124

COMPUTER SIMULATION OF AERATED WHEAT STORED IN TROPICAL AND SUBTROPICAL CLIMATES

BY

ROBERTO SINICIO

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering
University of Manitoba
Winnipeg, Manitoba

ISBN 0-612-13506-3

Name Roberto Sinicio

Dissertation Abstracts International is arranged by broad, general subject categories. Please select the one subject which most nearly describes the content of your dissertation. Enter the corresponding four-digit code in the spaces provided.

Agricultural Engineering | 0539 | U·M·I

SUBJECT TERM | SUBJECT CODE

Subject Categories

THE HUMANITIES AND SOCIAL SCIENCES

COMMUNICATIONS AND THE ARTS
Architecture 0729
Art History 0377
Cinema 0900
Dance 0378
Fine Arts 0357
Information Science 0723
Journalism 0391
Library Science 0399
Mass Communications 0708
Music 0413
Speech Communication 0459
Theater 0465

EDUCATION
General 0515
Administration 0514
Adult and Continuing 0516
Agricultural 0517
Art 0273
Bilingual and Multicultural 0282
Business 0688
Community College 0275
Curriculum and Instruction 0727
Early Childhood 0518
Elementary 0524
Finance 0277
Guidance and Counseling 0519
Health 0680
Higher 0745
History of 0520
Home Economics 0278
Industrial 0521
Language and Literature 0279
Mathematics 0280
Music 0522
Philosophy of 0998
Physical 0523
Psychology 0525
Reading 0535
Religious 0527
Sciences 0714
Secondary 0533
Social Sciences 0534
Sociology of 0340
Special 0529
Teacher Training 0530
Technology 0710
Tests and Measurements 0288
Vocational 0747

LANGUAGE, LITERATURE AND LINGUISTICS
Language
- General 0679
- Ancient 0289
- Linguistics 0290
- Modern 0291

Literature
- General 0401
- Classical 0294
- Comparative 0295
- Medieval 0297
- Modern 0298
- African 0316
- American 0591
- Asian 0305
- Canadian (English) 0352
- Canadian (French) 0355
- English 0593
- Germanic 0311
- Latin American 0312
- Middle Eastern 0315
- Romance 0313
- Slavic and East European 0314

PHILOSOPHY, RELIGION AND THEOLOGY
Philosophy 0422
Religion
- General 0318
- Biblical Studies 0321
- Clergy 0319
- History of 0320
- Philosophy of 0322

Theology 0469

SOCIAL SCIENCES
American Studies 0323
Anthropology
- Archaeology 0324
- Cultural 0326
- Physical 0327

Business Administration
- General 0310
- Accounting 0272
- Banking 0770
- Management 0454
- Marketing 0338

Canadian Studies 0385
Economics
- General 0501
- Agricultural 0503
- Commerce-Business 0505
- Finance 0508
- History 0509
- Labor 0510
- Theory 0511

Folklore 0358
Geography 0366
Gerontology 0351
History
- General 0578
- Ancient 0579
- Medieval 0581
- Modern 0582
- Black 0328
- African 0331
- Asia, Australia and Oceania 0332
- Canadian 0334
- European 0335
- Latin American 0336
- Middle Eastern 0333
- United States 0337

History of Science 0585
Law 0398
Political Science
- General 0615
- International Law and Relations 0616
- Public Administration 0617

Recreation 0814
Social Work 0452
Sociology
- General 0626
- Criminology and Penology 0627
- Demography 0938
- Ethnic and Racial Studies 0631
- Individual and Family Studies 0628
- Industrial and Labor Relations 0629
- Public and Social Welfare 0630
- Social Structure and Development 0700
- Theory and Methods 0344

Transportation 0709
Urban and Regional Planning 0999
Women's Studies 0453

THE SCIENCES AND ENGINEERING

BIOLOGICAL SCIENCES
Agriculture
- General 0473
- Agronomy 0285
- Animal Culture and Nutrition 0475
- Animal Pathology 0476
- Food Science and Technology 0359
- Forestry and Wildlife 0478
- Plant Culture 0479
- Plant Pathology 0480
- Plant Physiology 0817
- Range Management 0777
- Wood Technology 0746

Biology
- General 0306
- Anatomy 0287
- Biostatistics 0308
- Botany 0309
- Cell 0379
- Ecology 0329
- Entomology 0353
- Genetics 0369
- Limnology 0793
- Microbiology 0410
- Molecular 0307
- Neuroscience 0317
- Oceanography 0416
- Physiology 0433
- Radiation 0821
- Veterinary Science 0778
- Zoology 0472

Biophysics
- General 0786
- Medical 0760

EARTH SCIENCES
Biogeochemistry 0425
Geochemistry 0996
Geodesy 0370
Geology 0372
Geophysics 0373
Hydrology 0388
Mineralogy 0411
Paleobotany 0345
Paleoecology 0426
Paleontology 0418
Paleozoology 0985
Palynology 0427
Physical Geography 0368
Physical Oceanography 0415

HEALTH AND ENVIRONMENTAL SCIENCES
Environmental Sciences 0768
Health Sciences
- General 0566
- Audiology 0300
- Chemotherapy 0992
- Dentistry 0567
- Education 0350
- Hospital Management 0769
- Human Development 0758
- Immunology 0982
- Medicine and Surgery 0564
- Mental Health 0347
- Nursing 0569
- Nutrition 0570
- Obstetrics and Gynecology 0380
- Occupational Health and Therapy 0354
- Ophthalmology 0381
- Pathology 0571
- Pharmacology 0419
- Pharmacy 0572
- Physical Therapy 0382
- Public Health 0573
- Radiology 0574
- Recreation 0575
- Speech Pathology 0460
- Toxicology 0383

Home Economics 0386

PHYSICAL SCIENCES

Pure Sciences
Chemistry
- General 0485
- Agricultural 0749
- Analytical 0486
- Biochemistry 0487
- Inorganic 0488
- Nuclear 0738
- Organic 0490
- Pharmaceutical 0491
- Physical 0494
- Polymer 0495
- Radiation 0754

Mathematics 0405
Physics
- General 0605
- Acoustics 0986
- Astronomy and Astrophysics 0606
- Atmospheric Science 0608
- Atomic 0748
- Electronics and Electricity 0607
- Elementary Particles and High Energy 0798
- Fluid and Plasma 0759
- Molecular 0609
- Nuclear 0610
- Optics 0752
- Radiation 0756
- Solid State 0611

Statistics 0463

Applied Sciences
Applied Mechanics 0346
Computer Science 0984

Engineering
- General 0537
- Aerospace 0538
- Agricultural 0539
- Automotive 0540
- Biomedical 0541
- Chemical 0542
- Civil 0543
- Electronics and Electrical 0544
- Heat and Thermodynamics 0348
- Hydraulic 0545
- Industrial 0546
- Marine 0547
- Materials Science 0794
- Mechanical 0548
- Metallurgy 0743
- Mining 0551
- Nuclear 0552
- Packaging 0549
- Petroleum 0765
- Sanitary and Municipal 0554
- System Science 0790

Geotechnology 0428
Operations Research 0796
Plastics Technology 0795
Textile Technology 0994

PSYCHOLOGY
General 0621
Behavioral 0384
Clinical 0622
Developmental 0620
Experimental 0623
Industrial 0624
Personality 0625
Physiological 0989
Psychobiology 0349
Psychometrics 0632
Social 0451

Nom ____

Dissertation Abstracts International est organisé en catégories de sujets. Veuillez s.v.p. choisir le sujet qui décrit le mieux votre thèse et inscrivez le code numérique approprié dans l'espace réservé ci-dessous.

____ ☐☐☐☐ U·M·I

SUJET — CODE DE SUJET

Catégories par sujets

HUMANITÉS ET SCIENCES SOCIALES

COMMUNICATIONS ET LES ARTS
Architecture 0729
Beaux-arts 0357
Bibliothéconomie 0399
Cinéma 0900
Communication verbale 0459
Communications 0708
Danse 0378
Histoire de l'art 0377
Journalisme 0391
Musique 0413
Sciences de l'information 0723
Théâtre 0465

ÉDUCATION
Généralités 515
Administration 0514
Art 0273
Collèges communautaires 0275
Commerce 0688
Économie domestique 0278
Éducation permanente 0516
Éducation préscolaire 0518
Éducation sanitaire 0680
Enseignement agricole 0517
Enseignement bilingue et multiculturel 0282
Enseignement industriel 0521
Enseignement primaire. 0524
Enseignement professionnel 0747
Enseignement religieux 0527
Enseignement secondaire 0533
Enseignement spécial 0529
Enseignement supérieur 0745
Évaluation 0288
Finances 0277
Formation des enseignants 0530
Histoire de l'éducation 0520
Langues et littérature 0279
Lecture 0535
Mathématiques 0280
Musique 0522
Orientation et consultation 0519
Philosophie de l'éducation 0998
Physique 0523
Programmes d'études et enseignement 0727
Psychologie 0525
Sciences 0714
Sciences sociales 0534
Sociologie de l'éducation 0340
Technologie 0710

LANGUE, LITTÉRATURE ET LINGUISTIQUE
Langues
- Généralités 0679
- Anciennes 0289
- Linguistique 0290
- Modernes 0291

Littérature
- Généralités 0401
- Anciennes 0294
- Comparée 0295
- Mediévale 0297
- Moderne 0298
- Africaine 0316
- Américaine 0591
- Anglaise 0593
- Asiatique 0305
- Canadienne (Anglaise) 0352
- Canadienne (Française) 0355
- Germanique 0311
- Latino-américaine 0312
- Moyen-orientale 0315
- Romane 0313
- Slave et est-européenne 0314

PHILOSOPHIE, RELIGION ET THÉOLOGIE
Philosophie 0422
Religion
- Généralités 0318
- Clergé 0319
- Études bibliques 0321
- Histoire des religions 0320
- Philosophie de la religion 0322

Théologie 0469

SCIENCES SOCIALES
Anthropologie
- Archéologie 0324
- Culturelle 0326
- Physique 0327

Droit 0398
Économie
- Généralités 0501
- Commerce-Affaires 0505
- Économie agricole 0503
- Économie du travail 0510
- Finances 0508
- Histoire 0509
- Théorie 0511

Études américaines 0323
Études canadiennes 0385
Études féministes 0453
Folklore 0358
Géographie 0366
Gérontologie 0351
Gestion des affaires
- Généralités 0310
- Administration 0454
- Banques 0770
- Comptabilité 0272
- Marketing 0338

Histoire
- Histoire générale 0578
- Ancienne 0579
- Médiévale 0581
- Moderne 0582
- Histoire des noirs 0328
- Africaine 0331
- Canadienne 0334
- États-Unis 0337
- Européenne 0335
- Moyen-orientale 0333
- Latino-américaine 0336
- Asie, Australie et Océanie 0332

Histoire des sciences 0585
Loisirs 0814
Planification urbaine et régionale 0999
Science politique
- Généralités 0615
- Administration publique 0617
- Droit et relations internationales 0616

Sociologie
- Généralités 0626
- Aide et bien-àtre social 0630
- Criminologie et établissements pénitentiaires 0627
- Démographie 0938
- Études de l' individu et de la famille 0628
- Études des relations interethniques et des relations raciales 0631
- Structure et développement social 0700
- Théorie et méthodes. 0344
- Travail et relations industrielles 0629

Transports 0709
Travail social 0452

SCIENCES ET INGÉNIERIE

SCIENCES BIOLOGIQUES
Agriculture
- Généralités 0473
- Agronomie. 0285
- Alimentation et technologie alimentaire 0359
- Culture 0479
- Élevage et alimentation 0475
- Exploitation des péturages 0777
- Pathologie animale 0476
- Pathologie végétale 0480
- Physiologie végétale 0817
- Sylviculture et faune 0478
- Technologie du bois 0746

Biologie
- Généralités 0306
- Anatomie 0287
- Biologie (Statistiques) 0308
- Biologie moléculaire 0307
- Botanique 0309
- Cellule 0379
- Écologie 0329
- Entomologie 0353
- Génétique 0369
- Limnologie 0793
- Microbiologie 0410
- Neurologie 0317
- Océanographie 0416
- Physiologie 0433
- Radiation 0821
- Science vétérinaire 0778
- Zoologie 0472

Biophysique
- Généralités 0786
- Medicale 0760

SCIENCES DE LA TERRE
Biogéochimie 0425
Géochimie 0996
Géodésie 0370
Géographie physique 0368
Géologie 0372
Géophysique 0373
Hydrologie 0388
Minéralogie 0411
Océanographie physique 0415
Paléobotanique 0345
Paléoécologie 0426
Paléontologie 0418
Paléozoologie 0985
Palynologie 0427

SCIENCES DE LA SANTÉ ET DE L'ENVIRONNEMENT
Économie domestique 0386
Sciences de l'environnement 0768
Sciences de la santé
- Généralités 0566
- Administration des hipitaux 0769
- Alimentation et nutrition 0570
- Audiologie 0300
- Chimiothérapie 0992
- Dentisterie 0567
- Développement humain 0758
- Enseignement 0350
- Immunologie 0982
- Loisirs 0575
- Médecine du travail et thérapie 0354
- Médecine et chirurgie 0564
- Obstétrique et gynécologie 0380
- Ophtalmologie 0381
- Orthophonie 0460
- Pathologie 0571
- Pharmacie 0572
- Pharmacologie 0419
- Physiothérapie 0382
- Radiologie 0574
- Santé mentale 0347
- Santé publique 0573
- Soins infirmiers 0569
- Toxicologie 0383

SCIENCES PHYSIQUES
Sciences Pures
Chimie
- Genéralités 0485
- Biochimie 487
- Chimie agricole 0749
- Chimie analytique 0486
- Chimie minérale 0488
- Chimie nucléaire 0738
- Chimie organique 0490
- Chimie pharmaceutique 0491
- Physique 0494
- PolymÇres 0495
- Radiation 0754

Mathématiques 0405
Physique
- Généralités 0605
- Acoustique 0986
- Astronomie et astrophysique 0606
- Electronique et électricité 0607
- Fluides et plasma 0759
- Météorologie 0608
- Optique 0752
- Particules (Physique nucléaire) 0798
- Physique atomique 0748
- Physique de l'état solide 0611
- Physique moléculaire 0609
- Physique nucléoire 0610
- Radiation 0756

Statistiques 0463

Sciences Appliqués Et Technologie
Informatique 0984
Ingénierie
- Généralités 0537
- Agricole 0539
- Automobile 0540
- Biomédicale 0541
- Chaleur et ther modynamique 0348
- Conditionnement (Emballage) 0549
- Génie aérospatial 0538
- Génie chimique 0542
- Génie civil 0543
- Génie électronique et électrique 0544
- Génie industriel 0546
- Génie mécanique 0548
- Génie nucléaire 0552
- Ingénierie des systämes 0790
- Mécanique navale 0547
- Métallurgie 0743
- Science des matériaux 0794
- Technique du pétrole 0765
- Technique minière 0551
- Techniques sanitaires et municipales 0554
- Technologie hydraulique 0545

Mécanique appliquée 0346
Géotechnologie 0428
Matières plastiques (Technologie) 0795
Recherche opérationnelle 0796
Textiles et tissus (Technologie) 0794

PSYCHOLOGIE
Généralités 0621
Personnalité 0625
Psychobiologie 0349
Psychologie clinique 0622
Psychologie du comportement 0384
Psychologie du développement 0620
Psychologie expérimentale 0623
Psychologie industrielle 0624
Psychologie physiologique 0989
Psychologie sociale 0451
Psychométrie 0632

COMPUTER SIMULATION OF AERATED WHEAT STORED IN

TROPICAL AND SUBTROPICAL CLIMATES

BY

ROBERTO SINICIO

A Thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

ABSTRACT

The main research objective was to determine the airflow rates, increases in air temperature, and fan control methods required to preserve the quality of aerated wheat stored in large horizontal storages under tropical and subtropical climatic conditions. The best airflow rates and increases in air temperature for a geographical region depend on the initial moisture content of the grain, airflow distribution, climate, and storage period. To reach this objective a reliable computer program was required to simulate heat and mass transfer in stored wheat with and without ventilation.

No reliable mathematical model had been developed to simulate forced convection in wheat stored under tropical and subtropical conditions. Accurate thin-layer drying and wetting equations were developed for use in a non-equilibrium model of forced convection in stored wheat. Thin-layer drying (43 data sets) and wetting (88 data sets) rates were obtained in 15 experimental tests by exposing simultaneously nine thin-layers of wheat kernels to constant airflows, temperatures, and relative humidities. The semi-empirical equation of Page was a more accurate model of the data than the theoretical diffusion equation with the diffusion coefficient dependent on temperature only.

The modified non-equilibrium model was validated by comparing it with an existing validated equilibrium model and by conducting sensitivity analyses of the proposed model for simulating aeration of wheat stored in Brazil and Winnipeg. A new approach was used in the comparisons and sensitivity analyses of the mathematical models for simulating aeration of stored wheat: deviations in predicted grain deterioration instead of deviations in grain moisture contents and temperatures were compared. The results produced by the equilibrium and non-equilibrium

models were significantly different for most conditions analyzed when simulating for Brazilian locations because the deviations in grain deterioration predicted by the models were equal to or higher than the uncertainty in predicting grain deterioration (±30%). For Winnipeg, however, the results were not significantly different when using the airflow rate and ventilation time recommended for the Canadian Prairies. The uncertainties in predicted grain deterioration generated in the computer program by several parameters for Brazilian locations and by all parameters for Winnipeg were much lower than ±30% suggesting that the deterioration model for wheat should be improved.

A computer model was developed to simulate intermittent aeration of wheat stored in large horizontal grain storages with linear and non-linear airflow distributions. The computer model simulated one-dimensional forced convection using the non-equilibrium model, heat conduction in the direction of the airflow for periods without ventilation, and grain deterioration. The best fan-control method to aerate wheat stored in eight Brazilian locations was a differential-thermostat which operated the fan according to the difference between the dry bulb temperature of the outside ambient air and the average grain temperature. The maximum allowed storage time for aerated wheat in the Brazilian locations correlated well with the annual average-time that the ambient air temperature was below 15°C.

ACKNOWLEDGEMENTS

I thank the Conselho Nacional de Pesquisa Científica e Tecnológica (National Scientific and Technological Research Council) of Brazil and the Natural Sciences and Engineering Research Council of Canada for their financial support. I also thank the Universidade Federal de Viçosa (Federal University of Viçosa) and Centro Nacional de Treinamento em Armazenagem (National Center for Training in Storage), Viçosa, MG, Brazil for permitting me to take the Ph. D. Program and for their financial support.

I am grateful to my advisor Dr. W. E. Muir for his excellent guidance, friendship, and understanding needed during this research. I also thank the thesis committee members Dr. Jayas, Dr. Cenkowski, and Dr. Stobbe for their valuable suggestions and remarks.

I also indebted to Colonel W. Gomes, Major J. Brandão, and researcher J. S. Silva Filho, Instituto de Aeronáutica e Espaço (Aeronautics and Space Institute) of Brazil for providing Brazilian weather data. Special thanks to my brother-in-law Luiz Arthur B. Tessarotto for contacting the staff from the Instituto de Aeronáutica e Espaço.

I also wish to thank Jack Putnam, Matthew McDonald, and Rob Ataman for their help and suggestions during the construction of the experimental equipment.

Thanks are due to my friends, colleagues, and all staff of the Agricultural Engineering Department for their friendship and help.

I wish to express my sincere appreciation to my wife Xiomara and son Roberto for their love, understanding, and support which were necessary throughout my studies.

Finally, I thank God for everything.

DEDICATED TO

My mother Gianete and my father Adônis

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A, B, C	parameters in the equilibrium moisture content equations
a_1, a_2	parameters in the diffusivity equation
AST	allowed storage time (mo)
ASTE	allowable storage time elapsed predicted by the deterioration model (decimal)
$ASTE_c$	ASTE predicted by the mathematical model when adding or subtracting an uncertainty from one or more variables (decimal)
$ASTE_{eq}$	ASTE predicted by the equilibrium model (decimal)
$ASTE_{neq}$	ASTE predicted by the non-equilibrium model (decimal)
b1, b2, b3	parameters in the equilibrium moisture content equation
c1, c2, c3	parameters in the thin-layer equations
D	diffusivity coefficient ($m^2 \cdot min^{-1}$)
D_R	modified diffusivity coefficient, $D_R = D/R^2$, (min^{-1})
db	dry mass basis
DC_{ASTE}	deviation between ASTE predicted by the equilibrium and non-equilibrium models in the comparison of models (%)
DM	initial moisture content minus the equilibrium moisture content of the grain (decimal, db)
DF	degrees of freedom of the regression model (N minus the number of parameters in the model)
DS_{ASTE}	deviation of ASTE caused by adding or subtracting uncertainties from one or more variables in the mathematical model (%)
EMC	equilibrium moisture content of the grain (decimal, db)
ERH	equilibrium relative humidity (%)
K, K', K''	parameters in the thin-layer equation
L	latent heat of vaporization or condensation of water in wheat ($kJ \cdot kg^{-1}$)
L'	latent heat of vaporization or condensation of free water ($kJ \cdot kg^{-1}$)

M	grain moisture content (decimal, db)
M. C.	moisture content (%, wb)
Mo	initial moisture content (decimal, db)
MR	moisture ratio (decimal)
n	identifying number of the term in the infinite series
N	number of experimental points
N, N', N''	parameters in the thin-layer equations
p1 to p4	parameters in the equilibrium moisture content equations
q1 to q4	parameters in the equilibrium moisture content equations
r1 to r6	parameters in the thin-layer equations
R	equivalent radius of the grain kernels (m)
RH	air relative humidity (decimal or %)
s1 to s6	parameters of thin-layer equations
t	time (min)
T	temperature (K)
T_c	temperature (°C)
T_{ave}	annual average ambient air temperature (°C)
T_{fan}	fan temperature rise (°C)
T_{gmax}	maximum grain temperature (°C)
T_{roof}	difference between the bin attic temperature and the ambient air temperature (°C)
TDIFF	ambient air temperature minus the average grain temperature (°C)
U_{ASTE}	probable uncertainty to predict ASTE (decimal)
U_M	uncertainty associated with measurement of grain moisture content (%, wb)
U_T	uncertainty associated with measurement of grain temperature (°C)
U_a, U_b, U_c	uncertainties in estimating the coefficients of the deterioration model
V	air velocity ($m \cdot s^{-1}$)
wb	wet mass basis
X	variable before any change in the sensitivity analysis
X_c	variable after adding the uncertainty in the sensitivity analysis

Y_i	measured moisture content (%, wb)
YC_i	estimated moisture content (%, wb)
z	random increment with a standard normal distribution of errors about a zero mean

Greek Symbols

α	statistical level of significance (decimal)
$\Delta\theta$	time interval used for the simulation (h)
θ_{15}	annual average-time that the ambient air temperature is below 15°C (%)
θ_{MAX}	Maximum allowed storage times before seed germination drops by 5% or visible mould appears in the deterioration model (h)
σ_X	standard error of the variable X (decimal)

1. INTRODUCTION

1.1. Scope of the Problem

1.1.1. Recommended airflow rates and fan control methods to aerate wheat stored in tropical and subtropical regions

It is more difficult to preserve the quality of stored grain aerated in tropical and subtropical climates than in temperate climates because the higher temperatures increase the rate of biological activity in the grain bulk. Grain preservability is yet much more difficult in a warm and humid climate because the higher relative humidities of the ambient air increase the water activity of the grain.

Grain storage ecosystems in the tropics are more difficult to analyze than those in the temperate climatic conditions because of the greater variety of type and size of storage structures; greater complexity of the marketing system; higher temperatures and in some regions higher relative humidities of the ambient air; and greater biological complexity and diversity (Haines 1994).

Large horizontal grain storages with capacities varying from 10 to 100 kt of grain are common in warm climates such as in Brazil and Australia. Grain aeration has become an essential method for the preservation of grain quality in these warm climates. In all these large grain storages the ventilating air is distributed by aeration ducts which produce a non-linear airflow in the grain mass.

A common problem during grain aeration in humid climates is grain wetting around the aeration ducts (Sutherland 1968, Navarro et al. 1973a and 1973b, Nash 1978, Sutherland et al. 1983, Ghaly 1984). This occurs when the relative humidity of the air coming from the ducts is consistently higher than the equilibrium relative humidity of the stored grain. Deterioration of the grain in this region depends mainly on its moisture content (i.e., water activity) and temperature during the storage period (Nash 1978, Ghaly 1984). Grain deterioration under these conditions is observed in both cold and warm regions (Sutherland 1968, Navarro et al. 1973a and 1973b, Ghaly 1984) but the problem is worse in warm-humid regions because the grain deterioration rate is accelerated by the higher grain temperatures. Therefore, control of grain aeration is more complex in tropical and subtropical regions than in temperate regions.

Commercial losses caused by incorrectly controlling grain aeration which can over dry the stored grain are common in countries like Brazil. These losses occur because grain storage managers do not understand the effect of fan control strategies and, thus, turn the aeration fans on or off during the wrong periods of the day. The main hindrance for the correct practice of grain aeration in Brazil is the lack of knowledge about the dynamic equilibrium between the psychrometric properties of the ambient air and the hygroscopic properties of the grain (Sartori et al. 1976). Information related to recommended airflow rates and fan control strategies for tropical and subtropical regions is lacking (Calderon 1972, Calderon 1974, Navarro 1974, Chung et al. 1986, Nour/Jantan et al. 1988, Covanich 1988). The recommended airflow rates for cooling grain during the storage period depend on the type of grain, size and type of storage structure, and climatic conditions (Foster and Tuite 1982).

A computer model is needed to determine the best airflow rates, increases in air temperature, and fan and heater control strategies during intermittent aeration of wheat stored in tropical and subtropical climates. The computer model must accurately predict temperature, moisture content, and deterioration of the grain caused by fungi as a function of time, weather conditions, and type and shape of storage structure (Metzger and Muir 1983a). In particular, it is necessary to predict accurately temperature, moisture content, and deterioration of the grain close to the aeration ducts where the grain undergoes multiple drying and wetting cycles.

1.1.2. Mathematical models for simulating forced convection in stored wheat

Metzger and Muir (1983b) validated the equilibrium model of Thompson (1972) for simulating forced-convection in stored wheat with a linear airflow distribution. Little is known, however, about the performance of equilibrium and non-equilibrium mathematical models for simulating aeration of wheat stored in tropical and subtropical climates using linear and non-linear airflow distributions.

1.1.3. Thin-layer drying and wetting equations for wheat

Non-equilibrium mathematical models use thin-layer drying and wetting equations to describe the rate of change in the grain moisture content for a single layer of grain kernels exposed to a constant temperature, relative humidity, and airflow. In a comprehensive review of studies on thin-layer drying of grains Jayas et al. (1991) indicated that little work has been done on thin-layer wetting of grains, particularly wheat. In fact, no thin-layer wetting equation was available for wheat and thin-layer drying equations for wheat were not available for near-ambient temperatures except for the equation of Jayas and Sokhansanj (1986). The standard error for the equation of Jayas and Sokhansanj (1986), however, was not reported.

