

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.

**MATHEMATICAL MODELLING AND  
IMPROVEMENT OF OPERATING  
PRACTICES OF SUN DRYING OF RICE**

**PYSETH MEAS**

2006

**MATHEMATICAL MODELLING AND  
IMPROVEMENT OF OPERATING  
PRACTICES OF SUN DRYING OF RICE**

A THESIS PRESENTED  
IN PARTIAL FULFILMENT OF THE REQUIREMENTS  
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY  
AT MASSEY UNIVERSITY

**PYSETH MEAS**

2006

សូមអម្ពិលស្នាមចេតនាចំពោះអ្នកម្តាយ លន់ កន

*To my mother (Kân Lun)*

ព្រមទាំង វិញ្ញាណក្ខន្ធលោកទីពេក មាស សៀង

*& spirit of my father (Sieng Meas),*

*This humble manuscript is lovingly dedicated*

## **ABSTRACT**

In Cambodia, sun drying of rice has always been of great importance for preserving rice. The main goal of this study was to find the conditions for sun drying that maximise the throughput while minimising quality loss.

A whole-bed approach was taken to investigate the conditions of the grain and the air at different layers during the drying process. Seven sets of sun-drying experiments were conducted in Cambodia using a range of methods practiced by rice farmers. These methods included drying with different bed depths (2 to 6 cm), with the bed on different pads (water-proof tarpaulin, mat, net, polystyrene or rice husk), and with different bed tempering methods (stirring regularly or shading and/or covering the bed around midday) for four Cambodian rice varieties (Pka Knhey, CAR11, Masary and IR66).

The grain temperature was found to be more affected by the solar intensity than the temperature of the ambient air. Fastest drying was achieved when the bed was thin, less compacted, stirred regularly but not shaded or covered around midday, dried on a pad which allows some air and moisture movement and with high or strong solar intensity.

Only the mechanical impact (MI) and milling tests of the rice quality provided useful results. Higher quality was found for grain that was dried in thin beds, stirred regularly, shaded with or without covering around midday and dried on pads with less air circulation.

Among the methods used to determine the glass transition temperature of the grain, only the Differential Scanning Calorimetry method gave meaningful results. The glass transition temperature data were highly variable but generally decreased with increasing moisture content and compared quite well with the published glass transition temperatures for other varieties of rice.

To provide additional detail on the local conditions within the bed, to better understand the drying process and the interactions between variables and to predict alternative parameters that might be used to correlate with the head rice yields (HRYs), a

mathematical model for heat and moisture transport within the bed was developed. The model covered all the drying methods/conditions studied experimentally. A lumped parameter approach to energy and mass transfer in individual kernels was used in the bed model.

The model was validated against experimental data. The predicted drying time, temperatures, moisture contents and water activities (relative humidity of the air within the bed) were found to compare very well with the experimental data except when a polystyrene pad was used. The model proved to be a very good mechanistic tool with advantages of simplicity and practical accuracy in the design and management of the sun drying system.

A number of parameters related to postulated grain damage mechanisms were derived from the predicted conditions within the bed during drying. The best predictors of the grain quality were found to be rewetting the kernels when the grain is bulked (especially when the kernels are partly below and partly above critical moisture content) grain temperature and distance from the glass transition temperature line.

It was concluded that in order to get the fastest drying conditions rice should be sun dried with thin bed, stirring, not shaded or covered around midday and dried on a pad with air circulation. For the highest quality grain, that is grain which would have the least breakage during milling, rice should be sun dried with a thin bed, stirring, shaded or covered around midday and dried on a pad with less air circulation. The optimal drying conditions to get the best quality combined with the fastest practical drying rate, the drying conditions should be drying with 2 cm bed depth, stirring the grain bed every hour, shading or covering the bed around midday and using a tarpaulin or net pad placed directly on the ground.

## ACKNOWLEDGEMENTS

Like most of my compatriots, I have suffered intolerable pain and misery through the conflicts in Cambodia. I lost my loving father in my childhood and have had to almost totally rely on my mother, brother and some relatives. Due to the fighting, shelling and many wild fighters, I have had many relocations and my mum was always scared to let me be away or out of her reach. During this, I had a lot of time to observe what she was doing. One of her businesses was to buy paddy grain, get it milled and graded and sell it to make a small profit.

What I saw was that the grain is produced in a very hard way with a high percentage of broken grains in the milled rice. Farmers in the country still do not have many chances to ease their hard work by the means of improved machinery or technology and rely almost totally on the weather for drying. In the end, they do not have good grain for their own consumption and my mother and Cambodian rice farmers can not sell the rice they have produced for a good price due to its low quality. As a result, Cambodia still remains one of the poorest nations. This led me into choosing to look at the effects of sun drying of rice on the quality of milled grain as the subject of my PhD.

