Contents

Certificate of Approval **i**

Declaration **iii**

Certificate **v**

Acknowledgement **vii**

Contents **ix**

List of Figures **xv**

List of Tables **xix**

List of Symbols **xxiii**

List of Abbreviations **xxvii**

Abstract **xxix**

1 Introduction **1**

1.1 Computer-based food process modeling and optimization 3

1.2 Fouling in heat exchangers 3

1.3 CFD modeling 4

1.4 Rice grain hydration during cooking 4

1.5 Objectives 5

2 Review of Literature **7**

2.1 Rice 7

2.1.1 Effect of different cooking conditions on rice 7

2.1.2 Rice grain hydration 8

2.2 Rice as an ingredient in dairy products 9

2.2.1 *Kheer* 9

2.2.1.1 Method of preparation of *kheer* and its composition . . 9

2.2.1.2 Shelf Life of *kheer* 11

2.2.2 Instant *kheer/phirni* mix 12

Copyright IIT Kharagpur

2.2.2.1 Method of preparation 12
2.2.2.2 Physico-chemical properties and shelf life 12
2.3 Computer-based food process modeling and optimization 13
2.3.1 Neural Network Fundamentals 13
2.3.2 Genetic Algorithm Fundamentals 14
2.3.3 Fuzzy Logic Fundamentals 15
2.4 Processing equipments 16
2.4.1 Helical coil heat exchanger 16
2.4.2 Screw conveyor 17
2.4.3 Shell and tube condenser 17
2.5 Fouling of heat exchangers 18
2.5.1 Distribution and composition of fouling deposit 19
2.5.2 Mechanism of fouling 19
2.5.3 Fouling models 20
2.5.4 Ways of reducing fouling 22
2.6 Simulation of fluid flow and heat transfer in helical coil heat exchanger using Computational Fluid Dynamics (CFD) 22
2.7 Mechanization of manufacture of traditional Indian dairy products 23

3 Theoretical Considerations 25
3.1 Neural Network Modeling 25
3.1.1 Normalization of data set for ANN modeling 26
3.1.2 ANN model development 26
3.2 Genetic Algorithm Optmization 27
3.2.1 Hybrid ANN-GA for modeling and optimization 28
3.3 Sensory evaluation of *kheer* using fuzzy logic modeling 30
3.3.1 Scorecard and training of judges 30
3.3.2 Fuzzy modelling of sensory score 30
3.3.2.1 Triplets associated with sensory scales 31
3.3.2.2 Triplets for sensory score of *kheer* samples 32

Copyright IIT Kharagpur

3.3.2.3 Triplets for sensory score of quality attribute 32
3.3.2.4 Triplets for 'relative weighage' of quality attributes . . . 33
3.3.2.5 Triplets for overall sensory score of *kheer* 33
3.3.2.6 Value of Membership Functions of Standard Fuzzy Scale 33
3.3.2.7 Overall membership functions of sensory score on standard fuzzy scale 34
3.3.2.8 Similarity values of *kheer* samples and quality attributes 34
3.4 Thermal property equations based on composition 35
3.4.1 Estimation of density, thermal conductivity and specific heat capacity 35
3.5 Design criteria of continuous *kheer* making machine 37
3.5.1 Cooking section 37
3.5.1.1 Heat transfer coefficient on product side 38
3.5.1.2 Heat transfer coefficient on steam side 39
3.5.1.3 Overall heat transfer coefficient 40
3.5.1.4 Length of helical coil 40
3.5.2 Flash chamber 41
3.5.3 Condenser 41
3.5.3.1 Heat transfer coefficient on liquid and vapor side 41
3.5.3.2 Overall heat transfer coefficient 41
3.5.3.3 Effective length of condenser 42
3.5.4 Rice and sugar conveyor 42
3.6 Model development: 2D Heat transfer 43
3.6.1 Problem formulation 43
3.6.2 Governing equations 43
3.6.2.1 Enthalpy balance in control volume 43
3.6.2.2 Estimation of overall heat transfer coefficient (with fouling) based on outer diameter 44
3.6.2.3 Fouling model for helical coil heating section 46
3.6.2.4 Governing Equation–Method of Characteristics 47
3.6.3 Numerical scheme for modeling 48