1.1.4. Relative importance of the variables in the mathematical models

Many research projects have been conducted to determine empirical data such as equilibrium moisture content, thin-layer drying and wetting rates, bulk density, specific heat, latent heat of vaporization, and resistance to airflow of grains. These data are needed in non-equilibrium heat and mass balance models to simulate aeration of stored grain. Little is known, however, about the relative importance or effect of such variables on the results of the simulations.

Sensitivity analysis, which is the study of changes in the parameters of mathematical models and the effects that these changes will have on the problem solution (Lee et al. 1985), can be used to determine the relative importance of one variable or interaction of many variables during the simulation of aeration of stored grains. The sensitivity of a computer model to one variable can be determined by changing that variable within its range of expected uncertainty and by calculating the effect of this change on the predicted grain deterioration over the storage period. The effects of changing variables on the predicted grain moisture contents and temperatures are not needed in the sensitivity analysis because grain deterioration, unlike grain moisture content and temperature, is a continuously increasing, cumulative variable.

Computer models used to simulate aeration of stored grain can be simplified based on the results of sensitivity analyses. Simplification of computer models is needed to simulate repeated processes that require long computer times especially when the research objective is system optimization. Research effort can be reduced by directing future work towards the measurement of the most important variables identified in the sensitivity analysis.

1.2. Hypotheses

The following hypotheses were formulated for testing:

1. Accurate thin-layer drying and wetting equations for wheat can be determined based on experimental data obtained by exposing thin-layers of wheat kernels to constant airflows, temperatures, and relative humidities;

2. Non-equilibrium heat and mass balance models, when compared with equilibrium models, are better to predict changes in grain moisture contents and temperatures during aeration of stored wheat in warm and humid climates with uniform and non-uniform airflow distributions;

3. The knowledge of the relative importance of variables such as airflow rate, thermal and physical properties of wheat, equilibrium moisture content, and thin-layer equations can be used to simplify computer models for simulating aeration of stored wheat and to direct future research towards the most important variables; and

4. The airflow rates and fan control methods required to preserve the quality of aerated wheat stored in large horizontal grain storages under tropical and subtropical climates can be determined using a simulation model to predict moisture contents, temperatures, and deterioration based on historical weather data for several storage years.

1.3. Assumptions

The following assumptions correspond to each of the formulated hypotheses, respectively:

1. The major variables that affect the thin-layer drying and wetting of wheat are related to the initial moisture content of the grain, air temperature and relative humidity, and air velocity;

2. Heat and mass balance models used for grain aeration normally over estimate wetting and drying for the bottom layers of grain close to the air inlet. The problem of over prediction is accelerated when the airflow rate is increased in regions close to aerations ducts;

3. The sensitivity of a computer model to simulate grain aeration relative to one variable can be determined by changing that variable within its range of uncertainty and by calculating the effect of this change on the predicted grain deterioration over the storage period; and

4. A computer model which predicts one-dimensional forced convection using a non-equilibrium mathematical model, heat conduction in the direction of the aiflow, and grain deteriorioration based on seed germination as a function of grain moisture content, temperature, and time can be used to determine various design parameters of aeration systems such as the best airflow rates and fan-control methods. This assumption applies to large grain storage units where linear or non-linear airflow distribution exists and where the heat conduction in the horizontal direction can be neglected. Historical weather data containing hourly dry-bulb temperature, relative humidity, and barometric pressure for several harvest years are necessary for the simulations.

1.4. Layout of the Thesis

The major problem identified in this research was the lack of knowledge about the best airflow rates, air-temperature increments, and fan-control methods required to preserve the quality of aerated wheat stored in tropical and subtropical regions with linear and non-linear airflow distributions. To solve this problem a reliable computer program was required to simulate heat and mass transfer in stored wheat with and without ventilation.

The mathematical model of Metzger and Muir (1983b) can be used to predict heat transfer during periods without ventilation. No reliable mathematical model, however, had been developed to simulate forced convection in wheat stored under tropical and subtropical conditions. Therefore, I proposed to use the non-equilibrium mathematical model of Thompson et al. (1968) to simulate the forced convection in stored wheat. Accurate thin-layer drying and wetting equations, which were not available for wheat, were developed to be used in the non-equilibrium mathematical model (objective 1).

The non-equilibrium model, however, should normally be validated against experimental data. The validation was questioned because: long duration tests and great economical resources would be necessary for constructing equipment and conducting the experiments and analyses; the validation would be applicable only for a specific range of experimental conditions and grain cultivar; and in an actual case simulation, the uncertainty in predicting grain deterioration could be higher than the errors introduced in the mathematical model of forced convection by random errors related to thermal and physical properties of the grain and grain cultivar, weather data, fan temperature rise, and airflow. Consequently, research was conducted to compare the non-equilibrium model with an existing equilibrium model which had been validated for Canadian conditions (objective 2).

The knowledge gained through the sensitivity analysis of the non-equilibrium mathematical model (objective 3) was used to simplify the mathematical model for simulating forced convection in stored wheat.

The comparison of equilibrium and non-equilibrium models and the sensitivity analyses of the non-equilibrium model were conducted using weather data from Brazilian locations and Winnipeg for linear and non-linear airflow distributions.

Finally, after finding evidence that the non-equilibrium model was reliable, it was used in a computer program for determining the best airflow rates and fan-control methods for intermittent aeration of wheat stored in selected tropical and subtropical locations (objective 4).

2. OBJECTIVES

The specific objectives of this research were:

1. To determine accurate thin-layer drying and wetting equations for wheat;
2. To compare equilibrium and non-equilibrium heat and mass balance models to simulate aeration of stored wheat with linear and non-linear airflow distributions;
3. To determine the relative importance of several variables for simulating aeration of stored wheat with linear and non-linear airflow distributions; and
4. To determine the best airflow rates, air-temperature increments, and fan control methods required to preserve the quality of aerated wheat stored in tropical and subtropical locations with linear and non-linear airflow distributions.

3. REVIEW OF THE LITERATURE

3.1. Grain Aeration in Tropical and Subtropical Regions

Forced ventilation of ambient air through stored grain (aeration) is necessary to maintain product quality (Foster and Tuite 1982, Sinha and Watters 1985, Sutherland 1986, Lasseran 1988, Noyes 1990, Sinha et al. 1991). The main purposes of grain aeration are to maintain a uniform temperature in the grain bulk and to keep that temperature as low as is practical (USDA 1960, Trisvyatskii 1969, Hall 1970, Nash 1978, Christensen and Sauer 1982, Foster and Tuite 1982, Chung et al. 1986, Thorpe 1986, Lasseran 1988, Noyes 1990). Grain cooling decreases biological activity in the grain ecosystem and prevents moisture migration (Christensen and Sauer 1982, Foster and Tuite 1982, Sutherland 1986, Armitage 1986, Covanich 1988, Muir et al. 1989). Moisture migration is prevented by maintaining a uniform temperature in the grain mass (Christensen and Sauer 1982, Foster and Tuite 1982, Sutherland 1986, Armitage 1986, Covanich 1988, Muir et al. 1989). Moisture migration is caused mainly by free convection of the interstitial air in the grain bulk (Muir 1973, Griffiths 1981, Smith and Sokhansanj 1990a) although moisture transfer by diffusion may occur over extended storage periods. The free convection currents of air inside the grain bulk are caused by temperature gradients in the grain mass. Temperature gradients may be caused by changes in external variables such as ambient air temperature, solar radiation, and wind interacting with the storage structure and grain. Also internal variables like heat generation by respiration of the grain, moulds, and insects (Calderwood et al. 1983) may produce temperature gradients in the grain bulk.

Aeration can kill insects in cold climates, e.g. by maintaining the grain temperature at -5°C for 8 wk kills *Cryptolestes ferrugineus* (Stephens), which is the stored-product insect species most resistant to low temperatures (Mills 1990). Most common insect species of stored grain in tropical and subtropical regions do not multiply at temperatures below 17°C (Navarro 1974, Cotton and Wilbur 1982, Sinha and Watters 1985). Aeration fan controllers for farm-stored wheat in Kansas successfully controlled insects by cooling the grain before significant deterioration occurred (Reed et al. 1993). It is not known, however, whether aeration can maintain the grain temperature below 17°C in tropical and subtropical regions.

It is a common practice in tropical countries such as Brazil to spray contact pesticides on the grain before storage to prevent insect infestations. Grain aeration can decrease the rate of pesticide decay by decreasing the grain temperature (Thorpe and Elder 1982, Sutherland 1986).

Grain aeration can be used to eliminate hot spots inside the grain bulk. A hot spot can be eliminated if a slight drying effect reduces the grain moisture content. Hot spots in the grain bulk may be caused by excessive grain moisture content or an insect infestation confined to a specific location in the grain bulk. Sometimes it is difficult to detect a hot spot using a thermometric system when the hot spot is between two measurement points. The thermal diffusivity of the grain is low and the grain may deteriorate before the hot spot is detected (Muir 1973, Bournas 1988, Muir et al. 1989). In some situations, hot spots can be eliminated by inserting into the grain bulk an aeration spear consisting of a perforated duct with a fan at its upper end. Then, ambient air is drawn through the warm areas of grain by suction (Armitage and Burrell 1978).

The average grain temperature was closely correlated with seasonal ambient air variations during aeration experiments conducted in tropical and subtropical climates (Bhatnagar and Bakshi 1975, Lu and Chen 1985, Sutherland 1986, Nour/Jantan et al. 1988). Grain aeration associated with head space ventilation has been beneficial to control the grain temperature and maintain the grain moisture content in subtropical climates (Ward and Calverley 1972, Navarro 1974, Griffiths

1981, Ghaly 1978, 1984, Halderson 1985, Chung et al. 1986, Cuperus et al. 1986, Gough et al. 1987a, 1987b).

The management of an aeration system is complex considering the many possible interactions among the physical and biological variables in the grain ecosystem. Aeration systems need to be well designed and operated. A centralized quality control system, consisting of computers, programmable controllers, software, and various transducers interacting in a network may solve or at least minimize the problem of providing efficient maintenance of grain quality through proper aeration (Pym and Adamczak 1986, Armitage and Llewellin 1987, Persson and Churchill 1983, Persson and Churchill 1987).

Bailey (1968) suggested that the relative potential for grain aeration in Australian regions could be roughly indicated by determining the time that the ambient air temperature was below 26.7, 21.1, and 15.6°C. The best airflow rates and fan-control methods, however, cannot be determined using this procedure. Atmospheric relative humidity reaches a maximum when the minimum temperatures occur and it is difficult to decide when to operate aeration fans. There are general guidelines to be followed in these situations for humid climates (Gough and McFarlene 1984, Driscoll 1986) but it is necessary to establish optimum fan-control strategies to optimize the use of aeration fans. Explanations about the use of psychrometric equations, grain hygroscopicity, rates of dry matter loss and insect increase, resistance of grain to airflow, economics of grades, handling costs, and probability analysis of percentage loss data for designing storage systems in the humid tropics are given in the literature (Teter 1986).

In subtropical regions it is usually possible to have adequately low temperatures for grain aeration in highland (upland) climates. For example, in a typical upland-savannah climate (near

São Paulo, Brazil) at about 800 m altitude, temperatures of 10-12°C prevail during several months of the year (Calderon 1974).

Aeration has been used as an effective method to control stored grain insects for several locations around the world (Sutherland 1968, Calderon 1972, Calderon 1974, Ghaly 1978, Nash 1978, Calderwood et al. 1983, Bloome and Cuppperus 1984, Ghaly 1984, Halderson 1985, Armitage 1986, Cuperus et al. 1986, Sutherland 1986, Armitage and Llewellin 1987, Epperly et al. 1987, Calderon et al. 1989, Noyes 1990, Reed et al. 1993, Willian et al. 1993) but for the warm regions or for the warm seasons occasional chemical treatment (spot fumigation) may be needed for insect control (Calderwood et al. 1983, Calderon et al. 1989). In the humid tropics, aeration cannot control insect growth and development in the internal environment of the aerated bulk storage, therefore, a supplementary system to control insects is needed (Chung et al. 1986, Nour/Jantan et al. 1988). Reducing grain temperatures by aeration, however, decreases biological activity in the grain bulk and decreases the rate of pesticide decay (Thorpe and Elder 1982, Sutherland 1986).

Other possibilities for grain aeration in warm climates are either to use refrigerated air to cool the grain and kill the grain insects during the normal storage period (Calderon 1972, Navarro et al. 1973a, 1973b, Donahaye et al. 1974, Calderon 1974, Navarro 1974, Hunter and Taylor 1980, Driscoll 1986, Sutherland 1986, Maier et al. 1989, Abe et al. 1993). To be economic the grain storage has to be thermally insulated and the cooled air recirculated (Hunter and Taylor 1980). In Brazil, grain storage managers have found that grain aeration using refrigerated air is not profitable because the grain storages are not thermally-insulated. However, there have been some cases of using this system for seed storage.

The use of heated air aeration systems has been also investigated for tropical climates to prevent wetting of stored grain (Pfost et al. 1976a). This method is feasible to control insects by maintaining the grain temperature above 44°C but seed will lose viability and grain quality will decrease.

Ferreira et al. (1979) evaluated the technical feasibility of continuous aeration of corn stored in six Brazilian locations using the model of Thompson (1972) modified by Fraser and Muir (1977) and adapted for the study of Ferreira et al. (1979). It was shown that the southern climate of Brazil is adequate for aeration of corn stored at 13% wb (wet mass basis). A 1°C rise in air temperature through the fan obtained by blowing the air was important for increasing the safe storage life of the stored corn compared with sucking the air through the grain. Ferreira et al. (1979) discouraged the storage of corn at the northern seaport, Belém, near the mouth of the Amazon River which is the warmest of the six locations considered. Only average monthly air temperatures and relative humidities were used and the heat and mass transfer in the grain bulk without ventilation was not included in the simulations.

Ferreira and Muir (1981) conducted simulations of continuous aeration of corn stored in five locations in São Paulo State, Brazil using the same procedure of Ferreira et al. (1979). The locations were selected so that all climate types of this State could be considered. Average daily air temperatures and relative humidities for 10 years were used for the simulations. Upward aeration of corn stored at 13% wb was feasible for at least one year storage period only for three locations. The best results were for locations which had a hot climate with a dry winter while the worst results were for locations which had tropical-wet or temperate wet climates.

The computer simulations conducted by Ferreira et al. (1979) and Ferreira and Muir (1981), however, did not investigate options for the fan control because only monthly and daily average weather data were available. Although the continuous ventilation method is not used by grain storage managers in Brazil, the results of this research showed that aerating corn in Brazil is technically feasible and that the fan temperature rise is an important variable affecting the safe storage life of stored corn.

Sinicio et al. (1991) simulated conductive heat transfer in the radial and vertical directions along with intermittent forced ventilation through corn and wheat stored in Sorocaba, Brazil using the mathematical model developed by Metzger and Muir (1983b). The best airflow rates and fan-control strategies were determined based on weather data for 3 years. Hourly weather data were generated based on daily records containing five air temperatures, three relative humidities, and daily averages. These researchers determined that controlling the fan with a differential-thermostat or time-clock resulted in decreased deterioration compared with either no ventilation or continuous ventilation. They determined also that to store corn and wheat safely for 10 and 6 mo, respectively, minimum airflow rates of 0.5 and 1.0 $L{\cdot}s^{-1}{\cdot}m^{-3}$ were required. Differential-thermostat control caused the least grain deterioration for wheat and the least energy consumption by the fan for both wheat and corn.

The research of Sinicio et al. (1991), however, was not conducted using actual hourly weather data and only 3 years of data were used in the simulations. The differential-thermostat method was based on the difference between the grain temperature 0.68 m below the top surface and the dry bulb temperature of the ambient air. This procedure, however, has some practical inconveniences because the grain depth is not fixed during the storage period and the thermocouple junctions for measuring the grain temperature might not be located at the required depth used as reference in the simulations.

Gonçalves (1992) developed an algorithm to control automatically the aeration fan based on the equilibrium relationship between the psychrometric properties of the ambient air and the moisture content and temperature of corn stored in a metalic bin with a fully perforated floor located in Botucatu, Brazil. The traditional fan-control methods were compared with a method where the fan operation was controlled by the difference between the maximum allowable dry-bulb temperature, determined by the simulation model or experimentally, and the grain temperature. Simulations were conducted to obtain information to formulate an algorithm for automatic control through software. The number of hours available for fan operation was the main factor in determining the fan control method. In the case of the automatic control, it was shown that the maximum allowable dry-bulb temperature should be set equal to the dew point temperature plus a correction factor, determined for the specific local climatic conditions. All fan control methods caused a maximum of 1% wb moisture reduction, similar cooling patterns, and moderate grain deterioration.

The fan control method proposed by Gonçalves (1992) also presents the same practical inconvenience as the differential-thermostat method used by Sinicio et al. (1991) because the grain temperature sensor is fixed at 0.5 m below the grain surface. Gonçalves (1992) conducted the simulations for the worst year only which was determined based on historical records of dry bulb ambient-air temperatures. The selection of the worst year based on the ambient-air temperatures was chosen because the main objective of the ventilation was to cool the grain. This procedure, however, may not be adequate for wet and warm regions. Grain may deteriorate in the bottom layers because excessive wetting is not compensated by the decrease in the grain temperature.

The common problems for the existing fan control methods are: i) actual weather conditions are not considered (e.g. thermostat control based on the grain temperature only); ii) actual weather and grain conditions are not taken into account (e.g. time-clock control); iii) changes from year to year in weather patterns and grain conditions are not considered (e.g. thermostat, humidistat, thermostat combined with humidistat); iv) grain moisture content and air relative humidity are not considered (e.g. differential-thermostat); and v) grain depth might change over the storage period (differential-thermostat control based on the temperature of the top layer).

The method normally used by grain storage managers in Brazil (Bronzatti et al. 1992, Cordeiro 1993) is thermostat control based on the grain temperature. The thermostat is set to turn the fan on when the grain temperature is above 25°C in the cold season (May to October) or above 30°C in the warm season (November to April). No research has been conducted, however, to determine the best thermostat settings for this traditional method.

The differential-thermostat method based on the average grain temperature, however, is the only method which takes into account the actual overall temperature of the grain bulk and ambient air temperature. This method presents a great potential for application in warm and humid climates because it guarantees that the average grain moisture content will not increase excessively by keeping a minimum differential temperature between the grain bulk and the ambient air. Excessive grain wetting will be prevented because a minimum differential temperature, to be determined by computer simulation for each geographical location, will create a vapor pressure for the water in the grain higher than that for the water in the ventilation air. Also, the differential-thermostat method provides grain cooling using the minimum daily temperatures of the ambient air.

Correct design and operation of aeration systems should result in high grain-quality and minimum capital and operational costs. The choice of an optimum aeration design and operation is not obvious because the actual grain spoilage costs are difficult to estimate and the capital costs are not readily available. On the other side, there is no standard size and shape for grain storages or aeration systems and each design will generate special airflow patterns making it difficult to generalize practical recommendations for different climates and initial grain conditions. It is important, however, to develop technology which is inexpensive, easy to operate manually or automatically, and safe for maintaining the grain quality.

3.2. Mathematical Models to Predict Heat and Mass Transfer During Forced Convection Through Stored Grain

3.2.1. Linear airflow distribution

Linear airflow distribution is characterized by parallel streamlines and constant air velocity along the streamlines. This is an ideal situation which actually does not occur even though bins with fully perforated floors are used because the resistance to airflow of grains depends on size and shape of the grain kernels and their distribution; grain levels; rate of grain packing; amount, size, and distribution of foreign material, fine material and broken grains.

The mathematical models used to predict grain drying are either partial-differential-equation models (Brooker et al. 1974, Ingram 1976, Sharp 1982, Bakker-Arkema et al. 1974, Bakker-Arkema 1986, Wilson 1987, 1988, Lu et al. 1987, Jiang and Rajapakse 1991) or heat and mass balance models (Boyce 1965, Boyce 1966, Thompson et al. 1968, Bloome and Shove 1971, O'Callaghan et al. 1971, Thompson et al. 1971, Bloome and Shove 1972, Thompson 1972, Morey et al. 1979, Sokhansanj et al. 1983). Each of them can be further divided into non-equilibrium and equilibrium models (Bakker-Arkema 1986). Equilibrium models assume total equilibrium of temperature and vapor pressure between air and grain in each layer, during each time interval. Non-equilibrium models assume only temperature equilibrium between air and grain. Simplified equilibrium and non-equilibrium models have also been presented to describe heat and mass transfer between air and grain (Sutherland et al. 1971, Ingram 1979, Sutherland et al. 1983, Bowden et al. 1983, Smith 1984a, 1984b).

Equilibrium models use desorption and adsorption equilibrium moisture content equations to calculate the changes in the grain moisture content during each time interval. Non-equilibrium models use thin-layer drying and wetting equations to describe the rate of change in the grain moisture content for a single layer of grain kernels exposed to a constant temperature, relative humidity, and airflow.

The partial differential equation models are fundamental models based on laws of heat and mass transfer and thermodynamics. Several of these models, solved numerically using the finite difference method, have been derived to predict near-ambient grain drying and aeration and most of them have been validated (Barrett et al. 1981, Thorpe and Elder 1982, Smith and Bailey 1983, Parry 1985, Beard and Arthur 1985, Wilson 1988, Bakker-Arkema 1986, Sinicio et al. 1986/1987). These models provide good accuracy and flexibility, but they require considerable computer time to simulate near-ambient grain drying and aeration. Therefore, they are not recommended for optimization studies (Sharp 1982, Parry 1985, Bakker-Arkema 1986).

Logarithmic models (Sabbah et al. 1979) can be obtained by simplifying the partial differential equation models. These models are used for near-ambient drying, provide a good prediction for the average grain moisture content of the bin, are computationally efficient, but they cannot be used for grain aeration because they are inadequate to predict grain wetting (Sharp 1982).

Several simulation studies for near-ambient grain drying and aeration have been conducted using validated heat and mass balance models assuming either an equilibrium or a non-equilibrium condition. These models are recommended for optimization studies because most of them are reasonably accurate and require low computer time (Sharp 1982, Sharp 1984, Bowden et al. 1983). In these models, different combinations of equilibrium moisture content equations for desorption and adsorption and thin-layer drying and wetting equations have been used for the mass balance (Sharma and Muir 1974, Morey et al. 1979, Mittal and Otten 1980, 1982, Morey et al. 1981, Bailey and Smith 1982, Mühlbauer et al. 1982, Metzger and Muir 1983a, Sharp 1984, Schultz et al. 1984, Anderson and Kline 1986, Sinicio et al. 1986/1987, Biondi et al. 1988, Lynch and Morey 1989, Bunn and DeWitt 1990, Bunn and Krueger Wishert 1991).

Most of the heat and mass balance models (Mittal and Otten 1982, Schultz et al. 1984, Sanderson et al. 1989) used for grain aeration predict reasonably well the average grain moisture content of the bin. These models, however, do not accurately simulate moisture contents for the bottom layers of grain close to the air inlet where the grain is exposed to multiple drying and wetting cycles as the weather conditions change.

Morey et al. (1979) simulated near-ambient corn drying and determined that the equilibrium model of Thompson (1972) over predicts the rates of both drying and wetting near the air entrance. Therefore, they modified the model of Thompson (1972) to improve the predictions of moisture content as follows: a thin-layer drying equation was included to check for over prediction of drying for each grain layer and time step; an equation for the equilibrium relative humidity under adsorption conditions was added to decrease the over prediction of wetting and to provide a hysteresis effect in their model; and airflow rates 20-30% lower than those calculated from fan performance curves were used to compensate for non-uniform airflow in the bin.

Mittal and Otten (1980, 1982) simulated near-ambient corn drying and they found that the equilibrium model over predicted the rate of drying and wetting especially in the bottom layers, which also agrees with results obtained by Van Ee and Kline (1979a, 1979b). A combination of equilibrium model with thin-layer drying and wetting equations was used to predict grain moisture content within ±1% moisture content (Mittal and Otten 1980, 1982).

Metzger and Muir (1983b) developed and validated a computer model to predict two-dimensional heat conduction and one-dimensional forced-convection in stored grain. The model can be used to simulate grain temperature and moisture changes in cylindrical granaries aerated intermittently using hourly weather data. The heat transfer model is based on heat conduction and was developed by Muir et al. (1980). Metzger and Muir (1983b) found that equilibrium was not a good assumption for airflow rates as high as 9.0 $L{\cdot}s^{-1}{\cdot}m^{-3}$ while this assumption gave relatively accurate moisture content predictions for airflow rates of 1.9 $L{\cdot}s^{-1}{\cdot}m^{-3}$. Later, Metzger and Muir (1983a) used their model to determine the best airflow rates and fan-control strategies for four Canadian Prairie locations using historical weather data for 15 or more harvest years. In this research they found that the choice of control methods was independent of climate within the range of climates studied.

Sanderson et al. (1989) evaluated the mathematical model developed by Metzger and Muir (1983b) to simulate near-ambient drying of wheat using airflow rates from 0.8 to 23 $L{\cdot}s^{-1}{\cdot}m^{-3}$. The original model of Thompson (1972) used for the simulation had been modified to include an offset of 5% in the equilibrium relative humidity during moisture adsorption. The measured maximum moisture contents were lower than those simulated and the simulated drying front speeds were normally slower than those measured for almost all tests. The weather data used for the simulations were obtained from Environment Canada at a site which is 20 km from the experimental location. Sanderson et al. (1989) concluded that the model of Metzger and Muir (1983b) is sufficiently accurate to predict airflow rates required to cool and dry stored wheat.

Schultz et al. (1984) obtained the best correlations to predict grain aeration using the equilibrium model of Thompson (1972) in drying and the non-equilibrium model of Thompson et al. (1968) in wetting. This indicates that adsorption should be considered separately and hysteresis must be included if the model is to accurately predict wetting. They found that the equilibrium model over predicted wetting while the non-equilibrium model over predicted drying.

Thorpe and Whitaker (1992a, 1992b) developed an explanatory model to predict heat and mass transfer in ventilated grain bulks based on the laws of continuum mechanics expressed by a set of differential equations that govern the transport phenomena in each phase. These researchers showed that thermal equilibrium is likely to exist in aerated bulks of grain. The thermal equilibrium is one of the assumptions in the mathematical models of Thompson (1972) and Thompson et al. (1968) for simulating forced convection in grain bulks.

3.2.2. Non-linear airflow distribution

Non-linear airflow distribution, which occurs when aeration ducts are used to distribute air inside the grain bulk, is characterized by curved streamlines and variable air velocities along the streamlines.