I have been very fortunate to have had tremendous support and assistance from a number of countries and organisations and to be in very safe hands of many people to complete some useful work in the determining of better ways to use the sun for the drying of rice so that the grain quality is not compromised. I, therefore take this opportunity to gratefully thank:

- My chief supervisor (Associate Professor **Tony Paterson**) and my other Supervisors (Professor **Don Cleland**, Dr **John Bronlund**, Associate Professor **John Mawson**, Mr **Allan Hardacre** and Mr **Joe Rickman**) for supervising this work, giving very valuable technical advice, continual guidance, support and encouragement. I deeply appreciate and will always remember all your scientific capability, assistance, suggestions and constructive criticisms
- **The very friendly people of New Zealand**, through **the New Zealand Ministry of Foreign Affairs** for granting me the NZAID Scholarship to do this and

previous degrees. I will always remember the country's beauty and peaceful environment. You are behind the development of my country and I promise to try my best not to make you disappointed

- **The International Rice Research Institute (IRRI)** for accepting me as a research scholar and for giving me a huge additional fund to enable me to pursue this PhD study
- **The country, people and government of Cambodia** for all the assistance and trust for me to learn and bring in some unknown and improved technology from scientists of the developed world
- **Massey University and The Crop and Food Research of New Zealand, The Agricultural Quality Improvement Project (AQIP), Cambodian Ministry for Industry, Mines and Energy and The British and American Tobacco (based in Cambodia)** for all the knowledge, technical assistance, research facilities, support and hospitality
- **The management and staff of the Institute of Technology and Engineering, the workshop, the labs, the Seed Technology Centre and the International Students Office**, especially to **Joan Brookes, John Heyward, John Edwards, Craig Bellhouse, Bruce Collins, Michael Sahayam, Robert Southward, Sue Flynn and Sylvia Hooker** for being very patient with me, looking after me very well and for giving me a helping hand
- **Dr Nigel Grigg** for giving a hand in the statistical design and analysis
- Ms **Suzanne M. Clark** for her valuable technical advice
- **The people and my teachers in Slovakia** for giving me the support and opportunity to be with them and to start learning how to apply research and mechanization in Agriculture
- **My parents** for giving me life, protecting me from all the dangers during my childhood and providing me with all the food, care, education and loving hearts that have made my life worthwhile
- **My brother (Bunna), all my relatives and friends** who have strongly and infinitely supported me and given me all the necessary encouragement that I needed throughout my studies and especially
- **My lovely wife (Leakhena), daughter (Kanika) and sons (Sakan & Sakun)** for being there to see me through.



# TABLE OF CONTENTS

	<i>Page</i>
<b>ABSTRACT</b>	<b>iii</b>
<b>ACKNOWLEDGEMENTS</b>	<b>v</b>
<b>TABLE OF CONTENTS</b>	<b>vii</b>
<b>LIST OF TABLES</b>	<b>xv</b>
<b>LIST OF FIGURES</b>	<b>xvii</b>
<b>LIST OF APPENDICES</b>	<b>xxiii</b>
<b><i>Chapter 1: INTRODUCTION</i></b> .....	<b>1</b>
1.1 INTRODUCTION .....	1
1.2 RESEARCH GOAL .....	3
1.3 RESEARCH OBJECTIVES .....	3
<b><i>Chapter 2: LITERATURE REVIEW</i></b> .....	<b>5</b>
2.1 RICE GRAIN STRUCTURE AND CONSTITUENTS .....	5
2.2 RICE GRAIN QUALITY .....	9
2.2.1 Quality characteristics .....	10
2.2.1.1 Physical characteristics of paddy grain .....	10
2.2.1.2 Physical characteristics of milled rice .....	12
2.2.1.3 Chemical characteristics of milled rice .....	16
2.2.1.4 Thermal and moisture-transport properties .....	17
2.2.1.5 Grain viability .....	19
2.2.2 Losses in quality .....	21
2.2.3 Grading of rice grain and standards .....	22
2.3 POSTHARVEST HANDLING OF RICE .....	23
2.3.1 Harvest .....	23
2.3.1.1 Optimum harvesting time for the grain yield and quality .....	24
2.3.1.2 Manual harvesting .....	25
2.3.1.3 Mechanised harvesting .....	26
2.3.2 Threshing .....	26
2.3.2.1 Traditional threshing .....	27