Copyright IIT Kharagpur

3.6.3.1 Initial and boundary conditions 48
3.6.3.2 Modified Euler Method 48
3.7 Model development: 3D fluid flow, heat transfer and fouling study 50
3.7.1 Problem formulation 50
3.7.2 Governing equations 50
3.7.2.1 Turbulence model 50
3.7.2.2 Heat transfer in fluids 52
3.7.2.3 Kinetics of milk fouling 52
3.7.3 Initial and boundary conditions 52
3.7.4 Input parameters and numerical implementation 53
3.8 Model development: Rice hydration during cooking 55
3.8.1 Governing equation for moisture migration in rice 55
3.8.2 Moisture diffusivity 58
3.8.3 Particle density 59
3.8.4 Starch gelatinization kinetics 59
3.8.5 Ceiling moisture content 59
3.9 Initial and boundary conditions 60
3.9.1 Initial condition 60
3.9.2 Boundary condition 60
3.9.3 Input Parameters and numerical implementation 62

4 Materials and Methods 63
4.1 Preparation of kheer 63
4.1.1 Raw materials for *kheer* preparation 63
4.1.2 *Kheer* prepared in open pan 63
4.1.3 *Kheer* prepared at elevated pressures 64
4.2 Analysis of process parameters of *Kheer* prepared in open pan and pressure cooking vessel 65
4.2.1 Color Measurements 65
4.2.2 Texture Analysis 66

Copyright IIT Kharagpur

4.2.3 Optimization of process parameters 67
4.2.4 Fuzzy logic modeling 67
4.3 Determination of thermo physical properties of rice-milk mixture 67
4.3.1 Sample preparation 67
4.3.2 Determination of density 67
4.3.3 Determination of specific heat capacity 68
4.3.4 Determination of thermal conductivity 68
4.3.5 Determination of viscosity 69
4.4 Proximate analysis of rice-milk mixture 70
4.4.1 Moisture content 70
4.4.2 Ash content 70
4.4.3 Protein content 71
4.4.4 Fat content 71
4.4.5 Carbohydrate content 71
4.5 Fouling study 71
4.5.1 2D heat transfer model 71
4.5.2 3D CFD model 72
4.6 Rice cooking experiments 72
4.6.1 Measurement of Moisture Content 73
4.6.2 CFD Modeling 73

5 Results and Discussion 75
5.1 Optimization of process parameters 75
5.1.1 Open pan experiments 75
5.1.1.1 Whiteness Index and Hardness 76
5.1.1.2 Sensory evaluation of open pan samples 76
5.1.1.3 Fuzzy logic evaluation of open pan samples 77
5.1.2 Elevated pressure experiments 79
5.1.2.1 Hardness and Whiteness Index 79
5.1.2.2 Sensory evaluation of elevated pressure samples 80

Copyright IIT Kharagpur

5.1.2.3 Fuzzy logic evaluation of elevated pressure samples . . 81
5.1.3 Neural network modeling 83
5.1.4 Genetic algorithm for constrained optimization 84
5.1.5 Optimum cooking parameters for the continuous *kheer*-making machine 85
5.2 Thermo–physical properties of rice-milk mixture 86
5.3 Design and development of continuous *kheer* making machine 87
5.3.1 Cooking section 87
5.3.2 Heating section 89
5.3.3 Holding section 90
5.3.4 Flash chamber 90
5.3.5 Condenser 90
5.3.6 Rice conveyor 93
5.3.7 Sugar conveyor 94
5.4 2-Dimensional heat transfer model 95
5.4.1 Variation of bulk-mean temperature with time and length 95
5.4.2 Variation of fouling thickness with time and length 97
5.4.3 Variation of Biot number with time and length 97
5.5 3-D fluid flow, heat transfer and fouling model 99
5.5.1 Velocity profile 101
5.5.2 Temperature profile 101
5.5.3 Variation of overall heat transfer coefficient 102
5.5.4 Variation of Biot number and fouling thickness 103
5.5.5 Optimizing the design features of the heating section 106
5.6 Modeling rice grain hydration during cooking 110
5.6.1 Experimental results 110
5.6.2 Simulation of rice cooking process 110
5.6.2.1 Moisture profile in rice grains at different cooking times 110

6 Summary and Conclusion 115

Copyright IIT Kharagpur

7 Recommendations for future work **123**

References **125**

Appendix A Scorecard used for sensory evaluation **135**

Appendix B Fuzzy Logic Code **137**

Appendix C Sensory Scores and Fuzzy Logic Calculations **147**

Appendix D ANN–GA Code **153**

Appendix E Heating Section and Condenser Design Calculations **159**

About the author **163**

Copyright IIT Kharagpur