Traverse times in relation to bulk seed fumigation, drying, or cooling indicate the position of temperature and moisture fronts since the speed of these fronts are directly proportional to the speed of the fluid (Saul and Lind 1958, Hunter 1986).

Smith (1982) obtained experimental and theoretical results indicating that anisotropic resistances are required to predict non-uniform airflow through a grain bed and that the streamlines are not perpendicular to the lines of constant pressure. In fact, experimental data for different types of grain have shown that air travels more easily horizontally than vertically (Lamond and Smith 1982, Kumar and Muir 1986, Jayas et al. 1987, Kay et al. 1989, Sinicio et al. 1992).

Smith et al. (1992a , 1992b) developed and validated a computer model to simulate near-ambient grain drying. The computer model simulated three-dimensional heat and mass transfer along the streamlines in a grain bulk with non-linear airflow distribution. Smith et al. (1992b) concluded that the drying front and isotraverse lines have a similar shape when the air and grain are approaching thermal and mass equilibrium. Also, they concluded that the streamlines are not perperdicular to the lines of constant pressure because of the anisotropic resistance of grain to airflow and that the isobars are not adequate to describe the airflow distribution and drying pattern. The following procedures were used by Smith et al. (1992b) to predict heat and mass transfer in near-ambient drying: (i) a finite element method was used to determine the pressure gradients in the grain bulk; (ii) the velocity components were calculated using the pressure gradients; (iii) the streamlines and isotraverse lines were determined based on the velocity components; and (iv) the heat and mass transfer were simulated along the streamlines assuming that the isotraverse lines were similar to the lines of constant grain moisture content.

3.3. Thin-layer Drying and Wetting Equations and Equilibrium Moisture Content Equations for Desorption and Adsorption

Thin-layer equations describe the rate of mass transfer in a single grain layer assuming that the kernel temperature reaches the bulk air temperature immediately at the beginning of the process (Parti 1993). Thin-layer equations can be classified as empirical, semi-empirical, or theoretical equations (Parti 1993). Thin-layer drying and wetting equations for different types of grain have been developed for use in near-ambient grain drying and aeration (Flood et al. 1972, Roa et al. 1977, Krueger and Bunn 1985, Duggal et al. 1982, Sinicio et al. 1984/1985, Haghighi and Segerlind 1988, Parti 1990, Banaszek and Siebenmorgen 1990, Haghighi et al. 1990, Jayas et al. 1991, Liu and Cheng 1991, Osborn et al. 1991, Irudayaraj et al. 1992). The empirical equations are preferred because they provide good accuracy and are more efficient computationally although the theoretical equations are frequently used (Sharp 1982, Parry 1985, Jayas et al. 1991).

A common semi-empirical equation to describe thin-layer drying and wetting of grains is the equation of Page (1949):

$$MR = \frac{(M - EMC)}{(Mo - EMC)} = \exp\left(-K\, t^{N}\right) \tag{3.1}$$

where: MR = moisture ratio (decimal),

M = moisture content (decimal, dry mass basis-db),

EMC = equilibrium moisture content (decimal, db),

Mo = initial moisture content (decimal, db),

t = time (min),

K, N = grain dependent coefficients.

The major variables that affect thin-layer drying and wetting rates of grain are the initial moisture content, air temperature, relative humidity, and air velocity (Misra and Brooker 1980). Most thin-layer models do not include air velocity as an independent variable, however, air velocity affects thin-layer drying of corn (Misra and Brooker 1980) and wheat (Henderson and Pabis 1962).

A theoretical thin-layer equation used by many investigators (Jayas et al. 1991) for simulating grain drying is the diffusion equation and its analytical solution is:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-n^2 \pi^2 D_R\, t) \qquad \textbf{(3.2)}$$

where: D_R = D/R^2 = modified diffusivity coefficient (min^{-1}),

D = diffusivity coefficient ($m^2 \cdot min^{-1}$),

R = equivalent radius of the grain kernels (m),

n = identifying number of the term in the infinite series.

The diffusion equation takes into account the resistance to internal mass transfer, neglects the external resistance, and assumes temperature equilibrium between the kernel and its surroundings (Parti 1993). The modified diffusivity coefficient as a function of temperature in an Arrhenius type equation (Pabis and Henderson 1961) may be expressed as:

$$D_R = a_1 \exp\left(\frac{-a_2}{T}\right) \qquad \textbf{(3.3)}$$

where: T = temperature (K),

a_1, a_2 = product dependent parameters.

Detailed explanations of the thin-layer equations and their use in mathematical models to simulate heat and mass transfer in deep-bed grain drying are given elsewhere (Bakker-Arkema et al. 1974, Brooker et al. 1974, Parry 1985, Jayas et al. 1991, Parti 1993).

Several theoretical and empirical equations and experimental data have been obtained for equilibrium moisture content for desorption and adsorption by grains for modeling near-ambient grain drying and aeration (Chung and Pfost 1967, Strohman and Yoerger 1967, Young and Nelson 1967, Pixton and Warburton 1973, Brooker et al. 1974, Pfost et al. 1976b, Sinicio and Roa 1979, Pixton and Henderson 1981, Iglesias and Chirife 1982, Labuza 1984, Henderson 1987, Chen and Morey 1989a, 1989b). Empirical equations for equilibrium moisture contents are normally used because they provide good accuracy and are computationally efficient (Sharp 1982, Parry 1985, Jayas et al. 1991). Jayas et al. (1991) recommended that a standard format for the equilibrium moisture content equation should not be created until more is known about the nature of moisture sorption and the variables affecting hygroscopicity.

Sun and Woods (1993) reviewed 33 sets of hygroscopic data for wheat and found that the modified Oswin, modified Chung-Pfost, modified Henderson, Strohman-Yoerger, and Chen-Clayton equations are the most suitable for wheat amongst the many isotherm equations available in the literature.

3.4. Mathematical Models to Predict Temperature and Moisture Changes of Stored Grain for Periods Without Aeration

Temperature gradients in grain bulks caused by seasonal changes in weather conditions and solar radiation have been reported for different climates around the world (Holman and Carter 1952, Bakshi and Bhatnagar 1972, Ward and Calverly 1972, Foster and Tuite 1982, Buschermohle et al. 1988, Uiso et al. 1990). Free-convection generated by these temperature gradients carries the grain moisture from the warmer to the cooler parts of the grain bulk and grain deterioration may occur depending on grain conditions and time (Sutherland 1968, Bakshi and Bhatnagar 1972, Ward and Calverley 1972, Muir 1973, Ghaly 1978, Griffiths 1981, Gough et al. 1987a and 1987b, Foster and Tuite 1982, Covanich 1988, Muir et al. 1989, Gough et al. 1990).

Significant increases in grain moisture content in the top of the grain bulk and head space condensation have occurred in metal bins due to free-convection currents in tropical field trials (Gough et al. 1987b, Uiso et al. 1990). Similar cases have been reported by grain storage managers in Brazil for different types of storage structures without grain ventilation (Bronzatti et al. 1992, Cordeiro 1993, Pascoali 1993) and for other humid tropical regions (Griffiths 1981, Covanich 1988). In addition, there have been reports in North and South hemispheres about the formation of thermal gradients along the north-south axis that are great enough to drive moisture horizontally along this axis (Gough et al. 1987b, Buschermohle et al. 1989).

An approximate analysis of heat transfer by convection and conduction showed that for small cereal grains such as wheat, heat transfer is dominated by conduction, but for larger particles the effect of convection is more important (Smith and Sokhansanj 1990b). Khankari et al. (1993) also showed that heat transfer in wheat and corn is mainly governed by conduction.

Analytical and numerical models have been derived to predict one-dimensional (Muir 1970, Converse et al. 1973, Yaciuk et al. 1975, Lo et al. 1975, White 1988, Bala et al. 1990), two-dimensional (Muir et al. 1980, Chang et al. 1993, Abbouda et al. 1992a), and three-dimensional (Bell 1978, Alagusundaram et al. 1991) heat transfer in grain bulks based on heat conduction only.

Muir et al. (1980) included heat transfer by free-convection in their model but it did not improve the temperature prediction for stored wheat. The inclusion of free convection and heat generation in the model of Muir et al. (1980) used for predicting temperatures of stored milo, however, improved the accuracy of predictions for 1 year of storage without ventilation (Abbouda et al. 1992a). Unlike the model of Muir et al. (1980), the model developed by Chang et al. (1993) can be used to predict grain temperatures with and without aeration and the predicted and experimental results are in close agreement for a test period of 32 mo (standard error of estimate between 0.9 and 1.8°C).

The results of a computer model to predict two-dimensional heat transfer based on free-convection were similar to previouly published experimental results for wheat and soybeans (Dona and Stewart 1988).

Finite difference has been the main numerical method used to solve the partial differential equations but recently the finite element method has been used more frequently (Alagusunduram et al. 1990). Most of these models have been validated with experimental data. The model of Alagusundaram et al. (1990), which was solved using the finite element method, provided good accuracy for predicting temperature distributions in a grain storage bin without ventilation. The model can be used for any shape of storage structure and at any location for which hourly weather data including ambient air temperature, wind velocity, and solar radiation are known.

There are several mathematical models to predict two-dimensional (Nguyen 1986, Smith and Sokhansanj 1990a, Freer et al. 1990) and three-dimensional (Singh and Thorpe 1993) heat and mass transfer in grain bulks assuming free convection. Other numerical models have been presented to predict one-dimensional (Pixton and Griffiths 1971, Thorpe 1981) and two-dimensional (Thorpe et al. 1991a and 1991b, Obaldo et al. 1991) moisture transfer in grain bulks assuming moisture movement by vapor diffusion. Also, models have been developed to predict two-dimensional (Khankari et al. 1993) and three-dimensional (Singh et al. 1993) heat and mass transfer including both free convection and vapor diffusion phenomena.

Most researchers agree that moisture migration in unventilated bulks is transferred mainly by free-convection caused by temperature gradients in non-ventilated grain bulks (Muir 1973, Stewart 1975, Griffiths 1981, Smith and Sokhansanj 1990a). It has been shown analytically that moisture flows much slower by diffusion than by free convection, convective transport of moisture is always present, and convective heat transfer is important if the resistance to airflow is low enough and if the radius of the storage bin is approximately equal to the height of the bin (Smith and Sokhansanj 1990a). It has also been determined, both experimentally and theoretically, that moisture migration in wheat is mainly by diffusion whereas the effect of free convection is more important in corn (Khankari et al. 1993).

The mathematical model of Singh and Thorpe (1993), which can be used to predict free convective flow in grain storage systems of any shape, was applied to predict moisture content, temperature, movement of the intergranular air, dry matter loss, and pesticide decay for corn stored in a bunker-type store. The highest dry matter loss due to microorganism activity over a 90-d storage period predicted by their model occurred in the peak region and this was in agreement with practical observations in commercial grain storages.

There are also several works which present water vapor diffusion as the mechanism driving the moisture migration through non-isothermal grain bulks (Pixton and Griffiths 1971, Thorpe 1981, Thorpe 1982, Thorpe et al. 1991a, 1991b, Obaldo et al. 1991, Abbouda et al. 1992b).

Longstaff and Banks (1987) presented a mathematical model to predict the temperature fluctuations in the region within 40 cm of the upper surface of grain bulks. This model, based on one-dimensional convective and conductive heat transfer, was solved using the finite difference method. This model together with the one given by Bell (1978) can be used to predict the mean temperature in the head space of any type of grain storage structure, type of grain, and ambient conditions.

3.5. Grain Deterioration Models

Grain deterioration depends on many variables such as moisture content, temperature, time, mechanical damage, grain type and variety, grain history, species and amount of initial contamination by microflora. Grain deterioration is the most important variable to be predicted because all recommendations of airflow rates and fan control methods are based on its maximum value. At present it is not possible to calculate the exact quality parameters such as milling and baking quality, germination, and fat acidity values as a function of grain storage conditions. Deterioration predicted by empirical mathematical models give, however, an indication of quality changes and trends of spoilage of stored wheat under aeration (Sanderson et al. 1989).

To determine the best airflow rates and fan-control strategies to aerate grain stored in a specific geographical location it is necessary to predict the allowable safe storage time of the grain as a function of grain moisture content, temperature, and time using hourly weather data collected for several years.

Lissik and Latif (1986) developed a model to predict two-dimensional heat and mass movement within a grain bulk without aeration as a result of mould respiration. The model was solved using the finite difference method. The results indicated that although the grain temperature and moisture changes were relatively slow, the effects of temperature due to localized spoilage were considered important for the whole bin, but the amount of moisture produced during spoilage could be neglected. The heat removal by aeration is 10^3 to 10^5 times greater than heat generation due to respiration of grain and associated storage fungi under airflow rates of about 1 $L \cdot s^{-1} \cdot m^{-3}$ (Lissik 1986). Heat and moisture generation in dry bulks of intermittently aerated grain may be neglected considering the slowness of the process and the rate of heat removal by aeration using normal aeration rates.

Mathematical models to quantify grain deterioration based on the appearance of visible mould (Fraser and Muir 1981, Bowden et al. 1983, Sanderson et al. 1989) tend to underestimate the allowed storage time (Brook 1987, Sanderson et al. 1989) while the models based on dry matter decomposition and CO_2 production (Saul and Lind 1958, Steele et al. 1969, Saul 1970, Brooker and Duggal 1982) tend to over estimate the allowed storage time (Brook 1987). The deterioration model of Fraser and Muir (1981) predicts deterioration trends which compare favourably with trends in seed germination and fat acidity values (Sanderson et al. 1989).

Models based on visible mould provide a safety margin in the design of near-ambient ventilation systems (Brook 1987, Nellist 1988, Sanderson et al. 1989). The models based on dry matter decomposition, however, can be generalized for other types of grain and might provide a more quantitative means of defining storage life (Brook 1987). The generalization of the dry matter decomposition models is based on the fact that all cereal grains appear to be subject to the growth of the same storage mould species (Nash 1978, Busta et al. 1980).

3.6. Summary

The literature review identified the following major problems:

1. A lack of knowledge about the airflow rates, air-temperature increments, and fan control methods required to preserve the quality of aerated wheat stored in tropical and subtropical regions;

2. No accurate thin-layer drying and wetting equations were available for wheat;

3. No reliable mathematical model had been presented to simulate forced convection in wheat stored under the warm, humid tropical and subtropical climates; and

4. Information about the relative importance of several variables in non-equilibrium mathematical models for simulating aeration of stored wheat was not available.

Consequently, research reported in the next sections was devoted to solving these problems.

4. MATERIALS AND METHODS

4.1. Thin-layer Drying and Wetting Equations

4.1.1. Grain conditioning and experimental design

Experimental tests were conducted to obtain basic data needed for determining thin-layer drying and wetting equations to be used in a non-equilibrium mathematical model to simulate forced convection through deep beds of wheat. The experimental data of thin-layer drying and wetting were obtained by exposing thin-layers of wheat kernels to constant airflows, temperatures, and relative humidities.

The ranges of moisture content and air conditions were selected to generate basic data for determining thin-layer drying and wetting equations that could be used to develop mathematical models to simulate aeration of stored wheat in tropical and sub-tropical climates. The experiment was designed to have wetting for two-thirds of the tests.

Canada Hard Red Spring Wheat (*Triticum aestivum* L., cv 'Katepwa') harvested in August 1991 was used in this research.

The initial moisture content ranged from 12.2 to 13.6% (all reported moisture content are on a wet mass basis except where specified otherwise). The samples were conditioned to three moisture contents (9.2, 13.0, and 16.7%). The average air temperature and relative humidity used for conditioning the moisture of the samples were 35°C and 20% for drying and 27°C and 90% for wetting and the average airflow was 0.17 $m^3 \cdot s^{-1} \cdot m^{-2}$. The grain samples at 9.2 and 13.0% were stored at 4°C and the sample at 16.7% was stored at 0°C during the 4-mo test period. Four temperatures and three relative humidities were used (Table 4.1). Minimum average temperatures below 7.6°C were not used due to limitations of the air conditioning unit. The average air velocities were 0.04, 0.12, and 0.25 $m \cdot s^{-1}$.

Table 4.1. Average temperatures and relative humidities of the inlet air during the thin-layer drying and wetting tests

Temperature (°C)	Relative Humidity (%)		
7.6	69	80	87
15.1	52	75	90
25.0	38	70	92
35.1	28	66	85

4.1.2. Experimental equipment and procedure

The equipment (Fig. 4.1) consisted of a chamber with nine separated tray sections ventilated with air at approximately the same temperature and relative humidity in each section. The chamber was connected to a Climate-Lab-AA (C-L-AA) unit (Parameter Generation and Control, Inc., Black Mountain, NC) which provided constant air temperature, relative humidity, and airflow. A return-air duct recirculated the exhaust air to the C-L-AA unit. The conditioning chamber and transitions from the chamber to the ducts were constructed from wooden-particle boards 12.7-mm thick and surfaced with non-absorbing melamine. The chamber and transitions were thermally insulated with extruded polystyrene 50.8-mm thick. All joints were calked to prevent leaking. The ducts were thermally insulated with fibre-glass, 76.2-mm thick.

Valves located in each tray section controlled air velocities. The air velocities were measured between the air valves and the trays at nine points for each tray section using a hot-wire anemometer (TA400 Airflow Developments Ltd, Mississauga, Ontario) with a precision of $\pm 0.01\ m \cdot s^{-1}$. For each test, the air velocity was measured twice. The total airflow exhausted from

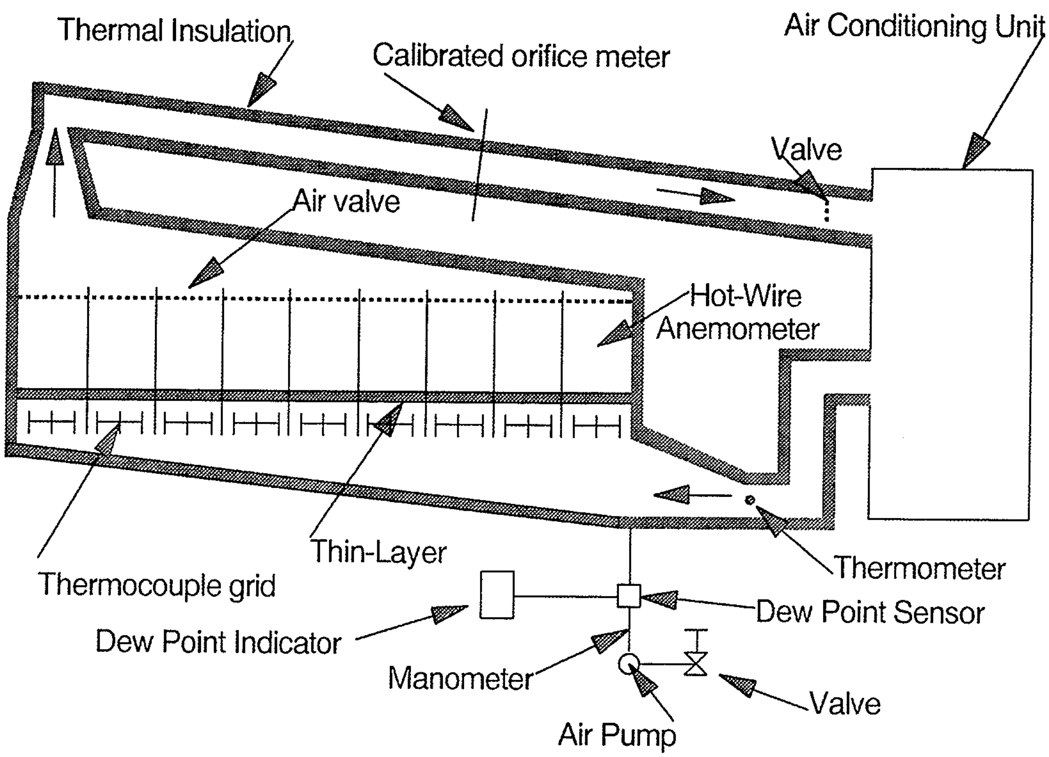

Fig. 4.1. Experimental equipment for thin-layer drying and wetting tests

the chamber was calculated based on measurements of the differential pressure drop across a calibrated orifice meter (ISO 1983). The measurements of pressure drop were done twice per test. A micromanometer (Autozero MP6KSR Air Instrument Resources Ltd, Chalgrove, Oxford, England) with a precision of ±1 Pa was used to measure the differential pressure across the orifice meter. The air velocities at different conditions of temperature and relative humidity in each tray section, were corrected by multiplying them by the total airflow determined using the calibrated orifice method and dividing them by the total airflow determined using the hot-wire anemometer method.

The average air temperature for each tray section was sensed by nine type-T thermocouples arranged in parallel (Benedict 1984). The thermocouples were installed 25-mm below the grain trays. The air temperatures were read by a digital thermometer (Pronto Plus Thermo-Electric Instruments, Saddle Brook, NJ) with a precision of ±0.1°C connected to a manual switch box. The thermocouples were calibrated with precision thermometers to ± 0.1°C in an ice bath placed in a vacuum-bottle and in boiling water. Dew point temperature was measured at the air inlet section using a Hygro-M1 dew-point humidity sensor (General Eastern Instruments Inc., Watertown, MA) with a precision of ±0.1°C. An aquarium type air pump sucked the air from five collecting points in the air inlet section through the dew point sensor. The air temperature and dew point temperature were measured at least 10 times per test. The air relative humidity for each thin layer was calculated based on the average temperature measured below the tray and the dew point temperature at the air entrance.

The sample holders were made of square, extruded-aluminum frames with aluminum screens 212 x 212 mm to hold the grains. The aluminum screens were held in place by compressing them with plastic splinters. Thin-layers of grain one kernel deep were prepared by distributing uniformly the grain over the aluminum screens. The grain and tray masses were measured using an electronic balance (Mettler PE1600 Mettler Instruments Corporation, Greifensee, Zürich, Switzerland) with a precision of ± 0.01 g. The initial grain mass was measured before placing the sample trays in the chamber. The equipment was turned on at least 20 h before placing the sample trays in the chamber. During the tests the trays were weighed outside the chamber. The tests at temperatures and relative humidities of 35.1°C and 28% and 7.6°C and 87% were repeated three and four times, respectively. The other tests were not repeated. In one test at 7.6°C and 87% and in another at 35.1°C and 28% relative humidity the grain samples were weighed only twice during the entire test period to determine the effect of the weighing time on the thin-layer drying and wetting rates. The tests at temperatures and relative humidities of 35.1°C and 28% and 7.6°C and 87% were replicated to determine the repeatibility of the experiments. The dry mass of the wheat samples was determined by oven (Thermolyne Mechanical Oven, Thermolyne Corporation, Dubuque, IA) drying the wheat at 130 °C for 19 h (ASAE 1993a) at the end of each experiment using triplicate samples.

The air temperature and relative humidity for each test were randomly selected from the values showed in Table 4.1. Three grain samples having the same initial moisture content were randomly placed in the sample trays at three air velocities.

4.1.3. Equilibrium moisture content for desorption and adsorption

Values of equilibrium moisture content (EMC) for desorption and adsorption by wheat were obtained by fitting Page's equation (Eq. 3.1, Sec. 3.3) using non-linear regression (SAS 1985) to each of the experimental data sets (43 for drying and 88 for wetting) obtained in 15 experimental tests (Appendix 1) and letting EMC be a third parameter. Jayas et al. (1988, 1991) suggested this method to determine the values of EMC . On average, 11 experimental points were used for each regression. The EMC values determined using this procedure are not true EMC but asymptotic values which give the best fit of the semi-empirical equations to the drying and wetting experimental data. These values of EMC have been named "dynamic EMC" (Simmonds et al. 1953, Westerman et al. 1973, Watson and Bhargava 1974). The concept of a dynamic EMC has been proven wrong at least for alfalfa wafers and the definition of such a quantity during the drying of other biological products is doubtful (Bakker-Arkema and Hall 1965). The asymptotic values of EMC, however, are important to improve the accuracy of the predictions of moisture content because they simulate the actual condition of equilibrium between air and grain that occurs during grain aeration.

A two step procedure was used to select EMC equations for desorption and adsorption. First, the best equations among four commonly used EMC equations (modified Henderson (Thompson et al. 1968), modified Chung-Pfost (Pfost et al. 1976b), modified Halsey (Iglesias and Chirife 1976), and modified Oswin (Chen and Morey 1989a)) were selected. The choice of the best equation was based on the average and maximum absolute and relative errors and on the standard error of moisture content. Then, the best EMC equations were further modified to obtain the final EMC equations. In addition, the best three-parameter equation which could be used for both desorption and adsorption by wheat was selected. The parameters of the EMC equations were determined by non-linear regression (SAS 1985). The average relative percent error (PE) and standard error of moisture content (SM) were defined as:

$$PE = \frac{100}{N} \sum_{i=1}^{N} \frac{|Y_i - YC_i|}{Y_i} \tag{4.1}$$

$$SM = \sqrt{\frac{\sum_{i=1}^{N} (Y_i - YC_i)^2}{DF}} \tag{4.2}$$

where: Y_i = measured moisture content (%, wb),

YC_i = estimated moisture content (%, wb),

N = number of experimental points,

DF = degrees of freedom of the regression model (N minus number of parameters in the model).

4.1.4. Mathematical modeling

Page's equation (Eq. 3.1, Sec. 3.3) and the diffusion equation (Eqs. 3.2 and 3.3, Sec. 3.3) were used to predict thin-layer drying and wetting of wheat. For Page's equation the parameters K and N for drying and K' and N' for wetting were determined by linear regression (Quattro Pro 4.0 Borland International, Inc.) and non-linear regression (SAS 1985) using the EMC predicted by the best EMC equations. The regressions were run using experimental data for each of the experimental data sets (42 for drying and 87 for wetting). These parameters were then correlated to the measured temperatures, relative humidities, initial moisture contents, and air velocities. Linear mathematical models were tested to determine this dependency but the correlation coefficients were not good even when using equations with more than 26 coefficients. Thus, I proposed new, non-linear, semi-empirical models to describe the parameters K and N for drying and K' and N' for wetting in Page's equation (Eq. 3.1, Sec. 3.3) because they showed small errors and used less coefficients. In addition, one attempt was made to find a simple mathematical model that could be used for both thin-layer drying and wetting of wheat.

For the diffusion equation (Eq. 3.2, Sec. 3.3) the parameters a_1 and a_2 of the modified diffusivity coefficient (Eq. 3.3, Sec. 3.3) were also determined by non-linear regression (SAS 1985).

4.2. Selection of Geographical Locations for the Simulations

The selection of tropical and subtropical locations for this study was based mainly on the availability of weather data from Brazil, and on the grain production level, and bulk storage capacities in each of the Brazilian states. A weather database for 1961 to 1970 for eight Brazilian state capitals (Belo Horizonte, Minas Gerais State; Campo Grande, Mato Grosso do Sul State; Cuiabá, Mato Grosso State; Curitiba, Paraná State; Florianópolis, Santa Catarina State; Goiânia, Goiás State; Porto Alegre, Rio Grande do Sul State; and São Paulo, São Paulo State) consisting of hourly dry-bulb and wet-bulb air temperatures and barometric pressures was used for the simulations (Table 4.2).