	<i>Page</i>
2.3.2.2 Mechanised threshing . . . . .	27
2.3.2.3 Performance and effects on the grain quality . . . . .	28
2.3.3 Cleaning and grading . . . . .	29
2.3.4 Drying . . . . .	29
2.3.4.1 Sun drying . . . . .	30
2.3.4.2 Mechanised drying . . . . .	36
2.3.4.3 General performance and effects on the grain quality . . . . .	36
2.3.4.4 Tempering research . . . . .	38
2.3.4.5 Variety resistance to the damage . . . . .	42
2.3.5 Storage . . . . .	42
2.4 MC OF RICE GRAIN . . . . .	43
2.4.1 Definition . . . . .	43
2.4.2 Measurement . . . . .	44
2.4.3 Variation during handling . . . . .	45
2.4.4 Equilibrium MC and isotherm . . . . .	47
2.5 GLASS TRANSITION IN RICE KERNEL . . . . .	50
2.5.1 Relationship with MC . . . . .	51
2.5.2 Measurement . . . . .	52
2.5.3 Application to rice drying . . . . .	55
2.6 DRYING MODELS . . . . .	57
2.6.1 Principles . . . . .	57
2.6.2 Previous works . . . . .	58
2.6.3 Thin-layer model . . . . .	59
2.7 CAMBODIAN RICE VARIETIES AND CLIMATE . . . . .	61
2.7.1 Rice varieties . . . . .	61
2.7.2 Climate . . . . .	62
2.7.2.1 Rainfall . . . . .	62
2.7.2.2 Temperature . . . . .	63
2.7.2.3 Humidity . . . . .	63

	<i>Page</i>
2.7.2.4 Daylength .....	64
2.7.2.5 Sunshine hours .....	65
2.8 SUMMARY .....	65
<b>Chapter 3: MATERIALS AND METHODS .....</b>	<b>67</b>
3.1 INTRODUCTION.....	67
3.2 OBJECTIVES .....	67
3.3 MATERIALS AND METHODS .....	68
3.3.1 Grain sample preparation .....	68
3.3.1.1 The rice varieties .....	68
3.3.1.2 Harvesting and handling .....	69
3.3.1.3 Establishment of initial MC .....	69
3.3.2 Experimental designs and measurements.....	70
3.3.2.1 Experiment One/03 - Effect of the bed depth .....	70
3.3.2.2 Experiment Two/03 - Effect of tempering .....	73
3.3.2.3 Experiment Three/03 - Effect of tempering, variety and drying day .....	74
3.3.2.4 Experiment Four/03 - Effect of the solar intensity and ambient air.....	74
3.3.2.5 Experiment One/04 - MC determination methods .....	75
3.3.2.6 Experiment Two/04 - Effect of bed depth and tempering .....	77
3.3.2.7 Experiment Three/04 - Effect of drying pad, variety, bed depth, tempering and drying day .....	79
3.3.3 Grain quality analysis .....	82
3.3.3.1 Three-point bending test .....	82
3.3.3.2 Mechanical impact test .....	85
3.3.3.3 Milling test .....	87
3.3.4 Statistical analysis .....	89
3.3.5 Determination of the glass transition temperature .....	89
3.3.5.1 Equilibrating the grain to different MC levels .....	89
3.3.5.2 Drop test .....	90
3.3.5.3 The compression test .....	91

	<i>Page</i>
3.3.5.4 Differential Scanning Calorimetry . . . . .	93
<b>Chapter 4: RESULTS OF THE EXPERIMENTS AND TESTS . . . . .</b>	<b>95</b>
4.1 EXPERIMENT ONE/03 - EFFECT OF BED DEPTH . . . . .	95
4.1.1 Effect of bed depth on the drying time. . . . .	95
4.1.2 Effect of bed depth on the grain quality . . . . .	96
4.2 EXPERIMENT TWO/03 - EFFECT OF TEMPERING . . . . .	96
4.2.1 Effect of tempering on the drying time . . . . .	96
4.2.2 Effect of tempering on the grain quality . . . . .	97
4.3 EXPERIMENT THREE/03 - EFFECT OF TEMPERING, VARIETY AND DRYING DAY . . . . .	97
4.3.1 Effect of grain variety on the drying time and the grain quality . . . . .	97
4.3.2 Effect of drying day on the drying time and the grain quality . . . . .	98
4.3.3 Effect of tempering on the drying time and the grain quality . . . . .	98
4.4 EXPERIMENT FOUR/03 - EFFECT OF SOLAR INTENSITY AND AMBIENT AIR CONDITIONS . . . . .	99
4.4.1 Change in solar intensity . . . . .	99
4.4.2 Change in the air RH . . . . .	100
4.4.3 Change in the temperature . . . . .	100
4.5 EXPERIMENT ONE/04 - MC DETERMINATION METHODS . . . . .	101
4.5.1 Effect of stirring on the HRY . . . . .	103
4.6 EXPERIMENT TWO/04 - EFFECT OF BED DEPTH AND TEMPERING. . . . .	103
4.6.1 Effect of bed depth on the drying time. . . . .	103
4.6.2 Effect on the HRY . . . . .	104
4.6.2.1 Effect of bed depth on the HRY . . . . .	104
4.6.2.2 Effect of stirring on the HRY . . . . .	105
4.6.2.3 Effect of covering on the HRY . . . . .	105
4.7 EXPERIMENT THREE/04 - EFFECT OF DRYING PAD, VARIETY, BED DEPTH, TEMPERING AND DRYING DAY . . . . .	105
4.7.1 Effect on the drying time . . . . .	105
4.7.1.1 Effect of grain variety on the drying time . . . . .	106

