundary condition. 131
7.3.2 Solutions for the third kind of boundary condition. 134

7.3.3 Empirical modifications and formulae. 134
7.3.3.1 Cylinders. 134
7.3.3.2 Spheres. 135
7.3.4 Present developments. 136
7.4 Rectangular Bricks. 137
7.4.1 Existing formulae. 137
7.4.2 Present developments. 141

8 COMPARISON OF NUMERICAL AND SIMPLE METHODS FOR PREDICTING FREEZING TIMES. 145

9 PREDICTION OF FOOD FREEZING TIMES FOR SITUATIONS WITH NON-CONSTANT CONDITIONS. 161
9.1 Introduction. 161
9.2 Varying Ambient Temperature. 161
9.3 Non-Uniform Initial Temperature. 162
9.4 Changing Surface Heat Transfer Coefficient. 163
9.5 Irregular Geometry. 164
9.6 Non-Homogeneous Food Material. 165
9.7 Summary. 165

10 CONCLUSIONS. 167

NOMENCLATURE. 169

REFERENCES. 172

APPENDICES.

1 General Description of Finite Difference Programs. 185
2 One-Dimensional Finite Difference Programs. 194
3 Two- and Three-Dimensional Finite Difference Programs. 204
4 Radial Finite Difference Program. 217
5 Derivation of Mellor's Formula. 222

6 Investigation of Changing Ambient Temperature. 225

7 Investigation of Non-Uniform Initial Temperature. 231

LIST OF FIGURES

4.1 Schematic outline of the experimental plate freezer. 36

4.2 Test slabs. 37

4.3 Typical temperature/time profiles for thermocouples placed at, or near, the surface of a freezing slab. 46

4.4 Schematic outline of the experimental liquid immersion freezer. 47

4.5 The sample oscillator used in liquid immersion freezing experiments 48

4.6 Schematic outline of the system used to oscillate cylinders in the liquid immersion freezer 49

4.7 Arrangement of the polystyrene foam caps and thermocouple leads for cylinders. 50

4.8 Insertion of thermocouples in the spheres. 53

4.9 Schematic outline of the experimental air blast freezer. 54

4.10 Typical finite difference results for freezing of a sphere. 61

4.11 Typical experimental results for air blast freezing of a cylinder. 62

4.12 Attachment of lids to the plastic boxes. 63

4.13 Typical polypropylene containers used in the experimental investigation into freezing of rectangular bricks. 64

5.1 Typical temperature curves for freezing of a slab of Karlsruhe test substance (Run F17). 86

5.2 Typical temperature curves for freezing of a slab of Karlsruhe test substance (Run F14). 87

5.3 Typical temperature curves for freezing of a cylinder of Karlsruhe test substance (Run C3). 88

5.4 Typical temperature curves for freezing of a sphere of Karlsruhe test substance (Run S1). 89

5.5 Typical temperature curves for freezing of a rectangular brick of Karlsruhe test substance (Run B72). 90

5.6 Typical temperature curves for freezing of a rectangular brick of Karlsruhe test substance (Run B55). 91

5.7 Typical temperature curves for freezing of a rectangular brick of Karlsruhe test substance (Run B43). 92

6.1 Thermal property curves used to approximate freezing at a unique phase change temperature. 98

6.2 The finite difference grid at the surface of a freezing slab. 98

6.3 Thermal conductivity data. 99

6.4 Apparent specific heat capacity data for Karlsruhe test substance. 99

6.5 Apparent specific heat capacity data for minced lean beef. 100

6.6 Apparent specific heat capacity data for mashed potato. 100

6.7 Frequency diagram of the percentage differences between experimental freezing times for slabs, and times calculated by finite differences. 104

6.8 Typical temperature and thermal conductivity profiles through a freezing sphere or cylinder showing the effect of a linear approximation of the thermal conductivity. 109

6.9 Frequency diagram of the percentage differences between experimental freezing times for cylinders, and times calculated by finite differences. 110

6.10 Frequency diagram of the percentage differences between experimental freezing times for spheres, and times calculated by finite differences. 110

7.1 Frequency diagram of the percentage differences between experimental freezing times for slabs, and times calculated by solutions with the first kind of boundary condition. 125

7.2 Frequency diagram of the percentage differences between experimental freezing times for slabs, and times calculated by solutions with the third kind of boundary condition. 125

7.3 Schematic diagram showing the heat to be removed in freezing of slabs. 126

7.4 Frequency diagram of the percentage differences between experimental freezing times for slabs, and times calculated by empirical modifications and formulae. 127

7.5 Frequency diagram of the percentage differences between experimental freezing times for cylinders, and times calculated by various methods. 133

7.6 Frequency diagram of the percentage differences between experimental freezing times for spheres, and times calculated by various methods. 133

7.7 Plot of the average prediction error (when comparing calculated freezing times to experimental results for rectangular bricks) versus number of equivalent heat transfer dimensions. 140

8.1 Frequency diagram of the percentage differences between experimental freezing times, and calculated freezing times. 146

A5.1 Schematic representation of typical temperature profiles within a freezing material where freezing occurs at a unique phase change temperature T_f. 223

A6.1 Ambient temperature profiles. 226

LIST OF TABLES

5.1 Typical conditions in food freezers. 76

5.2 Design of the factorial experiment for investigation of the freezing times of slabs of Karlsruhe test substance. 77

5.3 Experimental data for freezing of slabs of Karlsruhe test substance. 78

5.4 Experimental data for freezing of minced lean beef (M) and mashed potato (P) in slabs. 80

5.5 Experimental data for freezing of cylinders of Karlsruhe test substance. 81

5.6 Experimental data for freezing of spheres of Karlsruhe test substance. 82

5.7 Experimental data for freezing of rectangular bricks of Karlsruhe test substance. 83

6.1 Comparison of results from the three-dimensional program to a known analytical solution for cooling of a cube. 116

6.2 Results from the finite difference simulation of the freezing of rectangular bricks. 117

7.1 Thermal data for freezing food materials. 122

7.2 Comparison of experimental freezing times with times calculated by Neumann's method. 124

7.3 Prediction of freezing times of slabs of minced lean beef and mashed potato by equations 7.4 and 7.5. 132

7.4 Means and 95% confidence limits for the applicability of equations 7.19 to 7.27 to the experimental data. 144

8.1 Experimental and calculated freezing time data for all shapes. 151

8.2 Means and standard deviations of the percentage differences between experimental freezing times, and times calculated from (a) the three-level finite difference scheme, (b) equations 7.19 to 7.27. 158

8.3 Comparison of methods for prediction of food freezing times. 159

A6.1 Conditions used for the investigation of the effect of changing ambient temperature on freezing time. 228

A6.2 Results of the finite difference simulation of freezing of a slab subject to a cycling ambient temperature. 229

A6.3 Results of the finite difference simulation of freezing of a slab subject to an exponential fall in ambient temperature. 230

A7.1 Results from the finite difference simulation of freezing of a slab of Karlsruhe test substance with non-uniform initial temperature. 232