Campo Grande, Cuiabá, and Goiânia are classified as tropical climates because the average for every month is above 18°C. Belo Horizonte, Curitiba, Florianópolis, Porto Alegre, and São Paulo are classified as subtropical climates because they have at least 1 mo with average temperatures below 18°C and at least 8 mo averaging above 10°C (Lydolph 1985). The average temperature and relative humidity for 10 years of weather data indicate that Curitiba was the coldest and wettest location and Cuiabá was the warmest and dryest location among the eight Brazilian locations (Table 4.2).

The eight states selected for this research have together about 97% of the total Brazilian bulk storage capacity (Table 4.3). Paraná and Rio Grande do Sul States have 52.5 and 37.5% of the total Brazilian wheat production and 22.9 and 27.6% of the total Brazilian bulk storage

Table 4.2. Average weather conditions calculated for selected Brazilian locations from 1961 to 1970[1]

Location	Temperature (°C)	Relative Humidity (%)	Barometric Pressure (kPa)	South Latitude	W. Gr. Latitude[2]	Altitude (m)
Belo Horizonte	21.0	75.5	92.7	19°56'	43°56'	850
Campo Grande[3]	23.0	76.4	94.8	20°28'	54°40'	560
Cuiabá[4]	26.5	69.4	99.0	15°33'	56°07'	151
Curitiba	16.5	85.8	91.4	25°26'	49°16'	924
Florianópolis	20.5	82.7	101.5	27°35'	48°34'	18
Goiânia[5]	22.4	75.4	93.0	16°41'	49°17'	729
Porto Alegre	19.4	80.4	101.5	30°01'	51°13'	47
São Paulo	18.7	80.4	92.6	23°30'	46°37'	792

[1]Original weather data was obtained from Instituo de Aeronáutica e Espaço
[2]W. Gr. = West of Greenwich
[3]Year period: 1961 - 1969.
[4]Year period: 1963 - 1970.
[5]Year period: 1961 - 1967.

capacity, respectively (Table 4.3). Weather data from Curitiba were used for most of the simulations in the comparison of models and sensitivity analyses because based on 1993/94 statistics Paraná State has the highest wheat production, and the second highest grain production and bulk storage capacity among all Brazilian States.

Cuiabá, Goiânia, and Porto Alegre were included in the comparison of mathematical models and Campo Grande and Cuiabá were included in the sensitivity analysis to determine the effects of climatic conditions. In addition, a weather database from 1953 to 1992 for Winnipeg, Manitoba consisting of hourly dry-bulb temperatures and relative humidities, obtained from the

Environment Canada, was used in simulations to analyse the effects of a temperate climate on comparison of models and sensitivity analyses.

Table 4.3. Production of rice, corn, soybean, and wheat in 1993/94 and bulk storage capacity for Brazilian states

State	Grain Production[1] (kt)				Total Production (kt)	Bulk Storage Capacity[2] (kt)
	Rice	Corn	Soybean	Wheat		
Goiás	510	2835	2381	8	5734	7138
Mato Grosso	916	1027	5079	0	7022	4699
Mato Grosso do Sul	254	1105	2440	74	3873	3619
Minas Gerais	659	3954	1261	15	5889	2055
Paraná	236	8361	5275	1214	15086	10780
Rio Grande do Sul	4560	4390	5597	867	15414	12999
Santa Catarina	714	3435	562	84	4795	1590
São Paulo	259	4185	1265	50	5759	2815
Others	3530	2672	1222	0	7424	1455
Total	10780	32822	25082	2312	70996	47150

[1]Source: CONAB (1994a) — estimate based on seeded area and grain productivity.
[2]Source: CONAB (1994b) — only for the storage units registered at the Brazilian Companhia Nacional de Abastecimento (Nacional Supply Company of Brazil) - CONAB which corresponds to about 90% of Brazilian bulk storage capacity. Storage at farm level (about 5% of total Brazilian storage capacity) is not included.

4.3. Grain Deterioration Model

The mathematical model of grain deterioration presented by Fraser and Muir (1981) and used by Metzger and Muir (1983b) was used to predict the allowable safe storage times for wheat as a function of grain moisture content, temperature, and time. This model predicts maximum storage times for wheat before germination drops by 5% or visible mould appears. A numerical procedure to calculate the allowable storage time elapsed (ASTE) for each time interval was used by Sanderson et al. (1989). In that procedure, the deterioration model was used to calculate the allowable storage time at each time interval based on the predicted temperature and moisture content of each spatial element. The proportion of allowable storage time elapsed during the time interval is the length of the time interval divided by the allowable storage time. These decimal fractions for all preceding time increments were added to obtain an estimate of the total proportion of allowable storage time elapsed (ASTE).

Sanderson et al. (1989) speculate that the deterioration model of Fraser and Muir (1981) has a high factor of safety because it predicts spoilage (ASTE = 1.0) before measured seed-quality decreases excessively. Therefore, these researchers advise the use of an ASTE of 1.5 to indicate unacceptable deterioration. Also, according to these authors, the deterioration model predicts deterioration trends which compare favourably with trends in seed germination and fat acidity values.

4.4. Year of Simulation and Total Grain Depth Used in the Comparison of Models and Sensitivity Analysis

4.4.1. Brazilian locations

The median year (1966) and the worst year (1969) from 1961 to 1970 for Curitiba were selected on the basis of the maximum ASTE simulated for any grain layer when ventilating the stored wheat from 6:00 to 12:00 each day. The maximum ASTE for each year was determined by simulating aeration of stored wheat for 10 years of weather data using the equilibrium model of Metzger and Muir (1983b), 13% initial grain moisture content, 30°C initial grain temperature, 1 $L{\cdot}s^{-1}{\cdot}m^{-3}$ airflow rate, 1°C fan temperature rise, and 5.6 m grain depth. The aeration period from 6:00 to 12:00 was chosen because it gave less grain deterioration compared with 12:00-18:00, 18:00-24:00, or 0:00-6:00. This agrees with results presented by Sinicio et al. (1991) for the Brazilian city of Sorocaba, São Paulo State. The same ventilation period and initial moisture content and temperature of the grain were used in the comparison of models and sensitivity analyses for other Brazilian locations.

The grain depth was divided into 20 layers: the first grain layers from the bottom were 5, 10, 15, 20, and 25 cm thick and the remaining 15 layers were 32 cm thick. Variable grain layer thicknesses were used in an attempt to detect accurately grain deterioration in the first layers from the bottom, where the ventilation air enters the grain, without need to increase excessively the total number of layers. The grain layer thicknesses were determined according to the minimum amount of spoiled grain required to be detected in the grain bulk. It was important, however, to keep the total number of grain layers as small as possible because the computer execution time increased proportionally to this number.

In all the simulations to determine the median and the worst years the maximum grain deterioration occurred in the first layer from the bottom. Also the deterioration in the bottom 1 m was always greater than the average grain deterioration for the whole bulk. Therefore, the grain depth for the comparison of models was reduced to 1 m for the linear airflow distribution. The equilibrium model of Metzger and Muir (1983b) was used for determining the median and the worst years.

4.4.2. Winnipeg

The median year (1979) and the worst year (1963) from 1953 to 1992 for Winnipeg were selected on the basis of the maximum ASTE simulated for any grain layer when ventilating the stored wheat from 0:00 to 6:00 during 1 Sept. to 30 Nov. The maximum ASTE for each year was determined by simulating aeration of stored wheat for 40 years (1953 - 1992) of weather data using the equilibrium model of Metzger and Muir (1983b), 15% initial moisture content, 30°C initial grain temperature, 1 $L \cdot s^{-1} \cdot m^{-3}$ airflow rate, 1°C fan temperature rise, and 5.7 m grain depth. The grain depth was divided into 20 layers: the first grain layers from the bottom were 5, 10, 15, 20, and 25 cm thick and the remaining 15 layers were 33 cm thick. In all the simulations to determine the median and the worst years the maximum grain deterioration occurred in the top layers. Therefore, the grain depth selected for the comparison of models and the sensitivity analysis was 5.7 m for the linear airflow distribution.

Metzger and Muir (1983a) recommended an airflow rate of 1.0 $L \cdot s^{-1} \cdot m^{-3}$ and ventilation time of 0:00 to 6:00 for four Canadian Prairie locations including Winnipeg. They also compared this ventilation time with 6:00 - 12:00, 12:00 -18:00, or 18:00 -24:00, and concluded that this ventilation time provided effective grain quality control, reduced energy use, and minimized over drying.

The grain deterioration was highest during the worst year compared with the median year because 1963 was warmer than 1979 (Table 4.4) and most deterioration occurred primarily due to the grain temperature. Normally for the first layer from the bottom, where the ventilation air enters the grain, the predicted grain moisture content was the highest and the temperature was the lowest. Therefore, the effect of grain temperature was more important than that of grain moisture content for aeration of stored wheat under Winnipeg weather conditions.

Table 4.4. Average weather conditions during the worst (1963) and median (1979) years from 1953 to 1992 for aerating stored wheat in Winnipeg, Canada from 1 Sept. to 30 Nov. in each year from 1953 to 1992[1]

Year	Month	Temperature (°C)			Relative Humidity (%)	
		Mean[2]	Minimum[3]	Maximum[3]	Minimum[3]	Maximum[3]
1963	9	15	7	22	51	86
	10	13	6	20	50	78
	11	-2	-7	4	68	80
1979	9	13	7	19	49	90
	10	4	-1	10	51	90
	11	-5	-9	-1	70	90

[1]Weather data obtained from Environment Canada
[2] Daily mean temperature for 24 h.
[3] Daily minimum and maximum temperatures and relative humidities.

4.5. Comparison of Equilibrium and Non-Equilibrium Mathematical Models

4.5.1. Heat and mass transfer during forced convection

The equilibrium model of Metzger and Muir (1983b) was compared with the non-equilibrium model developed by Thompson et al. (1968). The non-equilibrium model was modified to include the thin-layer drying and wetting equations and EMC desorption and adsorption equations for wheat developed for this research (Sinicio et al. 1994). Equilibrium temperature (T_e) of the wheat and air was calculated by a heat balance between air and grain before calculating the moisture exchange using the equations presented by Thompson et al. (1968). Equilibrium relative humidity of the air (ERH) was calculated using the moisture content of the air and T_e. Equilibrium moisture contents for desorption and adsorption by wheat were calculated using T_e and ERH. Drying was assumed when desorption EMC was lower than the grain moisture content. Wetting was assumed when adsorption EMC was higher than the grain moisture content. No moisture exchange, i.e. hysteresis, was assumed when neither drying or wetting was possible.

The equilibrium model of Metzger and Muir (1983b), however, was used when ERH was equal to or higher than 95% due to the limitations of the EMC equations to predict above this limit and to predict vapor condensation although this event normally does not occur during aeration.

The net heat of desorption and adsorption, i.e. the amount by which the latent heat of vaporization or condensation, respectively, differs from that of free water, were calculated using the latent heat of vaporization equation (Eq. 4.3) and latent heat of condensation equations (Eqs. 4.4 and 4.5) which were based on the EMC desorption and adsorption equations presented by Sinicio et al. (1994):

$$\frac{L}{L'} = 1 + 3.23 \exp\left(-20.25M\right) \tag{4.3}$$

$$\frac{L}{L'} = 1 + 39.34 \exp\left(-43.63M\right) \qquad M < 0.2048 \tag{4.4}$$

$$\frac{L}{L'} = 1 \qquad M \geq 0.2048 \tag{4.5}$$

where: L = latent heat of vaporization or condensation of water in wheat ($kJ \cdot kg^{-1}$),

L' = latent heat of vaporization or condensation of free water ($kJ \cdot kg^{-1}$),

M = grain moisture content (decimal, db).

The latent heat of vaporization and condensation equations were determined using the method presented by Cenkowski et al. (1992).

For both equilibrium and non-equilibrium models the bulk density was calculated as a function of grain moisture content (Nelson 1980) for each grain layer during the ventilation period. Therefore, grain shrinkage was calculated and a constant dry mass was used in each grain layer throughout the simulation.

4.5.2. Uncertainties in predicting grain moisture content, temperature, and deterioration

The uncertainty in the measurement of grain moisture content was assumed to be ±0.20 percentage points (ASAE 1993a) and the uncertainty in the measurement of intergranular air temperatures using thermocouples was assumed to be ±0.5°C (Benedict 1984, Omega 1986) at 95% confidence level. The uncertainty to predict ASTE was determined by conducting an error analysis (Kline and McClintock 1953, Huggins 1991) of the deterioration model (Appendix 2) developed by Fraser and Muir (1981). The uncertainties in measuring grain moisture content and temperature were used to determine the uncertainty in predicting ASTE. The uncertainties in determining the coefficients of the deterioration model were calculated based on the standard deviations for the coefficients calculated by the linear regression of the deterioration data. A 95% confidence level was used for all variables and coefficients.

The uncertainty in predicting ASTE using the deterioration model of Fraser and Muir (1981) as a function of the uncertainties in measuring grain moisture content and temperature was ±12%. The uncertainty in predicting ASTE when the uncertainties in estimating the model's coefficients were included was much higher and depended on the grain moisture content and temperature (Table 4.5). Therefore, the uncertainty in predicting ASTE when comparing the equilibrium and non-equilibrium models was assumed to be ±30% which was less than the estimated minimum (Table 4.5). Thus, any absolute deviations in predicted ASTE that were less than 30% was not considered significant at the 95% confidence level in the comparison of mathematical models and sensitivity analyses.

Table 4.5. Uncertainties (%) in the prediction of allowable storage time elapsed (ASTE) for wheat determined at the 95% confidence level based on an error analysis of the deterioration model of Frazer and Muir (1981)

Moisture Content,	Temperature, °C		
%, wb	5	15	25
11	±32	±33	±35
13	±34	±35	±36
15	±36	±37	±38
17	±38	±39	±41

A high uncertainty in predicting ASTE can be expected because the dependance of wheat deterioration on variables such as mechanical damage, grain variety and history, and type and amount of initial contamination by microflora. The deterioration model of Fraser and Muir (1981) however, is the only one developed for wheat.

4.5.3. Comparison of equilibrium and non-equilibrium models for Brazilian locations

The grain deterioration (ASTE), calculated as a function of moisture contents and temperatures predicted by the equilibrium and non-equilibrium mathematical models for each grain layer, was compared at the end of each month for 12 mo of storage starting on 1 Dec. for various sets of input conditions. Most simulations with linear airflow were run using a total grain depth of 1 m to simulate the grain conditions in the bottom of a bin with a fully perforated floor. The grain depth for the non-linear airflow case was set at 6 m (actual grain depths vary from 15 to 30 m) because the main concern was to simulate the grain deterioration in the region close to the aeration ducts of large horizontal grain storages. The airflow rates used for linear airflow (5.6 and 27.8 $L \cdot s^{-1} \cdot m^{-3}$), however, were approximately the same as those used for non-linear airflow (5.5 and 27.3 $L \cdot s^{-1} \cdot m^{-3}$). The grain layer thickness used for both linear and non-linear airflow distribution was determined by dividing the total grain depth (1 m for linear airflow and 6 m for non-linear airflow distributions) into 20 layers of equal thicknesses.

Comparisons of grain moisture contents and temperatures were not necessary in the comparison of models because ASTE is a function of these variables and storage time. Grain deterioration is the major variable used when making decisions on selecting and optimizing aeration systems. The grain moisture content normally is kept as constant as possible during the storage period and the grain temperature is reduced as much as the weather conditions permit by using intermittent aeration. The moisture content and temperature of grain layers at the top surface and near the air entrance, however, can vary much more than the average conditions of the grain bulk. The variations of grain moisture content and temperature in these grain layers depend on variables such as ventilation schedule, weather conditions, amount of head space ventilation, and storage design. Grain deterioration calculated as a function of grain moisture contents and temperatures, which are predicted by the heat and mass transfer mathematical models, accumulates the effects of all these variations over the storage period. Therefore, the comparison of predicted allowable storage time elapsed is a practical method of comparing the performance of equilibrium and non-equilibrium mathematical models to simulate aeration of stored grain.

The deviation in ASTE between equilibrium and non-equilibrium models for each grain layer at any time was calculated as:

$$DC_{ASTE} = (1 - \frac{ASTE_{neq}}{ASTE_{eq}}) \; 100\% \qquad \textbf{(4.6)}$$

where: DC_{ASTE} = deviation between allowable storage times elapsed (ASTE) predicted by equilibrium and non-equilibrium models in the comparison of models (%),

$ASTE_{neq}$ = ASTE predicted by the non-equilibrium model (decimal),

$ASTE_{eq}$ = ASTE predicted by the equilibrium model (decimal).

4.5.4. Comparison of equilibrium and non-equilibrium models for Winnipeg

Grain deterioration (ASTE), calculated as a function of moisture contents and temperatures predicted by the equilibrium and non-equilibrium mathematical models, was compared for 3 mo of storage starting on 1 Sept. The same ventilation time, aeration period, total grain depth, and initial moisture content and temperature of the grain used to determine the median and the worst year for Winnipeg (Sec. 4.4.2) were used in the comparison of models and sensitivity analyses. The grain layer thickness was also determined by dividing the total grain depth (5.7 m for both linear and non-linear airflow distributions) into 20 layers of equal thicknesses.

4.6. Sensitivity Analyses of the Non-Equilibrium Mathematical Model

4.6.1. Variables and uncertainty in the measurement or calculation of the variables for Brazilian locations

The uncertainties of the variables associated with random errors (Table 4.6) were estimated at the 95% confidence level based on the standard deviations to measure or calculate these variables at the average grain moisture content (14.5%) and temperature (18.7°C) during the aeration period (1 Dec. 1965 - 30 Nov. 1966) in Curitiba. Therefore, the uncertainties of the variables (Table 4.6) were estimated by multiplying 1.96 (t=1.96 in the Student's test at α=0.05) times the estimated standard deviations to measure or calculate these variables and assuming a normal distribution of errors.

Table 4.6. Uncertainties (95% confidence level) in the measurement or calculation of the variables used in the sensitivity analysis for aerating wheat at an average moisture content of 14.5% and temperature of 18.7°C during 1 Dec. 1965 to 30 Nov. 1966 in Curitiba, Brazil

Variable	Uncertainty		References
	Estimated	Used	
Fan temperature rise	±0.5°C	±0.5°C	Benedict (1984), Omega (1986)
Wheat bulk density	±2.5%	±6%	Browne (1962), Muir and Sinha (1988), Nelson (1980), Jayas et al. (1992)
Wheat specific heat	±5.3%	±6%	Mohsenin (1980), Muir and Viravanichai (1972), Singh (1988)
EMC desorption equation	±7.0%	±6%	ASAE (1993b)
EMC adsorption equation	±7.0%	±6%	ASAE (1993b)
Thin-layer drying equation			
. parameter K	±56%	±50%	Sinicio et al. (1994), Jayas and Sokhansanj (1986)
. parameter N	±31%	±30%	
Thin-layer wetting equation			
. parameter K'	±138%	±90%	Sinicio et al. (1994), Misra and Brooker (1980)
. parameter N'	±10%	±10%	
Airflow	±15%	±6%	Metzger et al. (1981)

The uncertainty in measuring temperature using thermocouples can be ±0.5°C or higher (Benedict 1984, Omega 1986). The uncertainties estimated for bulk density (±2.5%) and specific heat (±5.3%) were increased to ±6% in an attempt to represent all wheat varieties. The standard error given by the Chung equation (ASAE 1993b) was used to determine the uncertainty in the EMC equations for desorption and adsorption by wheat. The uncertainties estimated for the EMC equations were decreased from ±7% to ±6% because other EMC equations such as that developed by Sinicio et al. (1994) for wheat have much less uncertainty (between ±3 and ±5% at moisture content of 14.5%).

Thin-layer drying equations of Sinicio et al. (1994) and Jayas and Sokhansanj (1986) were used to determine the uncertainty in the parameters K and N of the thin-layer drying equation (Eq. 3.1, Sec. 3.3). Thin-layer wetting equations for wheat (Sinicio et al. 1994) and for corn (Misra and Brooker 1980) were used to determine the uncertainty in the parameters K' and N' of Eq. 3.1. The thin-layer wetting equation for shelled corn developed by Misra and Brooker (1980) was used because this equation has been used in simulations of ambient air drying of wheat (Morey et al. 1981) and because no other equation is available for wheat. All uncertainties estimated for the thin-layer equations were rounded except that for the thin-layer wetting equation (parameter K') which was decreased from ±138% to ±90% because one of the thin-layer wetting equations was developed for corn.

Metzger et al. (1981) determined that the static pressures of axial-flow fans published by manufacturers are 15 to 45% higher than the test data. Also, the uncertainties introduced by the air resistance data may add errors to the calculated airflow. Therefore, an aeration fan may present much less airflow than that required by the system. The uncertainty for airflow was assumed to be ±6% to compare with bulk density, specific heat, and EMC desorption and adsorption equations although a deviation of 15% in static pressure would generate a deviation of about 15% in airflow depending on the fan type and performance.

4.6.2. Variables and uncertainty in the measurement or calculation of the variables for Winnipeg

The uncertainties of the variables for Winnipeg (Table 4.7) were also estimated at the 95%

Table 4.7. Uncertainties (95% confidence level) in the measurement or calculation of the variables used in the sensitivity analysis for aerating wheat at an average moisture content of 14.4% and temperature of 10.5°C during 1 Sept. to 30 Nov. 1979 in Winnipeg, Canada

Variable	Uncertainty		References
	Estimated	Used	
Thin-layer drying equation			
. parameter K	±21%	±20%	Sinicio et al. (1994); Jayas and
. parameter N	±32%	±30%	Sokhansanj (1986)
Thin-layer wetting equation			
. parameter K'	±139%	±90%	Sinicio et al. (1994); Misra and Brooker
. parameter N'	±12.9%	±10%	(1980)

confidence level based on the standard errors to measure or calculate the variables used in the sensitivity analysis. The same procedure used for determining the uncertainties of the variables for Brazilian conditions (Table 4.6) was used for Winnipeg except that the uncertainties for the thin-layer drying and wetting equations were estimated at the average moisture content (14.4%) and temperature (10.5°C) of the grain during the aeration period (1 Sept. to 30 Nov. 1979) in Winnipeg. The uncertainties for the parameters K and N of the thin-layer drying equation and K' and N' of the thin-layer wetting equation were estimated using the same method as used for Brazilian locations (Sec. 4.6.1).

4.6.3. Sensitivity analysis for Brazilian locations

The relative importance of each variable in the non-equilibrium model for simulating aeration of stored wheat was determined by adding or subtracting fixed uncertainties from that variable and by calculating the effect of these changes on the predicted grain deterioration. These fixed uncertainties correspond to the uncertainties in the measurement or calculation of each variable (Sec. 4.6.1).

The sensitivity of the non-equilibrium mathematical model relative to different variables was determined by the maximum deviations in ASTE for all grain layers for 1 year of storage. The percent deviation in ASTE for a given change in a variable was calculated as:

$$DS_{ASTE} = \left(1 - \frac{ASTE_c}{ASTE}\right) 100\% \qquad \textbf{(4.7)}$$

where: DS_{ASTE} = deviation of ASTE caused by adding or subtracting uncertainties from one or more variables in the mathematical model (%),

$ASTE_c$ = ASTE predicted by the mathematical model after adding or subtracting an uncertainty from one or more variables (decimal),

ASTE = ASTE predicted by the mathematical model with standard values of variables (decimal).

The sensitivity analysis relative to the grain bulk density was conducted at constant grain mass for two cases: first, assuming that the airflow did not change in proportion to the changes in grain volume; and second, calculating the new airflow for a change in grain volume.

The effect of reducing the air velocity to one-half by doubling the bin area for a constant grain volume and constant airflow per unit volume of grain was also investigated.

The effect of neglecting the net heat of sorption during drying and wetting was investigated in an attempt to simplify the mathematical model because the main objective of grain aeration is to cool the grain bulk at almost constant moisture content. Normally, only small variations in grain moisture content occur because low airflow rates are used in grain aeration (between 1 and 2 $L \cdot s^{-1} \cdot m^{-3}$, Manitoba Agriculture 1987). The net heat of sorption is the amount by which the latent heat of vaporization or condensation of the water in the grain differs from that of free water.

The grain moisture content, temperature, and deterioration were predicted for each grain layer, for 1 year of storage, for various input conditions of airflow, fan temperature rise, initial moisture content and temperature of the grain, and location. The same grain depth and grain layer thicknesses used for comparison of models for Brazilian locations (Sec. 4.5.3) were used in the sensitivity analyses. The effects of year of simulation (median and worst years), geographical location, grain depth, grain layer thickness, initial moisture content and temperature of the grain on the model's sensitivity were investigated.

Sensitivity analyses were also conducted with several variables changed simultaneously with random variation in the increments added to the variables. These increments were varied randomly within the range of uncertainties in the measurement or calculation of each variable (Sec. 4.6.1). The sensitivity analysis with random variations probably simulated a more realistic situation because all thermal and physical properties of the grain are empirical data with associated random errors. Therefore, each time a certain variable X was calculated, with random variation for the increments, the uncertainty associated with that variable was added to it as (Sokhansanj and Jayas 1990):

$$X_c = X\,(1 + z\,\sigma_X) \qquad \textbf{(4.8)}$$

where: X_c = variable after adding the uncertainty in the sensitivity analysis,

X = variable before any change in the sensitivity analysis,

z = random increment with a standard normal-distribution of errors about a zero mean,

σ_X = standard error of the variable X (decimal).

The subroutine GASDEV (Press et al. 1989) was called from the aeration simulation program to generate 100 random standard deviates (z), from which one was chosen randomly to calculate X_c.

The random errors associated with fan temperature rise and airflow were added for each time interval used during the simulations when conducting sensitivity analysis for the interaction of variables with random variation for the increments. The random errors associated with the remaining variables (bulk density, specific heat, EMC and thin-layer equations), however, were added to these variables for each grain layer and time interval.

4.6.4. Sensitivity analysis for Winnipeg

The procedure used in the sensitivity analysis for Brazilian locations (Sec. 4.6.3) was used for Winnipeg except that the maximum deviations in ASTE were determined for 3 mo of storage starting on 1 Sept. Further, the fixed uncertainties added or subtracted from each variable correspond to the uncertainties determined for Winnipeg conditions (Sec. 4.6.2). The same grain depth and grain layer thicknesses used in the comparison of models for Winnipeg (Sec. 4.5.4) were used in the sensitivity analyses.

4.7. Input Data Used in the Comparison of Mathematical Models and Sensitivity Analyses

4.7.1. Input data for Brazilian locations

The recommended moisture content for storing wheat in Brazil is 13% (Puzzi 1986). The standard starting date for storage was set at 1 Dec. because the wheat harvest in Brazil normally occurs during November, December, and January (Canada Grains Council 1994). A 1-h time interval was used to simulate forced convection in the comparison of models and sensitivity analyses for Brazilian locations and Winnipeg.