	<i>Page</i>
4.7.1.2 Effect of bed depth on the drying time. . . . .	106
4.7.1.3 Effect of stirring on the drying time. . . . .	106
4.7.1.4 Effect of covering on the drying time . . . . .	107
4.7.1.5 Effect of drying pad on the drying time . . . . .	107
4.7.2 Effect on the HRY. . . . .	107
4.7.2.1 Effect of variety on the HRY . . . . .	107
4.7.2.2 Effect of bed depth on the HRY. . . . .	108
4.7.2.3 Effect of stirring on the HRY. . . . .	108
4.7.2.4 Effect of covering on the HRY . . . . .	109
4.7.2.5 Effect of drying pad on the HRY . . . . .	109
4.7.2.6 Interaction effect from the milling test . . . . .	109
4.8 THE RICE GRAIN STATE DIAGRAM . . . . .	111
4.9 SUMMARY . . . . .	115
<b>Chapter 5: MATHEMATICAL MODEL FORMULATION . . . . .</b>	<b>117</b>
5.1 INTRODUCTION . . . . .	117
5.2 MODEL OBJECTIVES . . . . .	118
5.3 CONCEPTUAL MODEL DEVELOPMENT . . . . .	118
5.3.1 Transport processes . . . . .	118
5.3.2 Assumptions . . . . .	121
5.4 MATHEMATICAL MODEL FORMULATION . . . . .	123
5.4.1 Establishment of the basic equations . . . . .	123
5.4.1.1 Heat transfer within the solid materials . . . . .	123
5.4.1.2 Heat transfer at the boundaries. . . . .	123
5.4.1.3 Heat transfer for the shading tarpaulin . . . . .	125
5.4.1.4 Heat transfer for the covering tarpaulin . . . . .	126
5.4.1.5 Moisture transfer in the grain kernels within the grain bed . . . . .	127
5.4.1.6 Moisture transfer in the air within the grain bed . . . . .	128
5.4.1.7 Moisture transfer in the air within materials 2 and 3 . . . . .	128
5.4.1.8 Moisture transfer at the boundaries . . . . .	128

	<i>Page</i>
5.4.1.9 The initial conditions . . . . .	130
5.5 FINITE DIFFERENCE SOLUTION . . . . .	131
5.5.1 The grid . . . . .	132
5.5.2 ODE Equations. . . . .	133
5.5.2.1 For the surface of the grain bed . . . . .	133
5.5.2.2 For the grain bed, material 2 and material 3 . . . . .	134
5.5.2.3 For the rate of MC change within the grain bed . . . . .	135
5.5.2.4 For the bottom of the bed and bottom of material 2. . . . .	135
5.5.2.5 For the top of material 2 and material 3. . . . .	136
5.5.2.6 For the bottom of material 3. . . . .	136
5.5.2.7 For the initial conditions . . . . .	137
5.5.3 Ancillary equations . . . . .	137
5.5.4 Numerical solution . . . . .	138
5.5.5 Model checking . . . . .	138
5.6 SUMMARY . . . . .	139
<b>Chapter 6: MODEL VALIDATION . . . . .</b>	<b>141</b>
6.1 DETERMINATIONS OF THE SYSTEM INPUTS AND CONSEQUENTIAL VARIABLES . . . . .	141
6.1.1 Specific surface area of the paddy kernel . . . . .	141
6.1.2 Surface area of the drying bed and cross-sectional area of other materials . . . . .	141
6.1.3 Specific heat capacity of air, husk, mat, grain, polystyrene, soil, water vapour and water . . . . .	142
6.1.4 Thickness of the paddy kernel . . . . .	143
6.1.5 Diffusivity of moisture in the air within the exposed materials. . . . .	144
6.1.6 Geometric and emissivity correction factors for energy radiated between parallel surfaces . . . . .	148
6.1.7 Convective heat transfer coefficient. . . . .	149
6.1.8 Latent heat of evaporation . . . . .	151
6.1.9 Solar intensity . . . . .	151
6.1.10 Convective moisture transfer coefficient . . . . .	154

	<i>Page</i>
6.1.11 Thickness of the air gap between the grain and the covering tarpaulin or the drying pad below . . . . .	155
6.1.12 Depth or thickness of the materials . . . . .	155
6.1.13 Initial moisture content. . . . .	155
6.1.14 Ambient air relative humidity . . . . .	155
6.1.15 Resistance to moisture transfer through material . . . . .	157
6.1.16 Resistance to heat conduction . . . . .	158
6.1.17 Initial RH of the air within the materials . . . . .	158
6.1.18 Ambient air temperature . . . . .	158
6.1.19 Temperature of the ground . . . . .	160
6.1.20 Initial temperature of the grain . . . . .	160
6.1.21 Temperature of the sky . . . . .	161
6.1.22 Thermal conductivity of air, polystyrene, soil and tarpaulin . . . . .	161
6.1.23 Effective thermal conductivity of the husk, mat and grain . . . . .	162
6.1.24 Absorptivity and emissivity of radiation of the grain bed and tarpaulin . . . . .	162
6.1.25 True density of husk, mat, grain, polystyrene and soil . . . . .	163
6.1.26 Bulk density of rice husk, mat, grain, polystyrene and soil . . . . .	164
6.1.27 Porosity of the materials . . . . .	165
6.1.28 Coefficients for the drying rate . . . . .	165
6.1.29 Moisture isotherms for the exposed materials . . . . .	168
6.2 MODEL VALIDATION . . . . .	173
6.2.1 Sensitivity analysis . . . . .	174
6.2.2 Comparison of the predictions with measured data . . . . .	177
6.2.2.1 Drying time . . . . .	177
6.2.2.2 Temperature . . . . .	180
6.2.2.3 Moisture content . . . . .	185
6.2.2.4 Water activity . . . . .	189
6.3 SUMMARY . . . . .	193
<b>Chapter 7: MODEL APPLICATION . . . . .</b>	<b>195</b>
7.1 METHODOLOGY . . . . .	195
7.1.1 Parameter identifications . . . . .	195
7.1.1.1 Grain temperature . . . . .	195

	<i>Page</i>
7.1.1.2 Drying rate .....	196
7.1.1.3 Grain critical MC .....	197
7.1.1.4 Grain rewetting .....	198
7.1.1.5 Stress within the grain kernels .....	198
7.1.1.6 Glass transition .....	199
7.1.2 Effects on HRY .....	200
7.2 Results of the multiple regression analysis .....	201
7.3 SUMMARY .....	203
<b>Chapter 8: DISCUSSION AND CONCLUSIONS.</b> .....	<b>205</b>
8.1 GENERAL ASPECTS OF SUN DRYING .....	205
8.1.1 Ambient air conditions. ....	205
8.1.2 Drying time .....	206
8.1.3 The grain quality .....	207
8.2 DRYING MODELS AND CONCEPTUAL FRAMEWORK FOR MAINTAINING RICE QUALITY .....	210
8.3 CONCLUSIONS .....	213
8.4 FURTHER RESEARCH .....	215
<b>REFERENCES</b> .....	<b>217</b>



## LIST OF TABLES

	<i>Page</i>
Table 2.1: Percentage of starch molecule size of two rice varieties . . . . .	8
Table 2.2: Equations and values describing the specific heat as affected by its MCs	18
Table 2.3: MC <sub>e</sub> of paddy rice . . . . .	47
Table 2.4: Relative humidity at different temperatures above a number of saturated salt solutions . . . . .	48
Table 3.1: Characteristics of the rice grain used in the experiments . . . . .	68
Table 3.2: The applied treatments for Experiment Two/04 . . . . .	78
Table 3.3: The applied treatments for Experiment Three/04 . . . . .	80
Table 3.4: Storages conditions and the corresponding MC <sub>e</sub> of paddy . . . . .	90
Table 4.1: Effect of the bed depth on the drying time and the grain quality . . . . .	95
Table 4.2: Effect of the tempering methods on the drying time and the grain quality	96
Table 4.3: Effect of the grain variety on the drying time and the dried grain quality	97
Table 4.4: Effect of the drying day on the drying time and the grain quality . . . . .	98
Table 4.5: Effect of tempering on the drying time and the grain quality . . . . .	99
Table 4.6: Effect of stirring method on the HRY . . . . .	103
Table 4.7: Effect of bed depth, stirring and covering methods on the drying time. . .	104
Table 4.8: Effect of bed depth, stirring and covering methods on the HRY . . . . .	104
Table 4.9: Effect of variety, depth, stirring, covering and pad on the drying time. . .	106
Table 4.10: Effect of variety, depth, stirring, covering and pad on the HRY . . . . .	108
Table 6.1: The measured wind speed and corresponding convective heat transfer coefficient used in the model . . . . .	157
Table 6.2: Solar intensity vs day time as measured during the experiments . . . . .	154
Table 6.3: RH of the ambient air vs day time as measured during the experiments . . . . .	156
Table 6.4: Temperature of the ambient air vs day time as measured during the experiments . . . . .	160
Table 6.5: Initial temperature of the grain samples measured on the drying days	160
Table 6.6: Equilibrium MC of rice husk . . . . .	170
Table 6.7: Summary of the values and ranges of the system inputs used . . . . .	171
Table 6.8: Summary of the Consequential value variables used . . . . .	173

	<i>Page</i>
Table 6.9: Summary of the effects the system inputs have on the model predictions at 11:55 .....	175
Table 6.10: Summary of the effects the system inputs have on the model predictions at 15:55 .....	175
Table 6.11: Average measured and predicted drying times for individual drying pads .....	180
Table 7.1: Proposed mechanisms and parameters that could affect the HRYs with the ranges of their maximum values predicted by the model for Experiment Three/04 .....	200
Table 7.2: Parameters that were shown to have some effects in combination on the HRYs .....	202