Standard conditions with linear airflow distribution were selected to be 1 $L \cdot s^{-1} \cdot m^{-3}$ for 5.6 m grain depth and 5.5 m bin diameter (100 t of wheat at 13% moisture content) resulting in an airflow of 0.0056 $m^3 \cdot s^{-1} \cdot m^{-2}$. The standard conditions included a 1°C fan temperature rise and the other aeration conditions were as follows: weather data from Curitiba; fan temperature rise of 1°C; ventilation time of 6:00 to 12:00; airflow of 0.0056 $m^3 \cdot s^{-1} \cdot m^{-2}$; total grain depth of 1 m; grain layer thickness of 5 cm; initial grain moisture content of 13%; initial grain temperature of 30°C; storage period from 1 Dec. 1965 to 30 Nov. 1966; and an offset for hysteresis in the equilibrium relative humidity was not simulated in the equilibrium model.

The air velocity gradient for the non-linear airflow case was determined assuming that the air velocity was inversely proportional to the distance from the bottom of the horizontal storage with a V-shaped bottom (Fig. 4.2). Two air velocities leaving the duct (0.2 and 1.0 $m \cdot s^{-1}$) were tested. The temperature rise of the air as it passed through the fan and ducting was set at 1, 3, or 5°C because axial fans add about 1 to 3°C and centrifugal fans (static pressures of 1.24-3.73 kPa) add about 3 to 5°C due to heat of compression (Noyes 1990). Static pressures from 1500 to 3500 Pa in the aeration duct are normally used in Brazil (Bronzatti et al. 1992, Cordeiro 1993, Pascoali 1993). The static pressures against which fans have to deliver the required airflow correspond to the sum of all resistances caused by the grain, aeration ducts, and transitions.

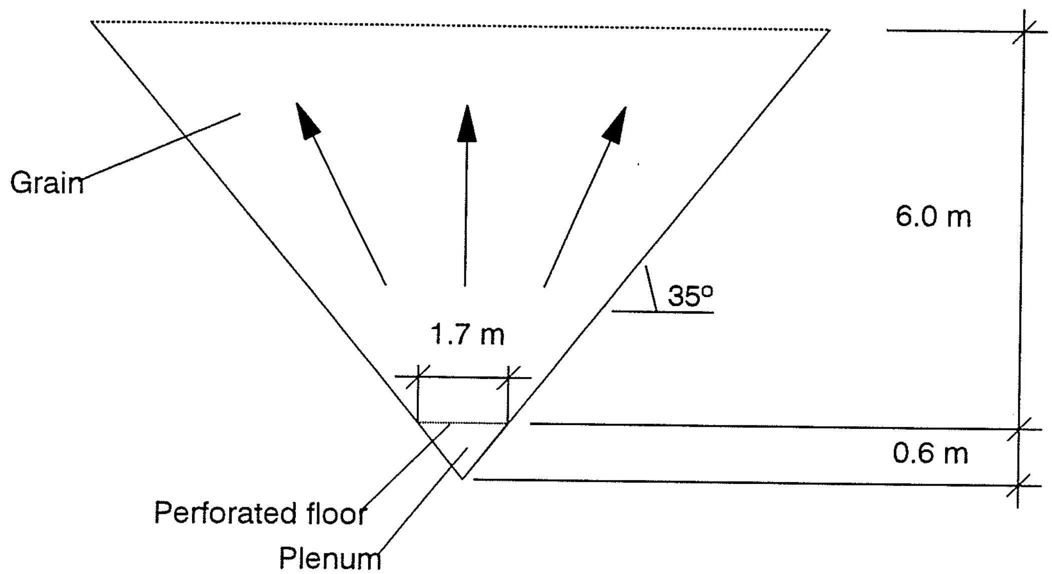

Fig. 4.2. Schema of storage used to simulate grain aeration using non-linear airflow distribution in the comparison of models and sensitivity analyses

4.7.2. Input data for Winnipeg

The initial moisture content of the grain (15%) and starting date (1 Sept.) for Winnipeg were the same as used by Metzger and Muir (1983a) for aeration of wheat stored in the Canadian Prairies.

The standard conditions with linear airflow were selected to be 1 $L \cdot s^{-1} \cdot m^{-3}$ for 5.7 m grain depth and 5.5 m bin diameter (100 t of wheat at 15% moisture content) resulting in an airflow of 0.0057 $m^3 \cdot s^{-1} \cdot m^{-2}$. The standard conditions included: fan temperature rise of 1°C, initial moisture content of 15%; initial grain temperature of 30°C; ventilation time of 0:00 - 6:00 h; storage period from 1 Sept. to 30 Nov. 1979; grain layer thickness of 28.4 cm; and an offset for hysteresis in the equilibrium relative humidity was not simulated in the equilibrium model.

The grain depth for the non-linear airflow case was also set at 5.7 m. The air velocity gradients for non-linear airflow were determined for a bin 5.5 m diameter at two airflow rates (1 and 5 $L \cdot s^{-1} \cdot m^{-3}$) assuming that the air velocity varied inversely proportional to the grain height above the perforated floor. A minimum of 15 and 40% perforated floor area was assumed for the airflow rates of 1 and 5 $L \cdot s^{-1} \cdot m^{-3}$, respectively (Manitoba Agriculture 1987). Thus, the air velocities leaving the perforated area were 0.0379 and 0.0711 $m \cdot s^{-1}$ at 1 and 5 $L \cdot s^{-1} \cdot m^{-3}$, respectively, while the air velocities at the top were 0.0057 and 0.0284 $m \cdot s^{-1}$, respectively.

4.8. Airflow Rates and Fan Control Methods for Selected Brazilian Locations

4.8.1. Granary shape and size

The studies for determining the best airflow rates and fan-control methods were conducted for two granary types in an attempt to simulate linear and non-linear airflow distributions in large horizontal grain storages.

Linear airflow distribution was simulated assuming a bin with a fully perforated floor, 5-m diameter, and 20-m grain depth containing 300 t of wheat. The bin diameter was not an important variable since the simulations were conducted for one-dimensional heat conduction and airflow in the vertical direction.

Non-linear airflow distribution was simulated using a Brazilian type of horizontal grain storage which is a large single storage bin dug into the ground in a V-shape (Fig. 4.3). The dimensions for the horizontal grain storage (width of 32 m) were chosen based on information provided by grain storage managers from Brazil (Bronzatti et al. 1992, Cordeiro 1993, Pascoali 1993). A duct with a width of 0.5 m located along the V-bottom provided non-linear airflow distribution in two dimensions. The ratio between the longest and the shortest airflow paths was less than 1.5 to ensure that there was minimum airflow through grain farthest from the aeration ducts (Navarro 1982, Noyes 1990).

4.8.2. Heat and mass transfer during forced convection

The non-equilibrium mathematical model developed here, which predicts grain moisture content and temperature for grain layers during forced convection, was simplified based on the results of the sensitivity analyses. Therefore, a constant wheat bulk density was assumed and the net heat of sorption was neglected for determining the best airflow rates and fan-control methods.

The mathematical model developed to simulate heat and mass transfer during forced convection in one-dimension can be used for two- or-three-dimensional problems provided that the air velocity gradient along the streamlines are calculated using the method developed by Smith et al. (1992a, 1992b).

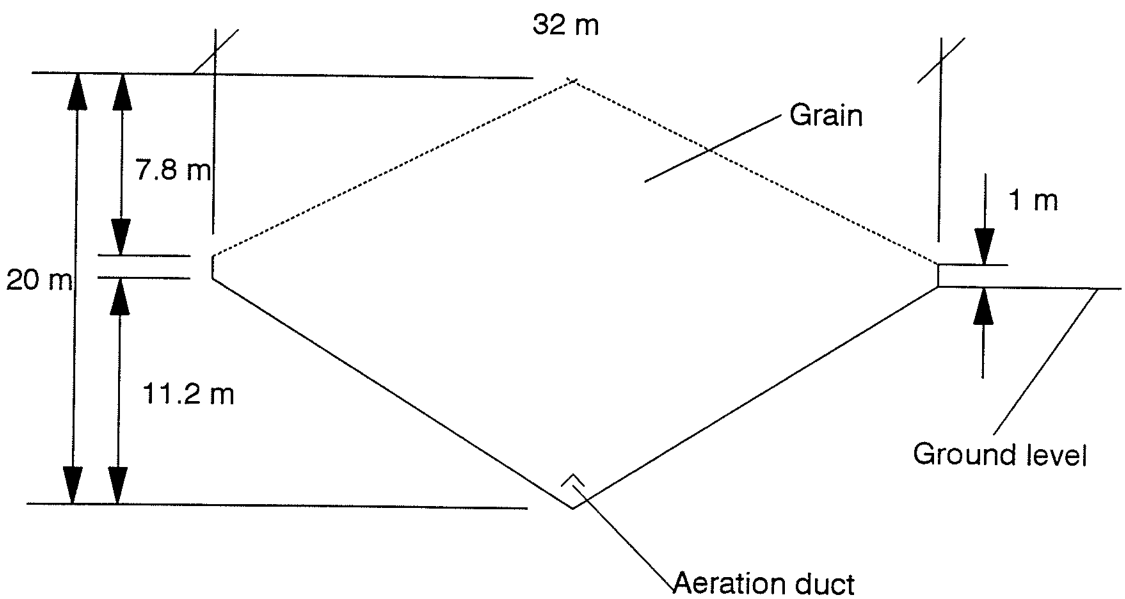

Fig. 4.3. Schema of the horizontal storage used to simulate aeration of wheat stored in Brazilian locations with non-linear airflow distribution

4.8.3. Heat and mass transfer for periods without aeration

A mathematical model computationally fast and relatively accurate was needed to simulate intermittent aeration of wheat stored in many locations, using historical weather data for a series of years, various test conditions, and using linear and non-linear airflow distributions. Because of this, the complex problem of heat and mass transfer in stored grain during periods without forced ventilation was simplified to a one-dimensional heat conduction problem (vertical direction) to decrease the computer execution time.

A complete mathematical model that predicts all heat and mass transfer phenomena occurring in periods of no ventilation was not developed because of the excessive computer-execution-time that would have been required to determine the best airflow rates and fan-control methods. Therefore, the heat transfer in the horizontal direction was neglected considering that the major interest was to simulate heat and mass transfer in the vertical direction for a central grain column (under the peak) in a large horizontal grain store with a V-shape bottom. Thus, the heat transferred by convection from the head space air to the grain at the top surface and by conduction into the grain bulk became the major factors affecting the grain temperature in periods of no ventilation. It was assumed that the heat transfer through the walls would affect only a small portion of the total grain bulk because of its large size and low thermal diffusivity of grain. In addition, heat generation, moisture transfer by vapor diffusion, and free convection within the grain bulk were assumed negligible considering that the grain bulk was being intermittently aerated to keep a uniform temperature distribution.

The method presented by Metzger and Muir (1983b) was used to predict heat transfer during periods without ventilation except that the heat transfer was simulated in one-dimension only (vertical direction). Convective heat transfer from the exterior surface of the elements to the surrounding air was included in the model for the bottom and top surface elements (Muir et al. 1980, Metzger and Muir 1983b). The heat transfer by convection for the top layer of grain was calculated assuming that the bin attic temperature was equal to the ambient air temperature plus a constant temperature increment (5°C). For the bottom layer of grain, the heat transferred by convection was calculated assuming that the plenum temperature was equal to the ambient air temperature. The finite difference method was used to solve the differential-equation of transient heat transfer (Fourier equation) (Incropera and DeWitt 1990, Kreith and Bohn 1993).

4.8.4. Simulation procedure

The best airflow rates and fan-control methods for Brazilian locations were selected based on the costs of over drying, spoilage, and electrical energy to operate the fan during aeration of wheat stored in eight Brazilian locations using 10 years (1961-1970) of weather data for most locations with linear and non-linear airflow distributions. The air was always forced from the bottom to the top layers and it was assumed that grain spoilage occurred in a grain layer when its ASTE was equal to or greater than 1.5.

The air heating costs were not included because in many situations the heat from the fan and motor would be sufficient to provide the simulated temperature rise. Centrifugal fans normally used to aerate grain in Brazil add about 3 to 5°C due to heat of compression (Noyes 1990). The costs of direct heating depend on the type of heating system and the source of energy. Heat sources such as oil, wood, and straw are used in Brazil. Capital, labour, interest, and other costs were not included. It was assumed that the grain storage and aeration system were already constructed.

Simulations of aerated wheat stored for 1 year in Curitiba (subtropical climate) and Goiânia (tropical climate) with linear airflow distribution were conducted to compare several fan control methods (Table 4.8).

To decide when to operate the fan, the vapor pressure of the water in the wheat was calculated using psychrometric equations (ASAE 1993c) and the Chung equation (ASAE 1993b) for the equilibrium moisture content of wheat based on the initial grain moisture content and on

Table 4.8. Fan control methods simulated to aerate wheat stored in Curitiba and Goiânia

Fan Control Method	Fan Operation
No ventilation	Fan was not used (simulation of vertical heat conduction only)
Continuous ventilation	Continuous fan operation
Time-clock	Ventilation at predetermined times of the day
Humidistat	Fan was operated when the ambient relative humidity was below a maximum setting of relative humidity
Thermostat	Fan was operated when the maximum grain temperature was greater than a preset limit
Differential-thermostat	Fan was operated when the difference between the dry bulb temperature of the outside ambient air and the average grain temperature was greater than the differential-temperature setting
Combinations	Differential-thermostat control combined with either a humidistat or a time-clock
Vapor-pressure-deficit	Fan was turned on when the vapor pressure of the water in wheat was equal to or higher than the the vapor pressure of the water in the ambient air

the average grain temperature for the bulk during each time interval used in the simulation of forced convection.

The results of simulations for the various fan control methods indicated that the differential-thermostat was the best method for Brazilian climatic conditions. Because of this, most simulations were run using the differential-thermostat method for all locations and series of years with linear and non-linear airflow distributions. It was not known, however, which were the best control parameters, i.e. the thermostat settings, airflow rates, and air-temperature increments above the ambient air temperature (fan temperature rise plus supplemental air heating).

Simulations using the differential-thermostat method were conducted for three airflow rates (1, 2, and 3 $L{\cdot}s^{-1}{\cdot}m^{-3}$) with linear airflow distribution and three static pressures (1500, 2500, and 3500 Pa) with non-linear airflow distribution, five differential-thermostat settings (-4, -5, -6, -7, and -8°C), and three air-temperature increments (1, 3, and 5°C) above the ambient air temperature.

Initially, the simulations with linear airflow distribution were conducted for 1 or 2 years taken randomly from each of the eight Brazilian locations to have a rough indication of the best ranges of variation of the control variables. Later the simulations were conducted for all years for the selected ranges of variation. This procedure was followed because it would require excessive computer time to simulate all combinations of test conditions, regions, and years.

Absolute differential temperature in the range of 4 to 8°C was used for the differential-thermostat setting because a differential greater than 8°C caused excessive grain spoilage in the top grain layers due to a lack of ventilation and increased the over drying costs. A setting of less than 4°C caused excessive grain spoilage in the bottom layers due to grain wetting and caused increased electricity costs because of the long ventilation time.

The effects of harvest date, grain depth, initial temperature of the grain, number of grain layers, and difference between the bin attic temperature and the ambient air temperature on the differential-thermostat method were investigated for Curitiba and Goiânia with linear airflow distribution. These effects were measured by the maximum and average allowable storage time elapsed, fan ventilation time, and costs of over drying, spoilage, and electricity to simulate aeration of wheat. The standard conditions used in these simulations included an aeration period from 1 Jan. to 31 Dec. 1961, -5°C differential-thermostat setting, 2 $L{\cdot}s^{-1}{\cdot}m^{3}$ airflow rate, 3°C air-temperature increment above the ambient temperature, 30°C initial grain temperature, 5°C difference between the bin attic temperature and the ambient air temperature, 20-m grain depth, 10 grain layers, and linear airflow distribution.

Simulations for all locations and series of years with linear airflow distribution were also conducted for the second best fan-control method, which was based on the vapor-pressure-deficit, for three airflow rates (1, 2, and 3 $L{\cdot}s^{-1}{\cdot}m^{-3}$) and two air-temperature increments (1 and 3°C) above the ambient air temperature.

4.8.5. Input data

The starting date for storage was set at 1 Jan. and the grain was at an initial moisture content of 13% and a temperature of 30°C. The effect of initial moisture content was investigated with 12% initial moisture content for Campo Grande and Goiânia and with 11 and 12% for Cuiabá. A 1-h time interval was used to simulate heat and mass transfer when determining the best airflow rates and fan-control methods.

The difference between the temperature of the head space air and the ambient air temperature was set at 5°C although information provided by Brazilian grain storage managers (Bronzatti et al. 1992, Cordeiro 1993, Pascoali 1993) indicated that this difference might be smaller than that because most Brazilian grain storages are equipped with fans to move ambient, outside air through the head space.

Over drying and spoilage costs were calculated based on a price of wheat of \$ 150.00 per tonne. The electricity cost was calculated using a price of \$ 0.15 / kW·h which is the minimum electricity cost for Brazilian industries and grain storage companies (Oliveira 1994).

Fan power was calculated using the equations of airflow resistance for a loose fill (not packed) of clean, relatively dry wheat given by ASAE (1993d). The calculated airflow resistance was then increased by 60% to account for grain packing and fines. A combined electrical and mechanical efficiency of 50% was assumed for the electric motor and fan.

The total grain depth (20 m) was divided into 20 layers of variable thicknesses (Table 4.9). The use of variable thicknesses was important because normally the grain deterioration was higher in the bottom and top layers. Therefore, it was possible to increase the accuracy on detecting grain spoilage in these critical locations without increasing excessively the total number of grain layers. For instance, with linear airflow distribution the first and last grain layers correspond to 2% of the total grain bulk rather than 5% for 20 equal layers. The predicted moisture contents, temperatures, grain deterioration, and costs of aeration for non-linear airflow distributions correspond to the central column of grain only. Because of this, the aeration costs for the non-linear airflow distribution may be over estimated.

The air velocity gradient for the central column of grain in the horizontal granary (Table 4.9) was determined using the methodology described by Smith et al. (1992a) for static pressures of 1500, 2500, and 3500 Pa in the aeration duct, which correspond to the static pressures normally used in Brazil (Bronzatti et al. 1992, Cordeiro 1993, Pascoali 1993). The finite element program of Smith et al. (1992a) was used to determine the pressure gradient in the grain bulk. A half section of the horizontal storage was discretized into 200 linear elements as input for the finite element program. The equations of airflow resistance for wheat in the horizontal and vertical

Table 4.9. Grain layer thicknesses and air velocities for the grain layers located under the peak in the horizontal granary for static pressures of 1500, 2500, and 3500 Pa in the aeration duct

Grain Layer[1] #	Grain Layer Thickness (m)	Air Velocity ($m \cdot s^{-1}$) for Different Static Pressures		
		1500 Pa	2500 Pa	3500 Pa
1	0.40	0.19258	0.29716	0.39543
2	0.60	0.11809	0.18270	0.24350
3	0.80	0.06083	0.09426	0.12572
4	1.17	0.03618	0.05608	0.07479
5	1.17	0.02446	0.03794	0.05061
6	1.17	0.01905	0.02954	0.03942
7	1.17	0.01562	0.02421	0.03230
8	1.17	0.01321	0.02046	0.02731
9	1.17	0.01141	0.01766	0.02359
10	1.17	0.01001	0.01547	0.02066
11	1.17	0.00886	0.01370	0.01829
12	1.17	0.00790	0.01221	0.01630
13	1.17	0.00707	0.01092	0.01457
14	1.17	0.00632	0.00975	0.01301
15	1.17	0.00560	0.00864	0.01153
16	1.17	0.00488	0.00753	0.01004
17	1.17	0.00413	0.00637	0.00849
18	0.80	0.00329	0.00506	0.00675
19	0.60	0.00237	0.00366	0.00487
20	0.40	0.00153	0.00236	0.00314

[1]Grain layers were numbered from the bottom to the top.

directions were determined by Kumar and Muir (1986) and the velocity components were calculated using the pressure gradient as described by Smith et al. (1992a).

Predicted isopressures lines for half section of the horizontal granary with a static pressure of 1500 Pa in the aeration duct (Fig. 4.4) indicated that the central column of grain (under the peak) has a smaller airflow rate than that predicted for other locations in the grain bulk. The air

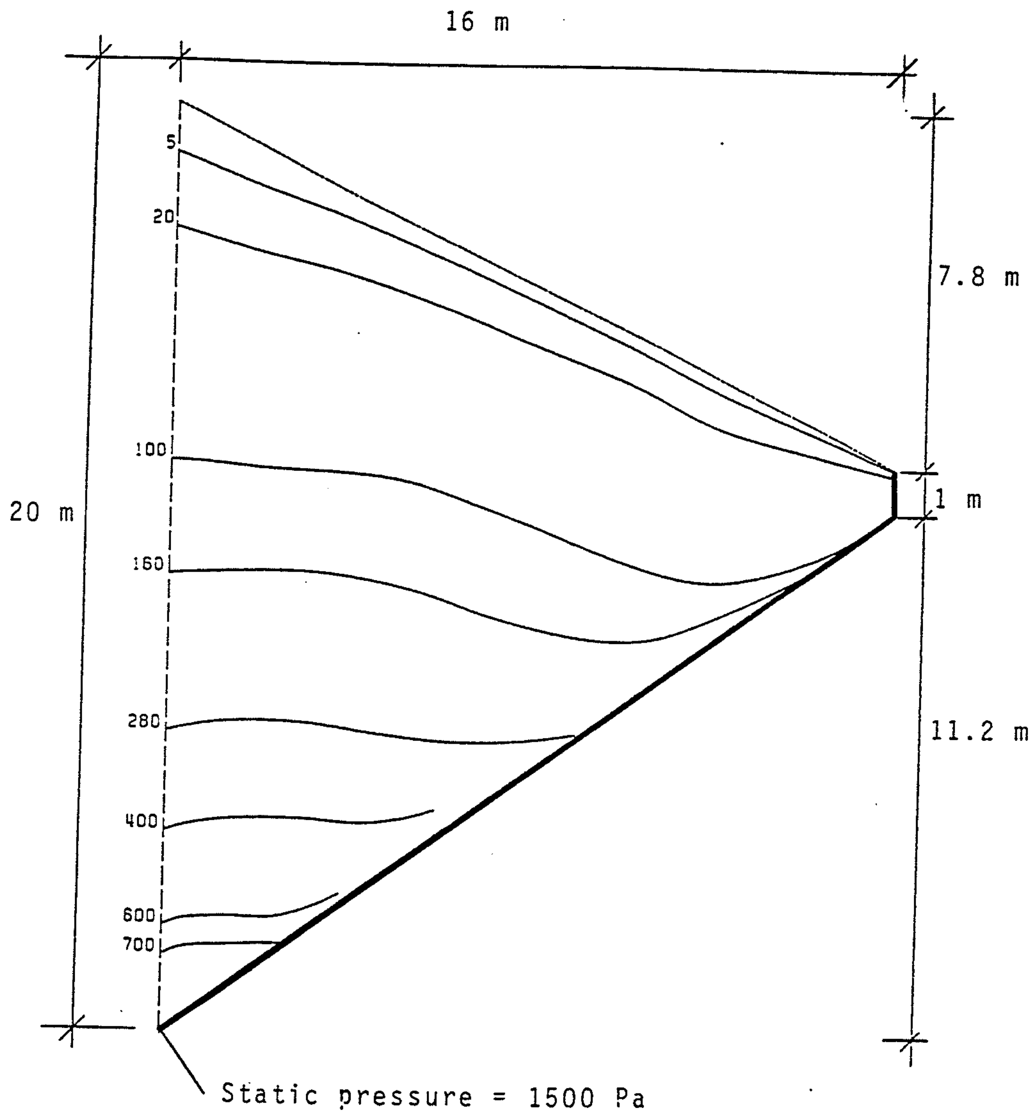

Fig. 4.4. Isopressure lines for the horizontal storage used in the simulation of aeration of wheat stored in Brazilian locations with non-linear airflow distribution

velocities calculated for the top surface elements increased as the horizontal distance from the centre of the storage was increased (Table 4.10). Therefore, it was assumed that the central

Table 4.10. Air velocity for the elements at the grain surface in the horizontal granary as a function of the horizontal distance from the centre of the storage calculated by the finite element method for different static pressures in the aeration duct

Horizontal Distance (m)	Air Velocity ($m \cdot s^{-1}$)		
	1500 Pa	2500 Pa	3500 Pa
0.13	0.00153	0.00236	0.00314
0.5	0.00164	0.0025	0.00337
1.25	0.00177	0.00272	0.0036
2.75	0.00250	0.00385	0.00514
4.77	0.00373	0.00576	0.00768
6.81	0.00479	0.00740	0.00986
8.85	0.00560	0.00863	0.01149
10.9	0.00588	0.00905	0.01205
12.94	0.00567	0.00871	0.01159
14.98	0.02529	0.03849	0.05083

column of grain was the most critical part of the grain bulk to be aerated. Measurements of air velocity over the grain surface in horizontal granaries in Brazil confirmed that the surface air velocity is lowest in the peak compared with other locations over the grain surface (Bronzatti et al. 1992).

The aeration costs for non-linear airflow distribution were relative to the total grain bulk for airflow rates of 0.6, 0.9, and 1.3 $L{\cdot}s^{-1}{\cdot}m^{-3}$ (which correspond to the static pressures in the aeration duct of 1500, 2500, and 3500 Pa) although the simulations had been conducted only for the central column of grain. These airflow rates were calculated based on the air velocity through the elements at the top grain surface. The air velocities for the elements close to the wall (at 14.98 m, Table 4.10) increased sharply and a greater number of elements would be necessary to increase accuracy of prediction in this region. An increase in the accuracy of these predictions, however, was not needed because the simulations were conducted only for the central column of grains. In addition, the total airflow rates based on the air velocities at the grain surface were used only for calculating the electricity costs of the fan.

5. RESULTS AND DISCUSSION

5.1. Thin-Layer Drying and Wetting Equations for Wheat

5.1.1. Equipment performance

The average standard deviations for all tests for individual thin-layers for the air temperature, relative humidity, and air velocity were 0.1°C, 0.3%, and 0.006 $m \cdot s^{-1}$, respectively. The small differences of temperature, relative humidity, and air velocity among the tray positions were taken into account during the modeling of the EMC equations and thin-layer equations.

Repetition of the tests at temperatures and relative humidities of 7.6°C and 87% and 35.1°C and 28% produced standard deviations in grain moisture content lower than the standard error (0.2%) accepted for the oven method of determining grain moisture content (ASAE 1993a). In addition, these tests showed no effect of the weighing time (a maximum of 0.3% of the total time) on the thin-layer drying and wetting results.