## LIST OF FIGURES

	<i>Page</i>
Fig 2.1: Paddy, brown rice and milled rice . . . . .	5
Fig 2.2: A dissected paddy grain . . . . .	5
Fig 2.3: Compound starch granules and protein bodies (arrows) near the aleurone layer of a rice kernel . . . . .	7
Fig 2.4: Compound starch granules near the centre of a rice kernel with certain granules broken . . . . .	7
Fig 2.5: A schematic model of the structure of a starch granule . . . . .	8
Fig 2.6: Paddy rice sample with single variety and mixed varieties . . . . .	11
Fig 2.7: Clean paddy grain and the grain mixed with dockage . . . . .	12
Fig 2.8: Damaged grains . . . . .	14
Fig 2.9: Chalky grains . . . . .	15
Fig 2.10: Red and red-streaked grains . . . . .	15
Fig 2.11: Discoloured milled rice . . . . .	16
Fig 2.12: Fissures in a rice kernel as seen through a red light filter. . . . .	24
Fig 2.13: Axial-flow rice thresher . . . . .	28
Fig 2.14: Sun drying of rice . . . . .	32
Fig 2.15: Electronic moisture meters used for grain . . . . .	45
Fig 2.16: $MC_e$ curves or moisture equilibrium isotherms using the Zuritz and Singh equation . . . . .	49
Fig 2.17: Brown rice state diagram (for Bengal and Cypress varieties combined)	52
Fig 2.18: Entire DSC plot . . . . .	54
Fig 2.19: Hypothetical response of the various sections of a rice kernel during tempering for two tempering scenarios . . . . .	56
Fig 2.20: Monthly rainfall and number of rainy days in Phnom Penh, Cambodia . . .	62
Fig 2.21: Monthly maximum and minimum temperatures in Phnom Penh, Cambodia	63
Fig 2.22: RH of the ambient air in Phnom Penh, Cambodia . . . . .	64
Fig 2.23: Monthly daylength means in Phnom Penh, Cambodia . . . . .	64
Fig 2.24: Monthly means of daily sunshine hours in Phnom Penh, Cambodia . . . . .	65
Fig 3.1: The rice grain of four varieties used. . . . .	68
Fig 3.2: Trampling to remove the grain . . . . .	69

	<i>Page</i>
Fig 3.3: Arrangement of the grain samples for drying in Experiment One/03 . . . . .	71
Fig 3.4: Positions of the electronic sensors . . . . .	72
Fig 3.5: Positions of the TinyTag relative humidity sensors . . . . .	72
Fig 3.6: Arrangement of the grain samples for drying in Experiment Two/03 . . . . .	73
Fig 3.7: Arrangement of the grain samples for drying in Experiment Three/03 . . . . .	74
Fig 3.8: Placement of the sample bags in the grain bed for MC determination . . . . .	76
Fig 3.9: Placement of the temperature and humidity sensors in the grain bed . . . . .	76
Fig 3.10: Placements of the sensors and the bags in Experiment One/04 . . . . .	77
Fig 3.11: The samples being dried in Experiment Two/04 . . . . .	79
Fig 3.12: The grain samples being dried on nylon net spread on husk and on the mat spread directly on soil . . . . .	82
Fig 3.13: Three-point bending cell . . . . .	84
Fig 3.14: The breakage tester . . . . .	85
Fig 3.15: Grain dehusking tool . . . . .	86
Fig 3.16: The cleaning machine . . . . .	88
Fig 3.17: The milling machine . . . . .	88
Fig 3.18: The drop tester . . . . .	91
Fig 3.19: The combination of a heating unit and the Food Texture Analyzer . . . . .	92
Fig 3.20: A typical plot produced by the combined system during a test . . . . .	92
Fig 3.21: The Differential Scanning Calorimeter. . . . .	93
Fig 3.22: A typical result produced by the DSC . . . . .	94
Fig 3.23: Determination of the $T_g$ . . . . .	94
Fig 4.1: Drying times for all the varieties for individual stirring method . . . . .	98
Fig 4.2: Solar intensity measured on site on Dec 20 and 21, 2003 . . . . .	99
Fig 4.3: RH of the air measured on site on Dec 20 and 21, 2003 . . . . .	100
Fig 4.4: Air and grain temperatures measured on site on Dec 20 and 21, 2003 . . . . .	101
Fig 4.5: The change in the grain MC as detected by the nylon-bag method and measured by the moisture meter . . . . .	102
Fig 4.6: Three-factor interaction between depth and stirring with covering on the milling HRY . . . . .	110

	<i>Page</i>
Fig 4.7: Three-factor interaction between depth and stirring with variety on the milling HRV .....	110
Fig 4.8: State diagram of $T_g$ versus MC for Phka Knhey .....	112
Fig 4.9: State diagram of $T_g$ versus MC for CAR11 .....	113
Fig 4.10: State diagram of $T_g$ versus MC for Masary .....	113
Fig 4.11: State diagram of $T_g$ versus MC for IR66 .....	113
Fig 4.12: State diagram of $T_g$ versus MC for all the 4 varieties. ....	114
Fig 4.13: State diagram of $T_g$ versus MC of the tested rice varieties compared with correlations reported by Perdon (1999) and Perdon et al. (2000), and Sun et al. (2002) .....	115
Fig 5.1: Conceptual diagram showing the heat and moisture transfer flows considered in the model .....	119
Fig 5.2: The finite difference grid used for all the materials during drying. ....	132
Fig 6.1: Wind speed measured during the 2004 experiments .....	150
Fig 6.2: The measured and curve-fitted solar intensity for December 10, 2004 . . . .	152
Fig 6.3: Solar intensity measured during the 2004 experiments .....	153
Fig 6.4: The ambient air relative humidity measured on December 10, 2004 .....	156
Fig 6.5: RH of the ambient air measured during the 2004 experiments .....	157
Fig 6.6: The temperature of the ambient air measured on December 10, 2004 .....	158
Fig 6.7: Temperature of the ambient air measured during the 2004 experiments . . .	159
Fig 6.8: Change in the moisture ratio of CAR11 variety during the drying time . . .	166
Fig 6.9: Fitting the $\frac{\partial MC}{\partial t}$ vs $MC - MC_e$ for CAR11 variety .....	168
Fig 6.10: Comparison of the equilibrium MC predicted by the developed isotherm equation against equilibrium MC reported .....	169
Fig 6.11: Assumed linear moisture isotherm for the husk .....	170
Fig 6.12: Prediction bands for the temperatures at the bed surface, middle and bottom and the measured data of Experiment One/04 .....	176
Fig 6.13: Prediction bands for the moisture contents at different layers of the bed and the measured data of Experiment One/04 .....	176
Fig 6.14: Prediction bands for the water activities at different layers of the bed and the measured data of Experiment One/04 .....	176

	<i>Page</i>
Fig 6.15: Comparison of the measured and predicted drying times (Variety and depth) . . . . .	177
Fig 6.16: Comparison of the measured and predicted drying times (Stirring and Covering methods). . . . .	178
Fig 6.17: Comparison of the measured and predicted drying times (Drying pads) . .	179
Fig 6.18: Comparison of the predicted and measured temperatures for Rep 1 of Experiment One/04 . . . . .	181
Fig 6.19: Comparison of the predicted and measured temperatures for Rep 2 of Experiment One/04 . . . . .	181
Fig 6.20: Comparison of the predicted and measured temperatures for treatment 5 of Experiment Two/04 . . . . .	181
Fig 6.21: Comparison of the predicted and measured temperatures for treatment 12 of Experiment Two/04 (Day One) . . . . .	181
Fig 6.22: Comparison of the predicted and measured temperatures for treatment 12 of Experiment Two/04 (Day Two). . . . .	182
Fig 6.23: Comparison of the predicted and measured temperatures for treatment 5 of Experiment Three/04 . . . . .	182
Fig 6.24: Comparison of the predicted and measured temperatures for treatment 8 of Experiment Three/04 . . . . .	182
Fig 6.25: Comparison of the predicted and measured temperatures for treatment 33 of Experiment Three/04 (Day One). . . . .	182
Fig 6.26: Comparison of the predicted and measured temperatures for treatment 33 of Experiment Three/04 (Day Two). . . . .	183
Fig 6.27: Comparison of the predicted and measured temperatures for treatment 41 of Experiment Three/04 . . . . .	183
Fig 6.28: Comparison of the predicted and measured temperatures for treatment 43 of Experiment Three/04 . . . . .	183
Fig 6.29: Comparison of the predicted and measured temperatures for treatment 51 of Experiment Three/04 (Day One) . . . . .	183
Fig 6.30: Comparison of the predicted and measured temperatures for treatment 51 of Experiment Three/04 (Day Two). . . . .	184
Fig 6.31: Comparison of the predicted and measured temperatures for treatment 53 of Experiment Three/04 (Day One) . . . . .	184
Fig 6.32: Comparison of the predicted and measured temperatures for treatment 53 of Experiment Three/04 (Day Two). . . . .	184