Grain moisture contents during drying reached equilibrium only when the difference between the initial moisture content and the equilibrium moisture content was less than one percentage point (wet basis). For example, equilibrium was reached within 30 h when drying from 9.0 to 8.4% at 35.2°C and 26.9% relative humidity (Trays 1, 2, and 7, Test 1, Appendix 1). Conversely, during the wetting tests, equilibrium was almost reached for most tests. For example, equilibrium was reached within 100 h at 25°C and 92% relative humidity (Trays 1 to 9, Test 8, Appendix 1). The time for the grain to approach equilibrium conditions (from 30 to 143 h) increased as the air temperature decreased.

5.1.2. Equilibrium moisture content equations

The EMC equations that best fit the data in the preliminary selection were the modified Chung-Pfost equation for desorption and the modified Halsey equation for adsorption. The initial moisture content was a significant variable only for the desorption data. The proposed EMC equations for desorption (Eq. 5.1) and adsorption (Eq. 5.2) are as follows:

$$EMC = \{\frac{-1}{q_1} \ln [\frac{(T - q_2) \ln (RH)}{-C}]\} \quad \textbf{(5.1)}$$

where: $C = q_3 + q_4 \ln (Mo)$,

RH = air relative humidity (decimal),

$q_1 = 20.25$; $q_2 = 239.9$; $q_3 = 1134$; $q_4 = 307.6$; and

$$EMC = [\frac{-A}{\ln (RH)}]^{(\frac{1}{B})} \quad \textbf{(5.2)}$$

where: $A = p_1 \, e^{p_2 T}$,

$B = p_3 \, T^{p_4}$,

$p_1 = 0.4209 \times 10^{-9}$; $p_2 = 0.05434$; $p_3 = 0.8254 \times 10^{10}$; $p_4 = -3.856$.

For the desorption equation the standard error was lower than the standard error for the moisture content measurements while for the adsorption equation it was about 2 times greater than the standard error for the moisture content measurements (Table 5.1). The effect of temperature on

Table 5.1. Errors for the EMC equations for desorption and adsorption by wheat

Process	Equation	Average Errors		Maximum Errors		Standard Error
		Absolute (%, wb)	Relative (%)	Absolute (%, wb)	Relative (%)	(%, wb)
Desorption	5.1	0.14	1.5	-0.48	-7.3	0.19
Desorption	5.3	0.45	5.0	-1.43	-21.6	0.59
Adsorption	5.2	0.31	1.8	1.02	5.1	0.39
Adsorption	5.3	0.62	3.6	1.88	9.4	0.80

adsorption EMC decreased as the relative humidities increased. The EMC increased as the temperature increased for relative humidities higher than about 85%. Young and Nelson (1967) showed this behaviour both theoretically and experimentally. Air velocity had no measurable effect on the EMC's for desorption and adsorption. Desorption EMC increased with an increased initial moisture content.

The best three-parameter equation suitable for both desorption and adsorption by wheat was the modified Chung-Pfost equation:

$$EMC = \{\frac{-1}{b_1} \ln [\frac{(T - b_2) \ln (RH)}{-b_3}]\} \qquad \textbf{(5.3)}$$

where: $b_1 = 16.88$; $b_2 = 216.9$; $b_3 = 518.2$ for desorption and

$b_1 = 14.19$; $b_2 = 1044$; $b_3 = 5140$ for adsorption.

The errors for the three-parameter, modified Chung-Pfost equation were higher than those for Eqs. (5.1) and (5.2) for the desorption and adsorption by wheat (Table 5.1) but Eq. (5.3) has only three parameters and can be used for both phenomena. Therefore, the three-parameter, modified Chung-Pfost equation (Eq. 5.3) is suitable for many practical applications.

The ranges of application for the desorption and adsorption EMC equations are given in Table 5.2.

Table 5.2. Ranges of application for the EMC and thin-layer equations for wheat

Process	Equation	Temperature (°C)	Relative Humidity (%)	Air Velocity ($m \cdot s^{-1}$)	Initial Moisture Content (%, wb)
Desorption EMC	5.1	7.5-35.3	27-75	NA	9.0-16.8
Desorption EMC	5.3	7.5-35.3	27-75	NA	NA
Adsorption EMC	5.1 and 5.3	7.4-35.2	37-92	NA	NA
Thin-layer drying	5.4, 5.5, 5.8, 5.9	7.5-35.3	27-75	NA	9.0-16.8
Thin-layer wetting	5.6 and 5.7	7.4-35.2	37-92	0.01-0.28	8.9-17.0
Thin-layer wetting	5.8 and 5.9	7.4-35.2	37-92	NA	8.9-17.0

5.1.3. Thin-layer drying and wetting equations

The EMC equations (Eqs. 5.1 and 5.2) for desorption and adsorption by wheat were used for determining, respectively, the thin-layer wetting and drying equations. The best equation of two equations considered to predict thin-layer drying and wetting of wheat was Page's equation (Eq. 3.1, Sec. 3.3). The parameters K and N of Page's equation for drying and K' and N' for wetting were obtained by non-linear regression. The most accurate prediction of thin-layer drying and wetting of wheat was obtained with Eqs. (5.4) and (5.5) for drying and Eqs. (5.6) and (5.7) for wetting:

$$K = r_1 \exp(r_2 T)\, DM^{(r_3 RH^{r_4})} \tag{5.4}$$

$$N = r_5 (Mo)^{r_6} \tag{5.5}$$

where: DM = Mo - EMC (decimal, db),

$r_1 = 0.6348 \times 10^{-6}$; $r_2 = 0.03733$; $r_3 = 0.1824$; $r_4 = -0.6724$

$r_5 = 1.13$; $r_6 = 0.3225$

$$K' = s_1 \exp(s_2\, T)\, V^{[s_3 \exp(s_4\, Mo)]} \tag{5.6}$$

$$N' = s_5 (RH)^{s_6} \tag{5.7}$$

where: V = air velocity ($m \cdot s^{-1}$),

$s_1 = 0.8072 \times 10^{-9}$; $s_2 = 0.05516$; $s_3 = 0.1844$; $s_4 = 2.849$;

$s_5 = 0.8599$; $s_6 = 0.2806$

The errors obtained from the non-linear regression (Table 5.3) for the thin-layer drying and wetting equations for all the experimental data indicate a good fit to the experimental points (452 points for drying and 951 for wetting). The errors obtained for the wetting equation were a little higher than those obtained for the drying equation. The higher errors for the EMC adsorption equation compared with the desorption equation (Table 5.1) may be the cause for these

Table 5.3. Errors for the thin-layer drying and wetting equations for wheat

Process	Equation	Average Errors		Maximum Errors		Standard Error (%, wb)
		Absolute (%, wb)	Relative (%)	Absolute (%, wb)	Relative (%)	
Drying	5.4 and 5.5	0.09	0.8	0.40	4.3	0.12
Drying	5.8 and 5.9	0.09	0.8	0.41	4.8	0.13
Drying	3.2 and 3.3	0.56	4.8	2.94	17.5	0.77
Wetting	5.6 and 5.7	0.17	1.2	1.06	-6.4	0.24
Wetting	5.8 and 5.9	0.27	1.8	1.94	-12.9	0.37
Wetting	3.2 and 3.3	0.89	7.2	5.59	-59.8	1.33

differences. The parameters K and N for the thin-layer drying equation (Eq. 5.4 and 5.5) showed no dependence on the air velocity while the parameter K' for wetting (Eq. 5.6) was slightly affected by air velocity. The wetting rate decreased slightly when the air velocity was decreased (Fig. 5.1). The parameter N for drying depended only on the initial moisture content while the parameter N' (Eq. 5.7) depended only on the relative humidity.

Good results were also obtained with Page's equation using the same variables to define the coefficients K'' and N'' (Eqs. 5.8 and 5.9) for both thin-layer drying and wetting of wheat:

$$K'' = c_1 \exp\left(\frac{-c_2}{T}\right) \tag{5.8}$$

$$N'' = c_3 \, (Mo)^{c_4} \, EMC^{\,c_5} \tag{5.9}$$

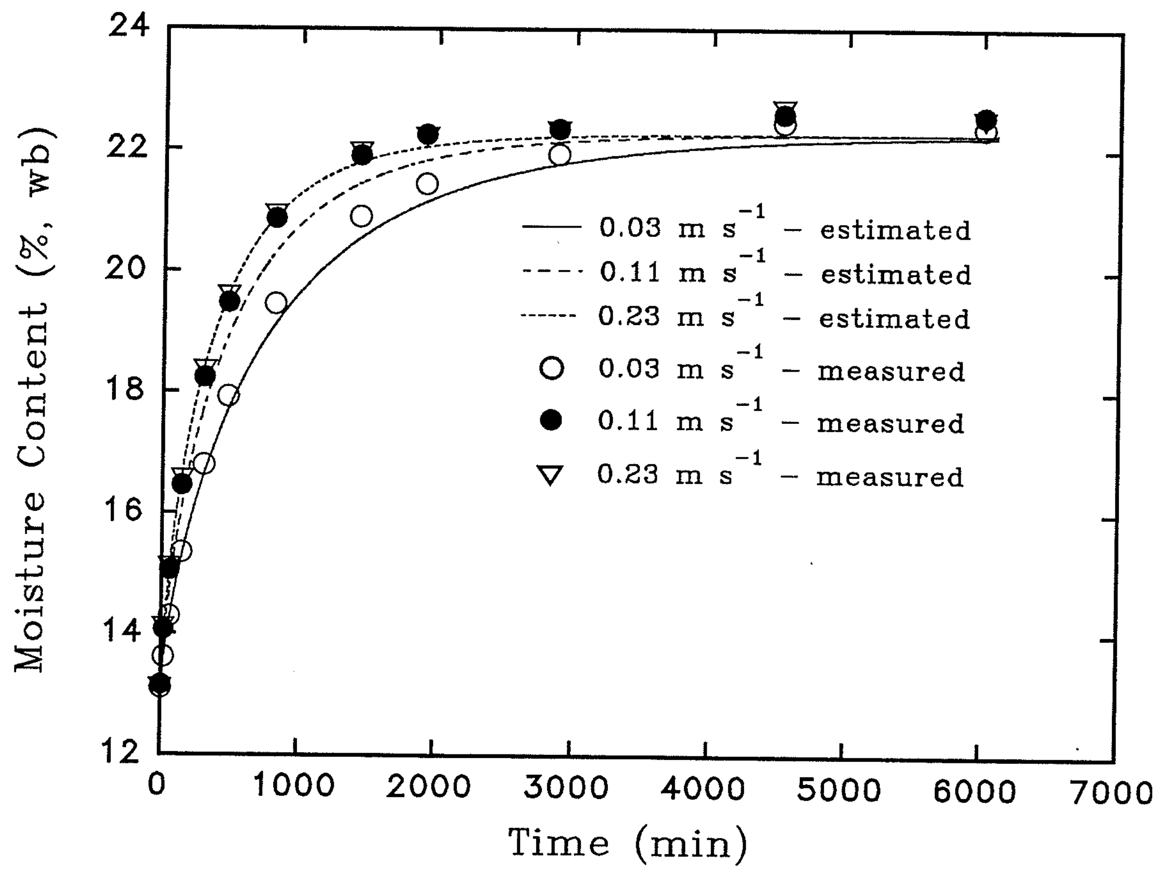

Fig. 5.1. Effect of air velocity on thin-layer wetting of wheat (T=25.0°C, Mo=13.1%, and RH=92%)

where: $c_1 = 509.1$; $c_2 = -3088$; $c_3 = 1.87$; $c_4 = 0.5322$; $c_5 = 0.0683$ for drying and

$c_1 = 20252$; $c_2 = -4438$; $c_3 = 0.859$; $c_4 = -0.04589$; $c_5 = 1143$ for wetting

The Eqs. (5.8) and (5.9) gave errors (Table 5.3) slightly higher than Eqs. (5.4) to (5.7) for both thin-layer drying and wetting of wheat. These are simpler equations, however, and have less parameters than Eqs. (5.4) to (5.7). The accuracy of Eqs. (5.8) and (5.9) may be sufficient for many practical applications such as simulation of wheat aeration using non-equilibrium mathematical models.

The diffusion equation (Eqs. 3.2 and 3.3, Sec. 3.3), with the modified diffusivity coefficient dependent on temperature only, gave much higher errors than Page's equation (Table 5.3) and should not be used as a thin-layer equation for wheat within the experimental range used in this research. The results were not affected when the number of terms (n) was increased above one. Indeed, the terms of the infinite series decrease very rapidly and for values of $D_R t$ less than 0.1 only the first term is needed (Parti 1993). The modified diffusivity coefficient may depend on moisture content as well as temperature. In addition, the moisture ratio does not converge to 1 when time approaches zero, i.e. during the first stages of drying or wetting. The modified diffusivity coefficients (Eq. 3.3, Sec. 3.3) obtained by non-linear regression were:

$a_1 = 0.7646$; $a_2 = 2677$ for drying; and

$a_1 = 13759$; $a_2 = 5590$ for wetting.

The ranges of application for the thin-layer drying and wetting equations are given in Table 5.2.

5.1.4. Comparison with published data

The equations obtained for EMC and for thin-layer drying and wetting of wheat were graphically compared with some available equations. The EMC equations used in the comparisons (Appendix 3) were determined for static conditions. The comparisons were done using air conditions within the applicable range of conditions for all equations. The equations for thin-layer drying and wetting of shelled corn presented by Misra and Brooker (1980) were included in these comparisons because these equations have been used in simulations of ambient air drying of wheat (Morey et al. 1981).

The proposed EMC equation for desorption (Eq. 5.1) was compared with the EMC equations given by Pfost et al. (1976b) and Sinicio et al. (1991) (Fig. 5.2). The equation of Pfost et al. (1976b) presented the closer agreement with the proposed equation at 25°C and 16% initial moisture content. The proposed equation presented less differences in EMC compared with the two equations at lower temperatures and at relative humidities above 65% and at an initial moisture content of 16%. The EMC calculated with the proposed equation decreased with decreased initial moisture content.

The proposed EMC equation for adsorption (Eq. 5.2) was compared at 25°C with the EMC equations given by Morey et al. (1981), Iglesias and Chirife (1982), and Chung (ASAE 1993b) (Fig. 5.3). The differences among the EMC adsorption equations increased at relative humidities above 75%. The equation of Iglesias and Chirife (1982) showed the closest agreement with the proposed equation. The differences in EMC among the proposed equation and the equations of Morey et al. (1981) and Chung (ASAE 1993b) increased at higher temperatures.

The proposed thin-layer drying equation (Eqs. 3.1, 5.4, and 5.5) was compared with the thin-layer drying equations given by Jayas and Sokhansanj (1986) for wheat and Misra and

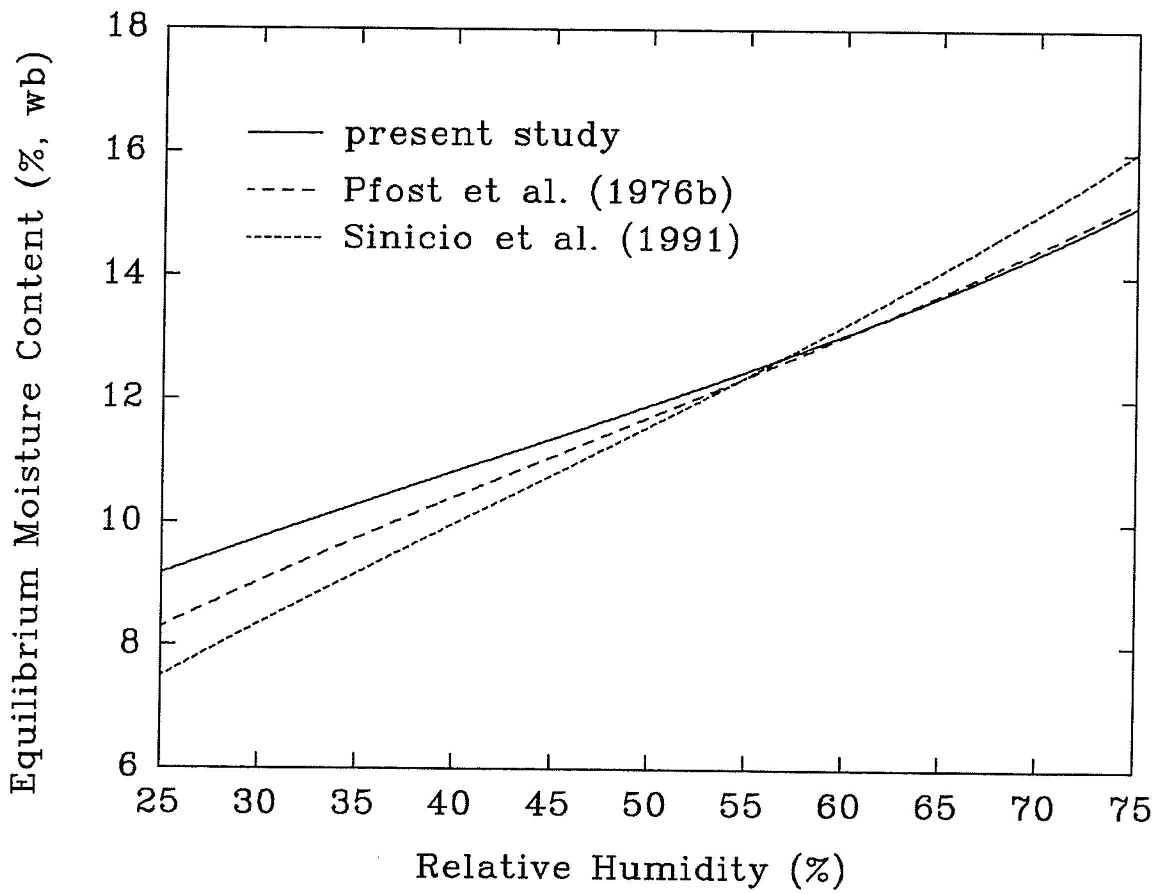

Fig. 5.2. Comparison of EMC equations for desorption by wheat (T=25°C and Mo=16%)

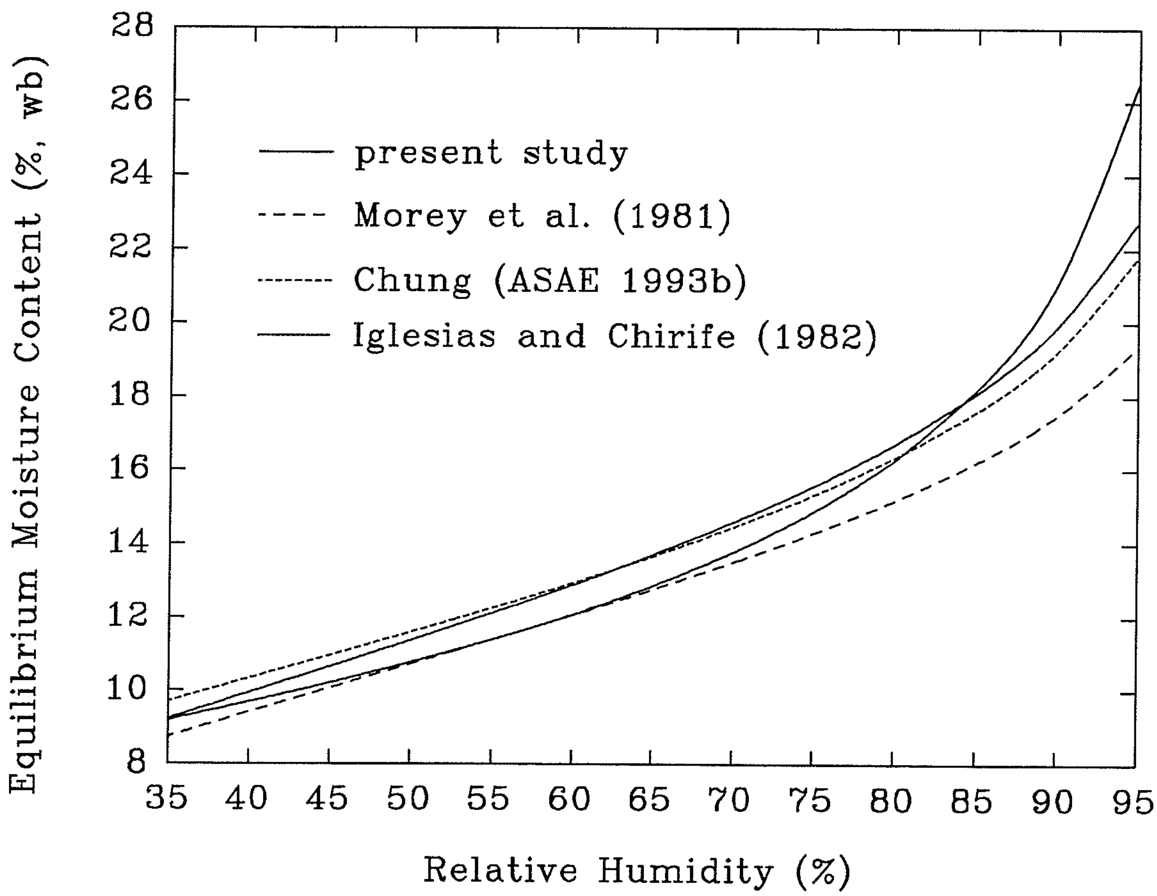

Fig. 5.3. Comparison of EMC equations for adsorption by wheat (T=25°C)

Brooker (1980) for corn (Fig. 5.4). The thin-layer drying and wetting equations used in these comparisons are given in the Appendix 4. Thin-layer drying of wheat was much faster than that for corn. The equation of Jayas and Sokhansanj (1986) presented the closer agreement with the proposed equation while the equation of Misra and Brooker (1980) deviated greatly from the other equations. The differences between the proposed equation and the equation of Jayas and Sokhansanj (1986) increased with decreased temperatures and decreased initial moisture contents. The differences between these equations did not not change as the relative humidity changed. The main factors that may explain the differences between the proposed equation and the equation of Jayas and Sokhansanj (1986) are the initial moisture content and grain cultivar. The equation of Jayas and Sokhansanj (1986) was based on one initial moisture content (18.5%) while the proposed equation is based on a range of initial moisture contents from 9.0 to 16.8%.

Thin-layer wetting predicted by the proposed equation for wheat (Eq. 3.1, 5.6, and 5.7) was faster than that predicted by the equation of Misra and Brooker (1980) for corn (Fig. 5.5). Differences between predicted thin-layer wetting of wheat and corn were about the same at other temperatures. The differences decreased as relative humidity or air velocity decreased or initial moisture content increased.

5.2. Comparison of Equilibrium and Non-Equilibrium Models for Brazilian Locations

5.2.1. Summary

The comparison of equilibrium and non-equilibrium mathematical models using linear and non-linear airflow distributions showed that the results produced by these models were significantly different (α=0.05) when simulating aeration of wheat stored for 1 year in Curitiba because the deviations in grain deterioration were equal to or greater than the uncertainty in

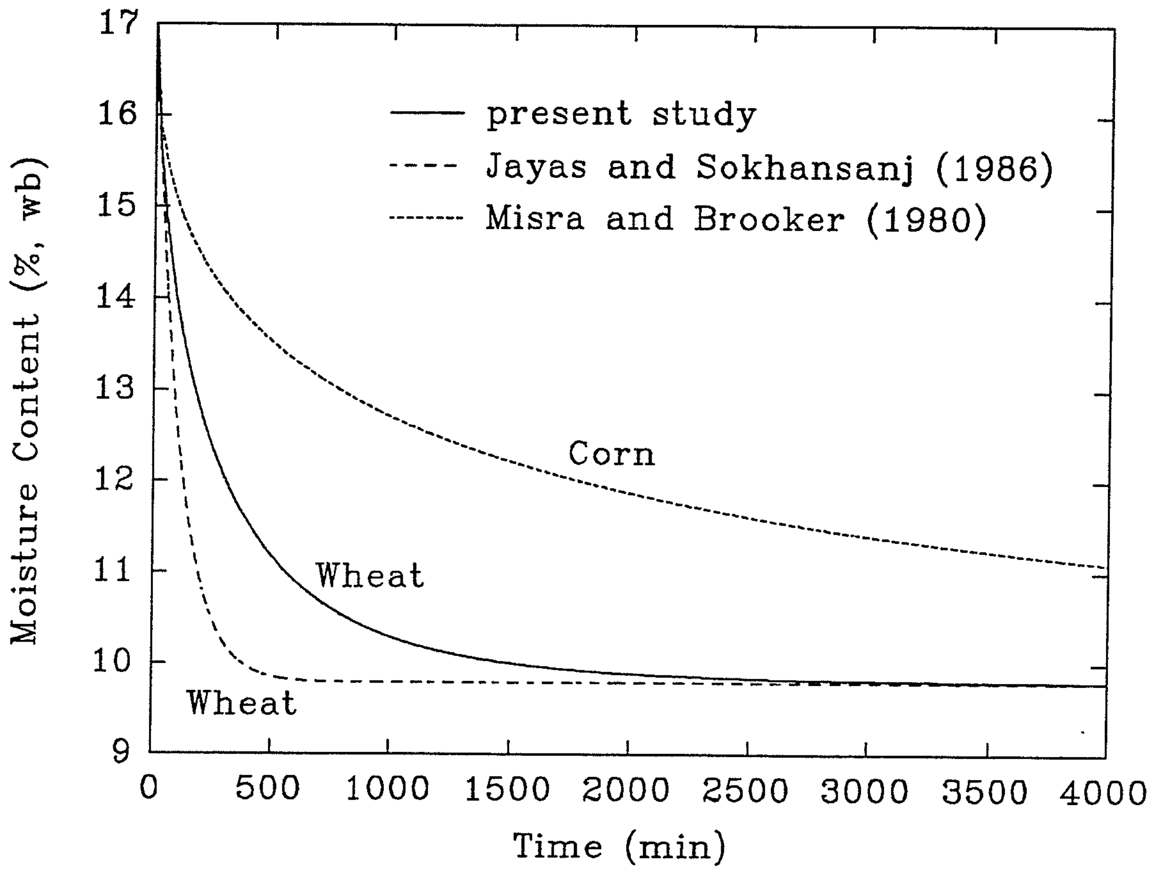

Fig. 5.4. Comparison of thin-layer drying equations for wheat and corn (T=35°C, RH=35%, Mo=17%, and V=0.30 m·s^{-1})

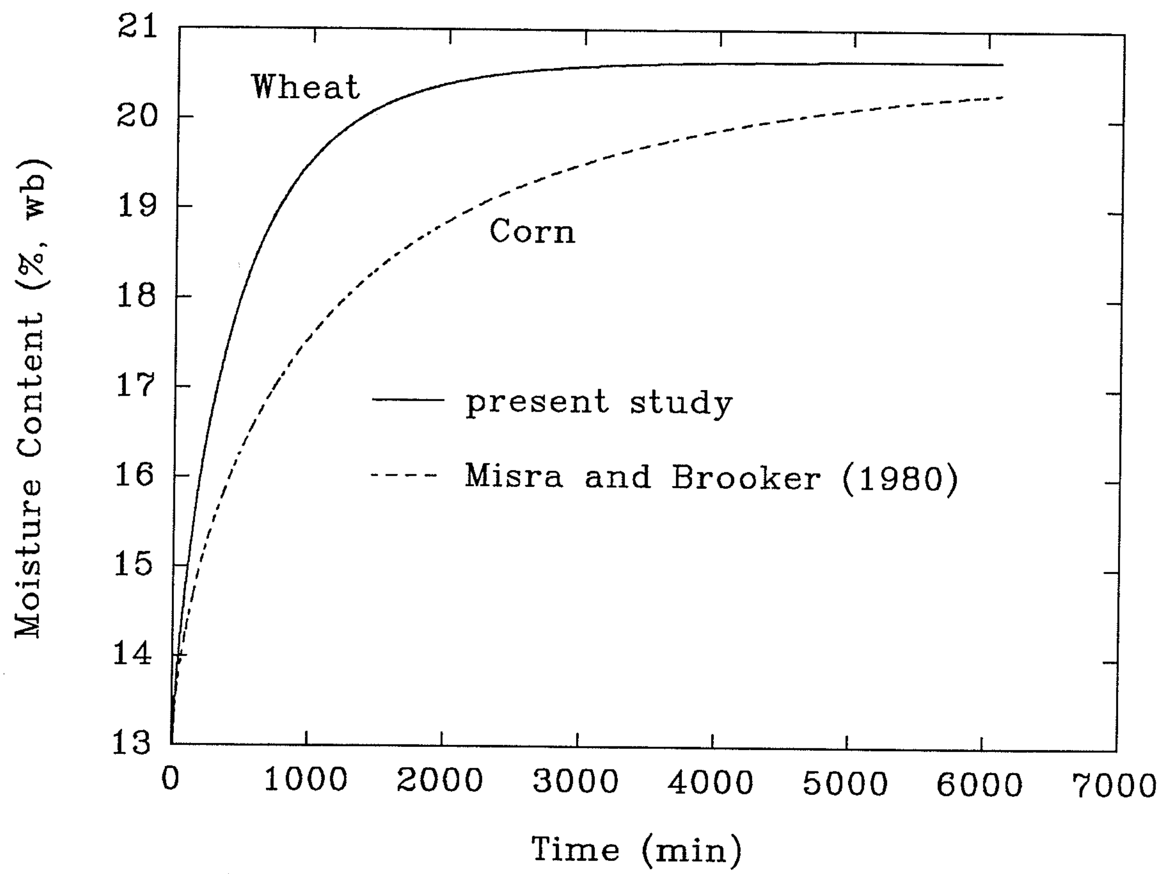

Fig. 5.5. Comparison of thin-layer wetting equations for wheat and corn (T=20°C, RH=90%, Mo=13%, and V=0.25 $m \cdot s^{-1}$)

predicting deterioration (±30%) for most test conditions. The differences in predicted grain deterioration were due to over prediction of drying and wetting rates by the equilibrium model especially in the bottom layers of grain near the air entrance.

The differences between the equilibrium and non-equilibrium models were affected by airflow rate, fan temperature rise, airflow distribution, grain layer thickness, grain depth, geographical location, ventilation period, and assuming a 5% offset in the equilibrium relative humidity in moisture adsorption calculated by the equilibrium model. The initial grain moisture content and temperature, year of simulation, or grain layer thicknesses less than 20 cm only slightly affected the differences between the models.

5.2.2. Execution time

The average execution time for the equilibrium model, using a IBM 370, model 3090 mainframe computer at the University of Manitoba, was about 0.14 s for the simulation of one grain layer for 100 h using a 1 h time interval. The non-equilibrium mathematical model was about 27% faster than the equilibrium model. Heat and mass balance models such as the non-equilibrium model are recommended for operational research studies because they are reasonably accurate and computationally efficient (Sharp 1982).

5.2.3. Changes of moisture content, temperature, and ASTE

The moisture content, temperature, and allowable storage time elapsed (ASTE) predicted by the non-equilibrium model for 1 year of storage at standard conditions and using linear airflow (Fig. 5.6) were similar to those obtained for non-linear airflow. The basic differences between the two airflow conditions, besides the airflow distribution, were the grain depth and airflow range.

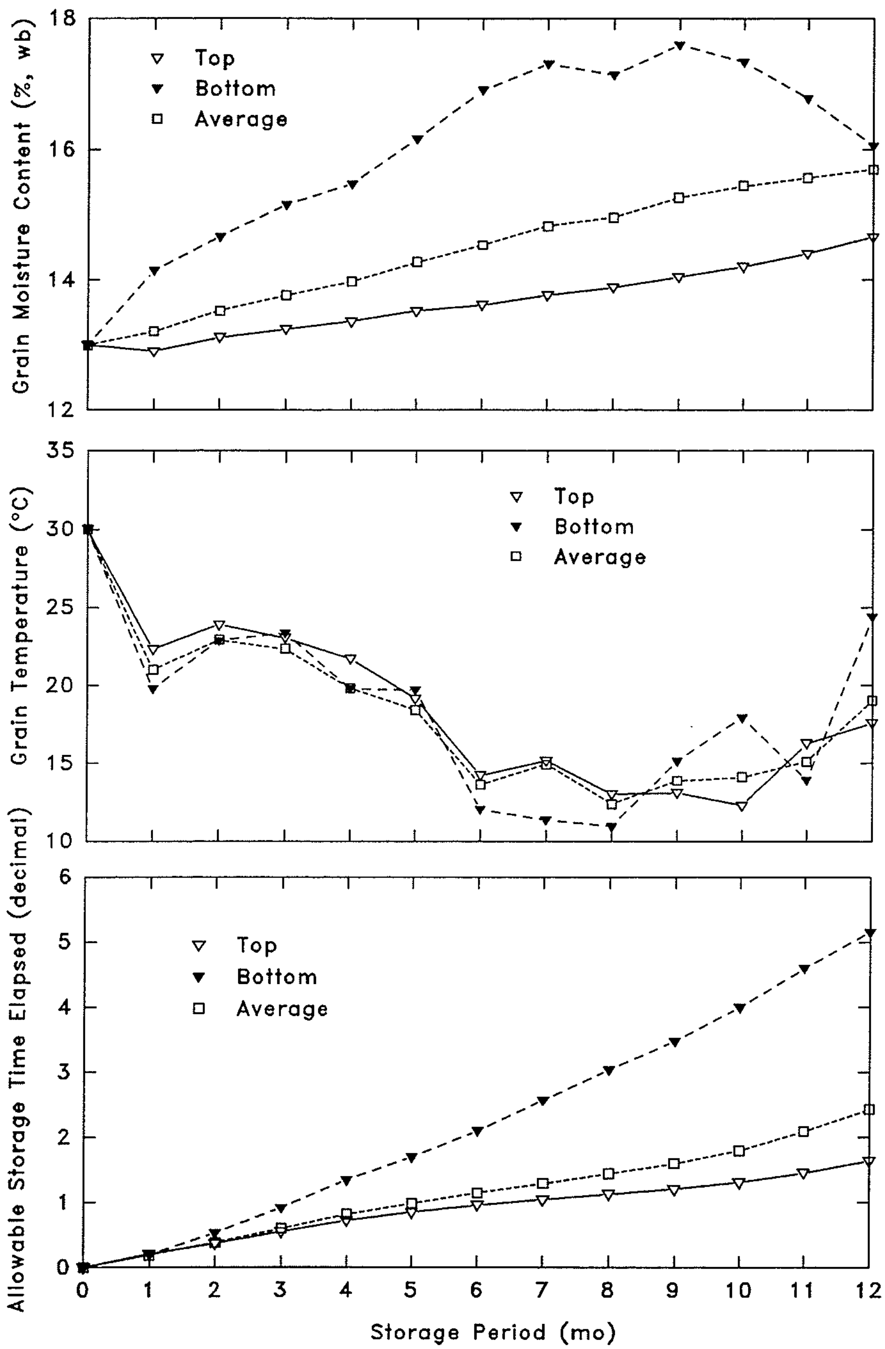

Fig. 5.6. Moisture content, temperature, and allowable storage time elapsed predicted by the non-equilibrium mathematical model for wheat stored for 12 mo at Curitiba, Brazil and aerated with a linear airflow distribution

The ASTE at 12 mo for the top and bottom layers and for the average of all layers were 1.6, 5.2, and 2.4 for linear airflow distribution compared with 1.7, 9.1, and 3.6 for non-linear airflow. The deterioration was higher for the non-linear airflow because the higher air velocity in the bottom layers brought in more moisture to these layers.

For the selected standard aeration conditions for Brazil the simulation results indicated that the climate should be considered humid because wetting, drying, and hysteresis conditions were predicted for 70, 20, and 10% of the time, respectively. Also, the percentage of times that the equilibrium relative humidity of the air entering any grain layer was equal to or greater than 95% was 0.8%. In other words, the search technique to find the final grain moisture content given by Thompson (1972) was used in only 0.8% of the moisture content calculations for all grain layers. In that search technique, three equations and three unknowns (final grain moisture content, air temperature, and humidity) are solved simultaneously. Therefore, for wetting conditions, the assumption of equilibrium used in the non-equilibrium model when the equilibrium relative humidity of the air entering any grain layer was equal to or greater than 95% (Sec. 4.5.1) did not affect the predictions of moisture content by the non-equilibrium model.

The deterioration (ASTE) for 12 mo of storage predicted by the equilibrium model was greater than that predicted by the non-equilibrium model for various air conditions and for both linear and non-linear airflow distributions (Figs. 5.7 and 5.8). Because of the humid climate that was used for the simulations, the over prediction of wetting was not balanced out by an over prediction of drying and therefore resulted in an over prediction of spoilage. Several other researchers have also found that equilibrium models over predict the drying and wetting rates especially in the bottom layers (Morey et al. 1979, Van Ee and Kline1979a, Mittal and Otten 1982).

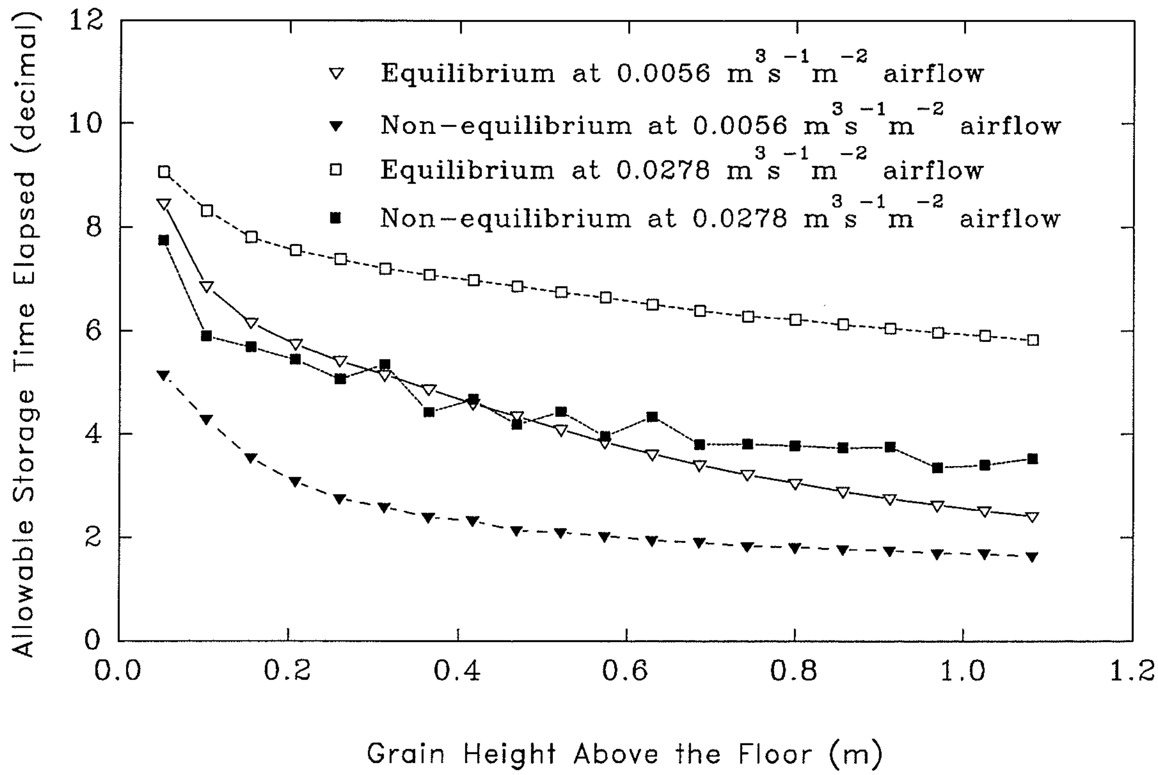

Fig. 5.7. Allowable storage time elapsed predicted by the equilibrium and non-equilibrium mathematical models for stored wheat aerated with a linear airflow distribution and 1°C fan temperature rise for 12 mo at Curitiba, Brazil

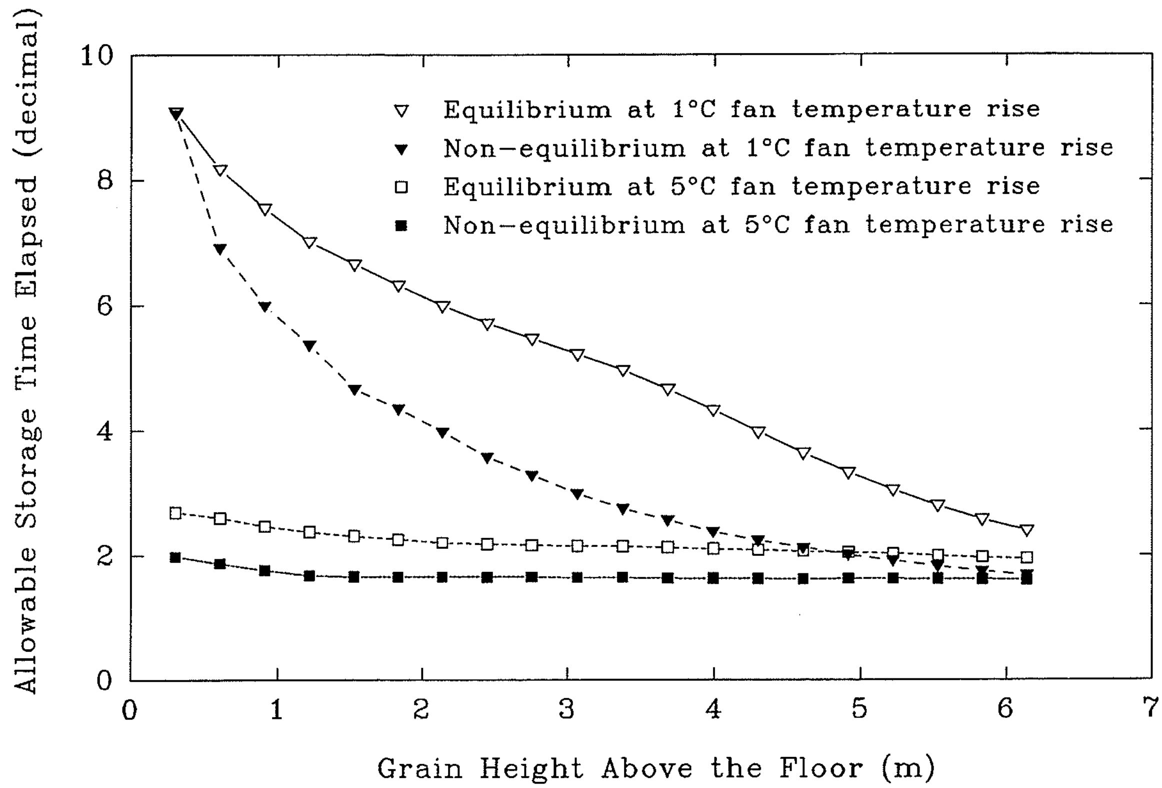

Fig. 5.8. Allowable storage time elapsed predicted by the equilibrium and non-equilibrium mathematical models for stored wheat aerated with air velocities varying from 0.018 $m^3 \cdot s^{-1} \cdot m^{-2}$ at the top to 0.159 $m^3 \cdot s^{-1} \cdot m^{-2}$ at the bottom for 12 mo at Curitiba, Brazil

The use of equilibrium models to determine the best airflow rates and fan-control methods would increase the factor of safety on the results because it over predicts grain deterioration, but on the other side, this could result in increased capital and operating costs because of the over sizing of the aeration fan.

The levels of grain deterioration (ASTE) determined in comparison of models and in the sensitivity analysis were above 1.5 for several cases indicating unacceptable deterioration. These high levels of grain deterioration indicated that ventilation from 6:00 to 12:00 for 1 year is not a good fan-control method. These high levels of grain deterioration, however, do not invalidate the results of the comparison of models because only the relative deviations between ASTE predicted by the models were compared. Also, in the sensitivity analysis, only the relative deviations of ASTE caused by adding or subtracting uncertainties from the variables were calculated.

5.2.4. Comparison of predictions of ASTE

The comparison of equilibrium and non-equilibrium mathematical models (Tables 5.4 and 5.5) showed that the results produced by these models were significantly different when simulating aeration of stored wheat because the maximum absolute deviations of ASTE between the models were equal or higher than 30% for all tests except for Tests 20 (Table 5.4), 29, and 30 (Table 5.5) where the maximum deviations of ASTE were 26, 29, and 22%, respectively. The comparison of mathematical models using non-linear airflow (Table 5.5) showed almost the same trend as shown for the linear airflow case. The deviations of ASTE, however, were less for the non-linear airflow because the air velocity range was much higher than that used for linear airflow. The deviations of ASTE between the equilibrium and non-equilibrium models changed over the year (Figs. 5.9 and 5.10, and Tests 33 and 34, Table 5.5).

Table 5.4. Comparison of equilibrium and non-equilibrium mathematical models using linear airflow distribution, determined by the maximum and average absolute deviations of ASTE, to simulate aeration of stored wheat in Brazil after 1 year of storage

Test #	Variable	Deviation of ASTE (%)	
		Maximum	Average
1	Standard conditions[1]	51	43
2	airflow: 0.0111 $m^3 \cdot s^{-1} \cdot m^{-2}$	51	44
3	airflow: 0.0278 $m^3 \cdot s^{-1} \cdot m^{-2}$	44	35
4	fan temperature rise: 0°C	59	45
5	fan temperature rise: 3°C	49	35
6	ventilation time: 4:00 - 10:00	61	48
7	ventilation time: 0:00 - 6:00	64	50
8	ventilation time: 12:00 - 18:00	38	23
9	ventilation time: 18:00 - 24:00	57	47
10	grain layer thickness: 2.5 cm	53	44
11	grain layer thickness: 10 cm	49	42
12	grain layer thickness: 20 cm	47	40
13	grain layer thickness: 100 cm	38	38
14	grain depth: 4 m; grain layer thickness: 20 cm; and airflow: 0.0040 $m^3 \cdot s^{-1} \cdot m^{-2}$	45	15
15	grain depth: 8 m; grain layer thickness: 20 cm; and airflow: 0.0080 $m^3 \cdot s^{-1} \cdot m^{-2}$	46	14
16	initial grain moisture content: 12%	61	53
17	initial grain moisture content: 14%	40	33
18	initial grain temperature: 40°C	52	45
19	Offset in the equilibrium relative humidity in the equilibrium model: 5%	37	29
20	same as Test 19 and ventilation time: 12:00 - 18:00	26	13
21	location: Porto Alegre	47	40
22	location: Cuiabá	43	27
23	location: Goiânia	49	42
24	worst year: 1969	52	45
25	storage period: 1 Nov. 1965 - 31 Oct. 1966	52	43

[1]Standard conditions were used as follow unless the variable specifies otherwise — location: Curitiba; ventilation time: 6:00 - 12:00; airflow: 0.0056 $m^3 \cdot s^{-1} \cdot m^{-2}$; fan temperature rise: 1°C; total grain depth: 1 m; grain layer thickness: 5 cm; initial grain moisture content: 13%; initial grain temperature: 30°C; storage period: 1 Dec. 1965 - 30 Nov. 1966; and offset in the equilibrium relative humidity was not simulated in the equilibrium model.

Table 5.5. Comparison of equilibrium and non-equilibrium mathematical models using non-linear airflow distribution, determined by the maximum and average absolute deviations of ASTE, to simulate aeration of stored wheat in Curitiba, Brazil after 1 year of storage

Test #	Variable	Deviation of ASTE (%)	
		Maximum	Average
26	Standard conditions[1]	45	33
27	airflow: 0.091 - 0.796 $m^3 \cdot s^{-1} \cdot m^{-2}$	34	24
28	fan temperature rise: 3°C	32	29
29	fan temperature rise: 5°C	29	24
30	ventilation time: 12:00 - 18:00	22	19
31	grain layer thickness: 60 cm	33	29
32	Offset in the equilibrium relative humidity in the equilibrium model: 5%	-30	20
33	same as Test 32 and storage period: 1 - 31 Dec. 1965	61	16
34	same as Test 32 and storage period: 1 Dec. 1965 - 31 Oct. 1966	30	20

[1]Standard conditions as given in Table 5.4 except — airflow: 0.018 - 0.159 $m^3 \cdot s^{-1} \cdot m^{-2}$; total grain depth: 6 m; grain layer thickness: 30 cm.

5.2.5. Effects of simulation conditions

5.2.5.1. Airflow and fan temperature rise

The maximum deviations of ASTE decreased when the airflow or fan temperature rise were increased for both linear (Fig. 5.9) and non-linear airflows (Fig. 5.10). These deviations decreased as the air velocity increased (Tests 1, 2, and 3, Table 5.4 or 26 and 27, Table 5.5) because, as the air velocity increases, the grain moisture contents predicted by the non-equilibrium model approach the same equilibrium moisture contents that are calculated in the equilibrium model. The results produced by the equilibrium and non-equilibrium models were not significantly different for 5°C fan temperature rise and ventilation time of 12:00 to 18:00 because the

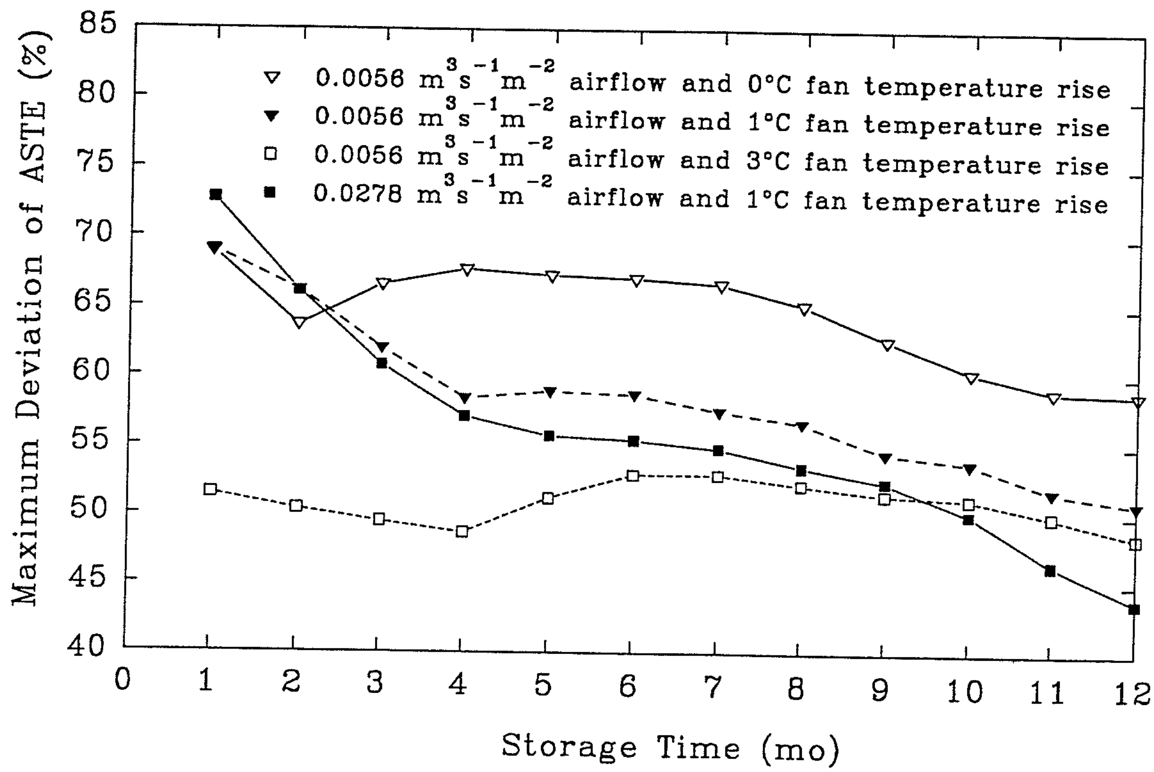

Fig. 5.9. Maximum deviations of allowable storage time elapsed predicted by the equilibrium and non-equilibrium mathematical models to simulate aeration of stored wheat with a linear airflow distribution at Curitiba, Brazil

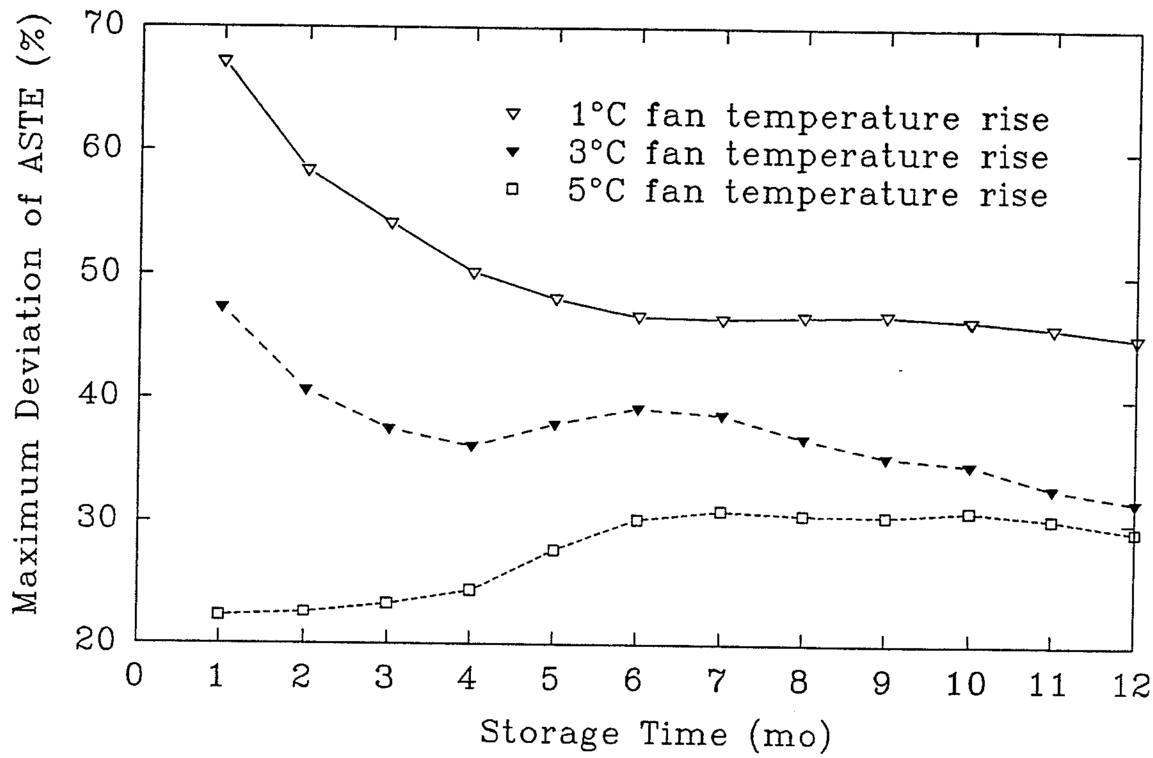

Fig. 5.10. Maximum deviations of allowable storage time elapsed predicted by the equilibrium and non-equilibrium mathematical models to simulate aeration of stored wheat with a non-linear airflow distribution at Curitiba, Brazil

differences in ASTE decreased as the airflow and the fan temperature rise were increased (Tests 29 and 30, Table 5.5).