	<i>Page</i>
Fig 6.33: Comparison of the predicted and measured temperatures for treatment 57 of Experiment Three/04 .....	184
Fig 6.34: Comparison of the predicted and measured MCs for Rep 1 of Experiment One/04 .....	185
Fig 6.35: Comparison of the predicted and measured MCs for Rep 2 of Experiment One/04 .....	185
Fig 6.36: Comparison of the predicted and measured MCs for treatment 5 of Experiment Two/04 .....	186
Fig 6.37: Comparison of the predicted and measured MCs for treatment 12 of Experiment Two/04 (Day One) .....	186
Fig 6.38: Comparison of the predicted and measured MCs for treatment 12 of Experiment Two/04 (Day Two) .....	186
Fig 6.39: Comparison of the predicted and measured MCs for treatment 5 of Experiment Three/04 .....	186
Fig 6.40: Comparison of the predicted and measured MCs for treatment 8 of Experiment Three/04 .....	187
Fig 6.41: Comparison of the predicted and measured MCs for treatment 33 of Experiment Three/04 (Day One) .....	187
Fig 6.42: Comparison of the predicted and measured MCs for treatment 33 of Experiment Three/04 (Day Two) .....	187
Fig 6.43: Comparison of the predicted and measured MCs for treatment 41 of Experiment Three/04 .....	187
Fig 6.44: Comparison of the predicted and measured MCs for treatment 43 of Experiment Three/04 .....	188
Fig 6.45: Comparison of the predicted and measured MCs for treatment 51 of Experiment Three/04 (Day One) .....	188
Fig 6.46: Comparison of the predicted and measured MCs for treatment 51 of Experiment Three/04 (Day Two) .....	188
Fig 6.47: Comparison of the predicted and measured MCs for treatment 53 of Experiment Three/04 (Day One) .....	188
Fig 6.48: Comparison of the predicted and measured MCs for treatment 53 of Experiment Three/04 (Day Two) .....	189
Fig 6.49: Comparison of the predicted and measured MCs for treatment 57 of Experiment Three/04 .....	189
Fig 6.50: Comparison of the predicted and measured water activities for Rep 1 of Experiment One/04 .....	190

	<i>Page</i>
Fig 6.51: Comparison of the predicted and measured water activities for Rep 2 of Experiment One/04 . . . . .	190
Fig 6.52: Comparison of the predicted and measured water activities for treatment 5 of Experiment Two/04 . . . . .	190
Fig 6.53: Comparison of the predicted and measured water activities for treatment 12 of Experiment Two/04 (Day One) . . . . .	190
Fig 6.54: Comparison of the predicted and measured water activities for treatment 12 of Experiment Two/04 (Day Two) . . . . .	191
Fig 6.55: Comparison of the predicted and measured water activities for treatment 5 of Experiment Three/04 . . . . .	191
Fig 6.56: Comparison of the predicted and measured water activities for treatment 8 of Experiment Three/04 . . . . .	191
Fig 6.57: Comparison of the predicted and measured water activities for treatment 33 of Experiment Three/04 (Day One). . . . .	191
Fig 6.58: Comparison of the predicted and measured water activities for treatment 33 of Experiment Three/04 (Day Two) . . . . .	192
Fig 6.59: Comparison of the predicted and measured water activities for treatment 41 of Experiment Three/04 . . . . .	192
Fig 6.60: Comparison of the predicted and measured water activities for treatment 43 of Experiment Three/04 . . . . .	192
Fig 6.61: Comparison of the predicted and measured water activities for treatment 51 of Experiment Three/04 . . . . .	192
Fig 6.62: Comparison of the predicted and measured water activities for treatment 53 of Experiment Three/04 . . . . .	193
Fig 6.63: Comparison of the predicted and measured water activities for treatment 57 of Experiment Three/04 . . . . .	193



# LIST OF APPENDICES

	<i>Page</i>
<b><i>I. As hard copies in this document</i></b>	
Appendix A1: NOMENCLATURE .....	239
Appendix A2: STATISTICAL ANALYSIS OF THE EXPERIMENTAL DATA .....	245
Appendix A3: MODEL FORMULATION AS ODEs .....	263
Appendix A4: MATLAB LANGUAGE FOR THE MODEL .....	287
Appendix A5: NUMERICAL AND ANALYTICAL ERROR CHECKING .....	307
Appendix A6: MEASUREMENTS OF THE GRAIN PHYSICAL PROPERTIES .....	319
Appendix A7: RESULTS OF THE SENSITIVITY ANALYSIS .....	325
Appendix A8: RESULTS OF REGRESSION ANALYSIS OF THE PROPOSED PARAMETERS THAT COULD AFFECT HRY .....	329
<b><i>II. As soft copies in CD</i></b>	
Appendix B1: MEASURED DATA OF EXPERIMENT ONE/03	
Appendix B2: MEASURED DATA OF EXPERIMENT TWO/03	
Appendix B3: MEASURED DATA OF EXPERIMENT THREE/03	
Appendix B4: MEASURED DATA OF EXPERIMENT FOUR/03	
Appendix B5: MEASURED DATA OF EXPERIMENT ONE/04	
Appendix B6: MEASURED DATA OF EXPERIMENT TWO/04	
Appendix B7: MEASURED DATA OF EXPERIMENT THREE/04	
Appendix B8: $T_g$ FROM DROP AND COMPRESSION TESTS	
Appendix B9: $T_g$ FROM DSC TEST	
Appendix B10: INTENSIVE MEASURED DATA	
Appendix B11: m FILES	
Appendix B12: SIMULATION RESULTS OF EXPERIMENT TWO/04	
Appendix B13: SIMULATION RESULTS OF EXPERIMENT THREE/04	
Appendix B14: PROPOSED HRY PARAMETERS CALCULATED FROM THE MODEL PREDICTIONS	