The maximum deviations of ASTE at 3°C fan temperature rise were much lower than the deviations at 1°C for the first 5 mo of storage at 0.0056 $m^3 \cdot s^{-1} \cdot m^{-2}$, for linear airflow (Fig. 5.9). A similar pattern of changes for the maximum deviations of ASTE over the year was obtained for non-linear airflow when the fan temperature rise was increased from 1 to 5°C (Fig. 5.10). These deviations, however, were greater for linear airflow compared with non-linear airflow at 3°C fan temperature rise. The grain under non-linear airflow showed a quicker response to climate changes because the airflow was much higher.

The percentages of calculations predicting drying, wetting, and hysteresis with non-linear airflow at standard conditions (1°C temperature rise) were about 25, 66, and 9%, respectively, while for a 5°C fan temperature rise they were 34, 48, and 18%, respectively. Therefore, deviations in ASTE predicted by the models decreased significantly for test conditions where drying predominated (Tests 8, 20, 22, 29, and 30, Tables 5.4 and 5.5). Other sets of conditions that promote drying had a similar effect as increased fan temperature rise.

5.2.5.2. Ventilation period

Of the five 6-h ventilation periods throughout the day that were compared (Tests 1 and 6 to 9, Table 5.4) for linear airflow the deviations in ASTE between the two models were all high except for the driest, warmest period of 12:00 to 18:00 (Test 8, Table 5.4). For example, the average absolute deviation in ASTE after 1 year of storage was 23% for 12:00 to 18:00 while for the other four time periods it varied between 43 and 50%. The maximum deviations of ASTE, however, were significant (greater than 30%) for all ventilation periods for linear airflow but not for non-linear airflow during the period 12:00 to 18:00 (Test 30, Table 5.5).

5.2.5.3. Grain layer thickness and grain depth

For linear airflow, the deviations in ASTE decreased when the grain layer thickness was increased from 20 to 100 cm (Tests 12 and 13, Table 5.4) and while they decreased only slightly when the thickness was increased from 2.5 to 20 cm (Tests 1, 10, and 11, Table 5.4). For non-linear airflow, the deviations decreased slightly when the grain layer thickness was increased from 30 to 60 cm (Tests 26 and 31, Table 5.5). When the grain layer thickness was doubled the changes in the deviations of ASTE for linear airflow (Tests 1 and 11, Table 5.4) were smaller than those for non-linear airflow (Tests 26 and 31, Table 5.5). The average absolute deviations of ASTE decreased significantly when the grain depth was increased to 4 or 8 m (Tests 14 and 15, Table 5.4). These deviations decreased when the grain depth was increased because the number of times that wetting was calculated was significantly decreased. The changes in the deviations, however, were not significant between 4 and 8 m. The maximum and average deviations in ASTE decreased for Tests 14 and 15 compared with Test 1 because the grain layer thickness was increased and because these deviations were calculated only in the bottom 1 m for Test 1 while they were calculated in the whole bin for Tests 14 and 15 although a same airflow rate was used for all three tests (1 $L \cdot s^{-1} \cdot m^{-3}$).

5.2.5.4. Initial moisture content and temperature of the grain

The deviations of ASTE decreased slightly when the initial grain moisture content was increased from 13 to 14% (Tests 1 and 17, Table 5.4). The average ASTE predicted by the equilibrium model for 13 and 14% initial moisture contents were 4.3 and 4.6, respectively, while they were 2.4 and 3.0 when using the non-equilibrium model. The increased initial moisture content caused an increase in the drying calculations and a decrease in the wetting calculations which led to a decrease in the deviations of ASTE. For the same reason, the deviations of ASTE decreased when the initial moisture content was increased from 12 to 13%. Changing the initial grain temperature from 30 to 40°C did not affect the deviations of ASTE.

5.2.5.5. Offset in the equilibrium relative humidity

A 5% offset in the equilibrium relative humidity in moisture adsorption in the equilibrium model decreased significantly the deviations of ASTE (Tests 19, Table 5.4 and 32, Table 5.5) after 1 year of storage for linear and non-linear airflow. Sanderson et al. (1989) found that a 5% offset in the equilibrium relative humidity was adequate for simulating the readsorption of water by wheat up to moisture contents of 15%. For readsorption to 17%, however, other modifications to the equilibrium model were needed. Therefore, it is reasonable that the non-equilibrium model has more accuracy when predicting aeration of stored wheat than the equilibrium model. The models presented no significant differences for the ventilation period 12:00 - 18:00 when the offset in the equilibrium relative humidty was included. Considering the results obtained by Schultz et al. (1984) and also considering the importance of accurately predicting wetting in the bottom of large horizontal grain storages in warm and humid climates, it is reasonable that the non-equilibrium model is preferable to the equilibrium model in such conditions.

The deviations of ASTE between the equilibrium model with and without a 5% offset in the equilibrium relative humidity were not significant for airflows of 0.0056 and 0.0278 $m^3 \cdot s^{-1} \cdot m^{-2}$ and fan temperature rises of 1 and 3°C (Table 5.6). These results show that a simple inclusion of

Table 5.6. Effect of 5% offset in the equilibrium relative humidity in the equilibrium mathematical model using linear airflow distribution, determined by the maximum and average absolute deviations of ASTE, to simulate aeration of stored wheat in Curitiba, Brazil after 1 year of storage[1]

Test #	Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Fan Temperature Rise (°C)	Deviation of ASTE (%)	
			Maximum	Average
35	0.0056	1	27	20
36	0.0056	3	20	16
37	0.0278	1	27	25
38	0.0278	3	22	19

[1]Standard conditions as given in Table 5.4.

an offset in the equilibrium relative humidity is not sufficient to generate a significant change in the equilibrium model. The over prediction in ASTE, however, was greatly decreased when the offset in the equilibrium relative humidity was assumed. These results agree with those of Schultz et al. (1984) who stated that adsorption should be considered separately and hysteresis must be included if the model is to accurately predict wetting. Schultz et al. (1984) also found that the equilibrium model over predicted wetting while the non-equilibrium model over predicted drying.

5.2.5.6. Geographical location, year of simulation, and storage period

The average absolute deviation of ASTE for Cuiabá, which has the highest average temperature and lowest relative humidity (Table 4.2), were much lower than those for the other geographical locations (Tests 1 and 21 to 23, Table 5.4). There were no significant differences among the maximum deviations of ASTE for the Brazilian locations. There was no significant difference in the deviations of ASTE simulated when comparing the median year and the worst year (Tests 1 and 24, Table 5.4) or when the storage date was advanced one month (Test 25, Table 5.4).

5.3. Comparison of Equilibrium and Non-Equilibrium Models for Winnipeg

5.3.1. Summary

The results produced by the equilibrium and non-equilibrium models were not significantly different (α=0.05) for simulating the aeration of wheat stored in Winnipeg from September to November for most test conditions including the aeration conditions recommended for the Canadian Prairies (airflow rate of 1 $L \cdot s^{-1} \cdot m^{-3}$ and ventilation time of 0:00 to 6:00) although it was observed that the equilibrium model had a tendency to over predict drying and wetting rates.

The differences between the equilibrium and non-equilibrium models were affected by airflow rate, fan temperature rise, airflow distribution, grain layer thickness, year of simulation, initial moisture content and temperature of the grain, ventilation period, and assuming a 5% offset in the equilibrium relative humidity in moisture adsorption calculated by the equilibrium model.

5.3.2. Changes of moisture content, temperature, and ASTE

The moisture content, temperature, and ASTE simulated using the non-equilibrium model at standard conditions with linear airflow (Fig. 5.11) were similar to those obtained for non-linear airflow. The ASTE at 3 mo of storage for the top and bottom layers, and for the average of all layers were 0.6, 0.2, and 0.4, respectively, for linear airflow compared with 0.4, 0.2, and 0.2 for non-linear airflow. The deterioration was lower for the non-linear airflow because the higher air velocity increased the speed of the cooling front although the average grain moisture content was slightly higher for non-linear airflow. An increased air velocity may increase the speed of the drying or wetting front depending on the air conditions during the ventilation period but the speed of the cooling front was the main factor affecting the rate of grain spoilage for Winnipeg weather conditions.

The climate in Winnipeg during September to November was relatively dry because the percentages of calculations predicting drying, wetting, and hysteresis were 71, 16, and 13%, respectively, when simulating standard conditions. Also, the percentage of times that the equilibrium relative humidity of the air entering any grain layer was equal to or greater than 95% was only 0.6%. Thus, the especial search technique given by Thompson (1972) for this wetting condition was used in only 0.6% of the moisture content calculations for all grain layers. Therefore, for drying conditions, the assumption of equilibrium used in the non-equilibrium model when the equilibrium relative humidity of the air entering any grain layer was equal to or greater than 95% (Sec. 4.5.1) did not affect the predictions of moisture content by the non-equilibrium model.

The deterioration (ASTE) after 3 mo of storage predicted by the equilibrium model was slightly lower than that predicted by the non-equilibrium model for most grain layers and air

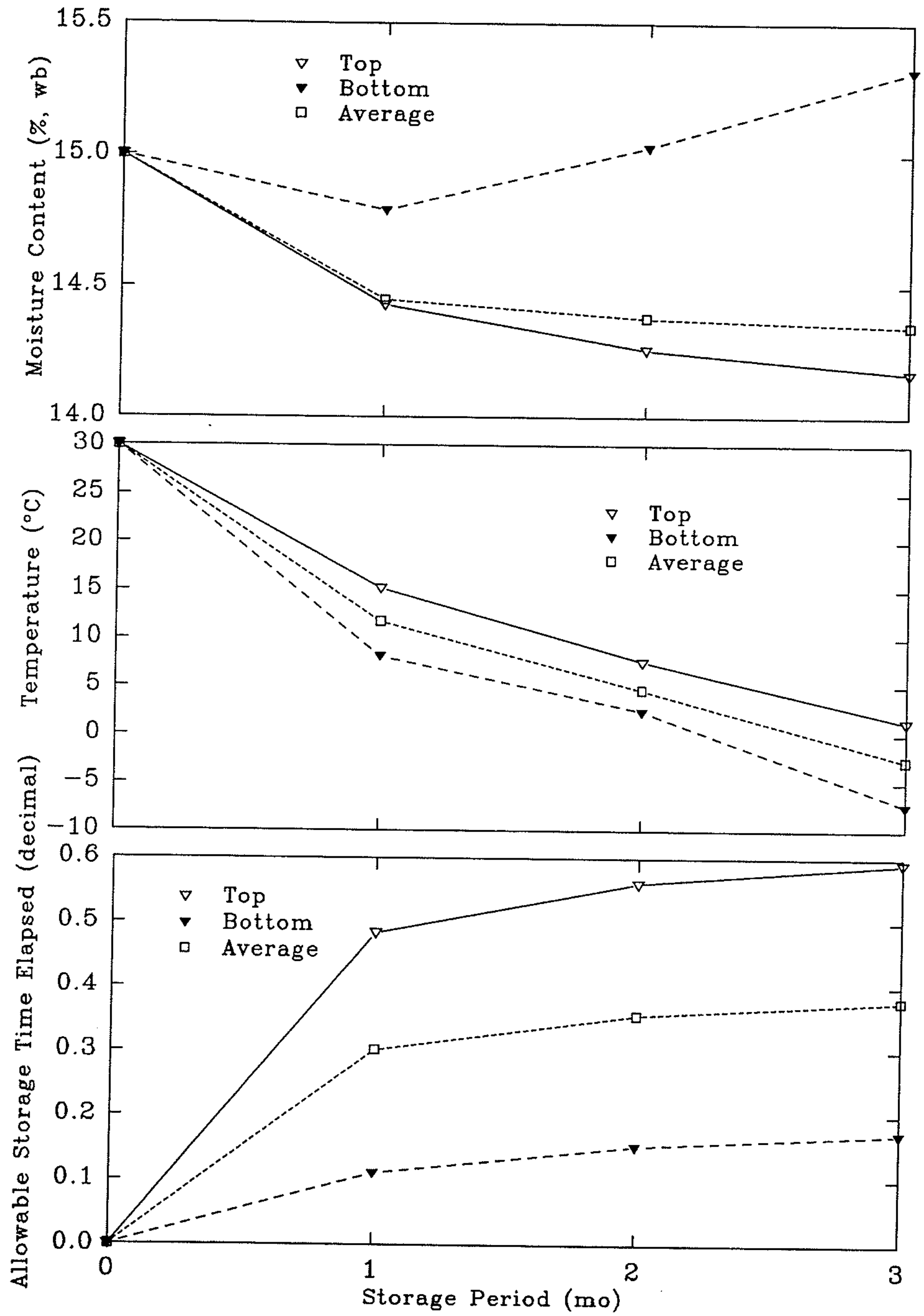

Fig. 5.11. Moisture content, temperature, and allowable storage time elapsed (ASTE) predicted by the non-equilibrium mathematical model for wheat stored at Winnipeg, Canada and intermittently aerated for September to November, 1979 with a linear airflow distribution from the bottom to the top

conditions for both linear and non-linear airflow distributions (Figs. 5.12 and 5.13). Because of the dry climate in Winnipeg, the over prediction of drying was not balanced out by an over prediction of wetting and therefore resulted in an underprediction of spoilage. Several other researchers have also found that equilibrium models over predict the drying and wetting rates especially in the bottom layers (Morey et al. 1979, Van Ee and Kline 1979a, Mittal and Otten 1982). For example, the equilibrium model over predicted the grain deterioration for the first grain layer where wetting conditions prevailed during the ventilation period and underpredicted it for most of the remaining layers where drying conditions prevailed (Figs. 5.12 and 5.13).

5.3.3. Comparison of predictions of ASTE

The results produced by the equilibrium and non-equilibrium mathematical models were not different when using a ventilation time of 0:00 to 6:00, initial moisture content of 15%, and grain layer thickness 28.4 cm (Tables 5.7 and 5.8) because the maximum absolute deviations in ASTE were equal to or lower than 30% for almost all tests. The results produced by the models, however, were different for Tests 60 and 73 because the maximum absolute deviations in ASTE for these tests were 37 and -34%, respectively (Table 5.8). The equilibrium model over predicted drying and wetting rates depending on the air conditions during the ventilation period, particularly in the bottom layers. For example, the ASTE was over predicted for Tests 39, 40, 43, 55, and 57 (Table 5.7) and Tests 59 to 61, 67, and 71 (Table 5.8) because there was an over prediction of wetting. Conversely, the ASTE was under predicted for Tests 39, 42, 44, 53, 54, 56, and 58 (Table 5.7) and Tests 62 to 64, 69, 70, 72, and 73 (Table 5.8) because there was an over prediction of drying.

The comparison of mathematical models using non-linear airflow (Table 5.8) showed

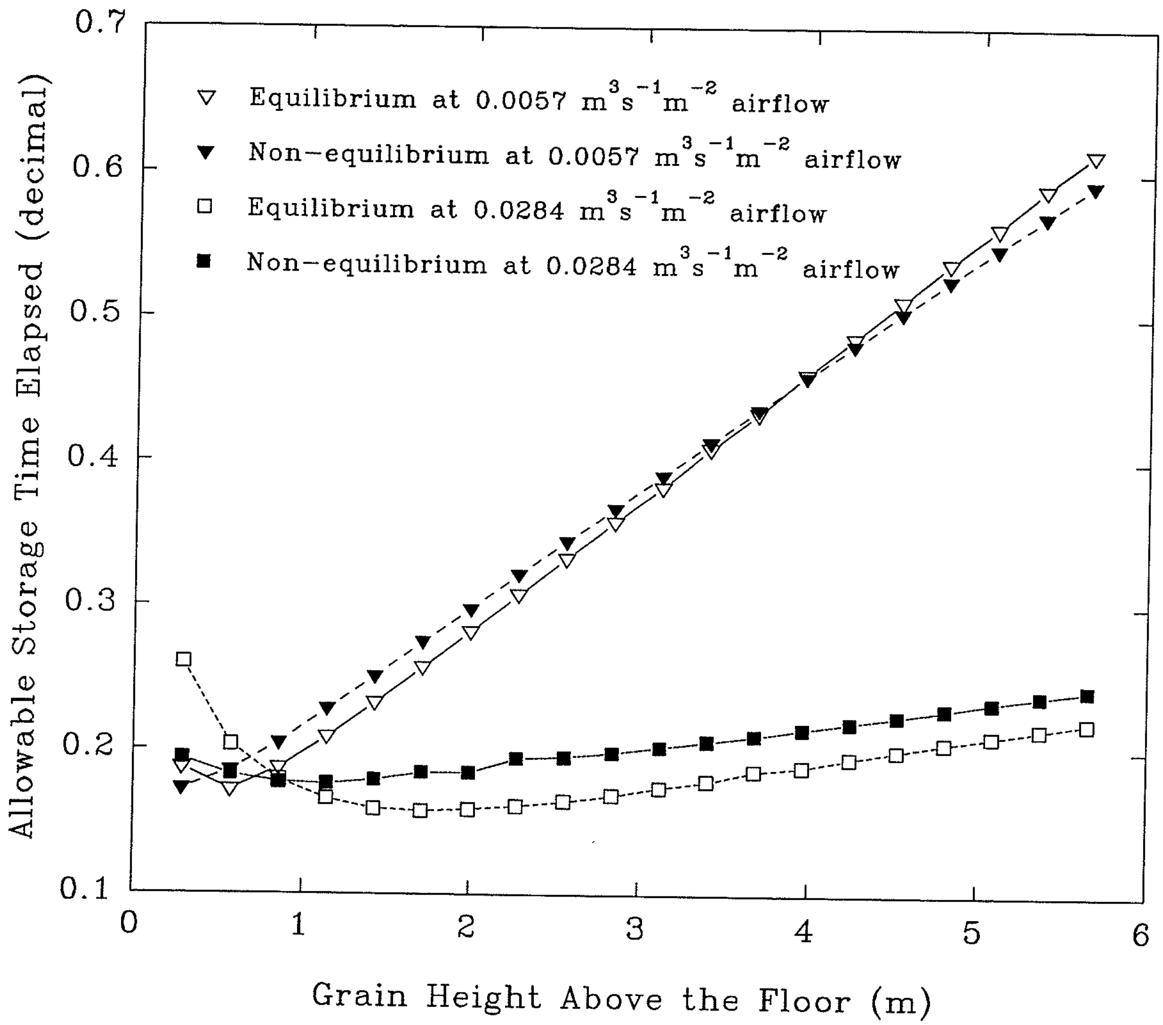

Fig. 5.12. Allowable storage time elapsed predicted by the equilibrium and non-equilibrium mathematical models for wheat stored at Winnipeg, Canada and aerated for 3 mo with linear airflow distribution and 1°C fan temperature rise

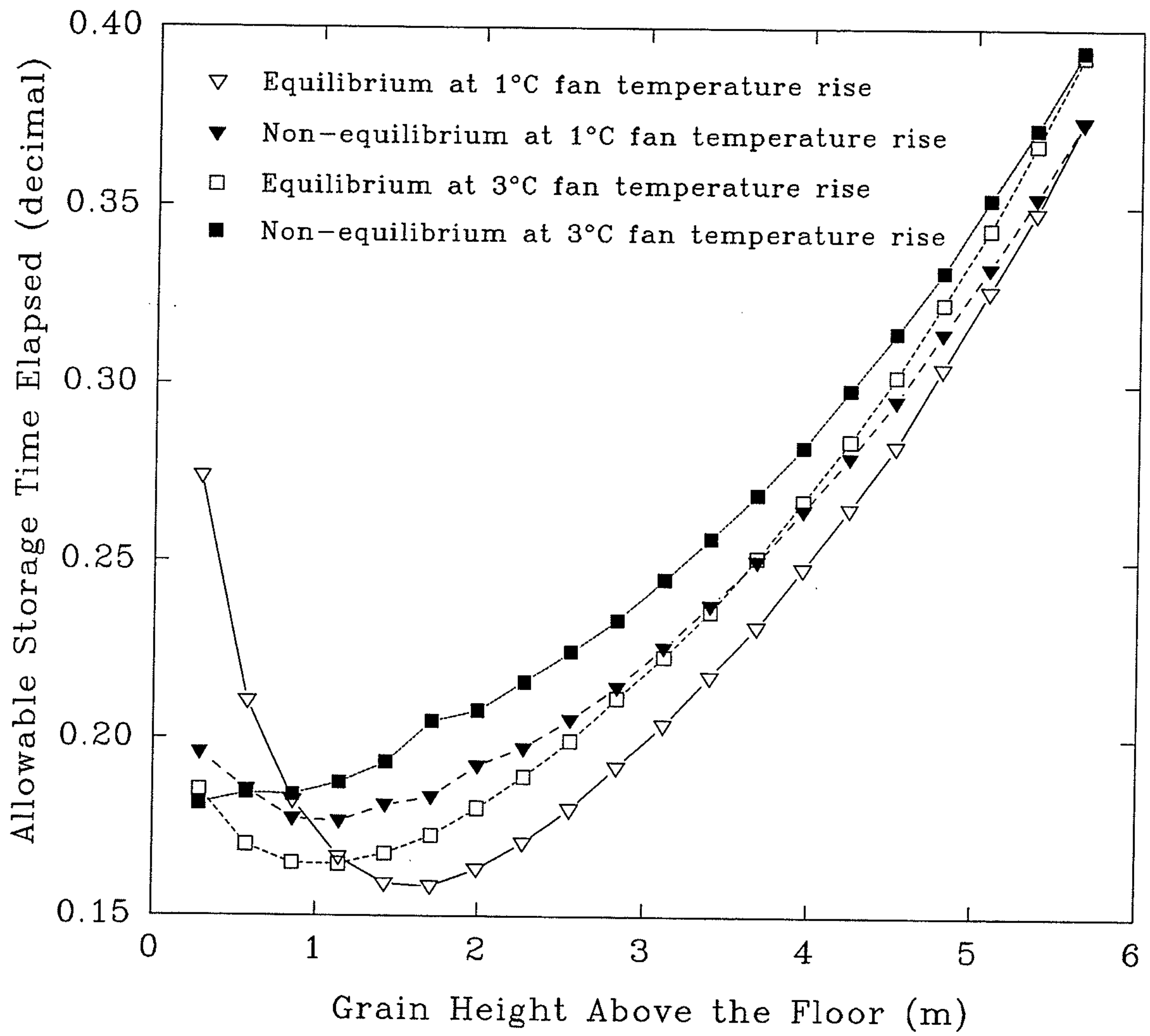

Fig. 5.13. Allowable storage time elapsed predicted by the equilibrium and non-equilibrium mathematical models for wheat stored at Winnipeg, Canada and aerated for 3 mo with air velocities varying from 0.0059 $m^3 \cdot s^{-1} \cdot m^{-2}$ at the top to 0.0351 $m^3 \cdot s^{-1} \cdot m^{-2}$ at the bottom

Table 5.7. Comparison of equilibrium and non-equilibrium mathematical models using linear airflow distribution, determined by the maximum and average absolute deviations in ASTE, to simulate aeration of stored wheat in Winnipeg, Canada after 3 mo of storage

Test #	Variable	Deviation in ASTE (%)	
		Maximum	Average
39	Standard conditions[1]	-9	4
40	airflow: 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$	26	14
41	fan temperature rise: 0°C	12	4
42	fan temperature rise: 3°C	-11	4
43	fan temperature rise: 0°C; airflow: 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$	28	15
44	fan temperature rise: 3°C; airflow: 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$	-19	13
45	ventilation time: 12:00 - 18:00	-34	5
46	grain layer thickness: 94.7 cm	33	13
47	grain layer thickness: 14.2 cm	17	5
48	grain depth: 4 m; grain layer thickness: 20 cm; and airflow: 0.0040 $m^3 \cdot s^{-1} \cdot m^{-2}$	-9	4
49	grain depth: 6 m; grain layer thickness: 20 cm; and airflow: 0.0060 $m^3 \cdot s^{-1} \cdot m^{-2}$	-13	5
50	initial moisture content: 12%	42	8
51	initial grain temperature: 15°C	11	3
52	Offset in the equilibrium relative humidity in the equilibrium model: 5%	-10	4
53	worst year: 1963	-6	3
54	worst year: 1963; airflow: 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$	-12	7
55	worst year: 1963; fan temperature rise: 0°C	7	3
56	worst year: 1963; fan temperature rise: 3°C	-5	3
57	same as Test 54 and fan temperature rise: 0°C	15	8
58	same as Test 54 and fan temperature rise: 3°C	-22	9

[1]Standard conditions were used as follows unless a variable is specified otherwise — initial moisture content: 15%; initial grain temperature: 30°C; ventilation time: 0:00 - 6:00; storage period: 1 Sept. - 30 Nov. 1979; airflow: 0.0057 $m^3 \cdot s^{-1} \cdot m^{-2}$; fan temperature rise: 1°C; total grain depth: 5.7 m; grain layer thickness: 28.4 cm; and offset in the equilibrium relative humidity was not simulated in the equilibrium model.

Table 5.8. Comparison of equilibrium and non-equilibrium mathematical models using non-linear airflow distribution, determined by the maximum and average absolute deviations in ASTE, to simulate aeration of stored wheat in Winnipeg, Canada after 3 mo of storage

Test #	Variable	Deviation in ASTE (%)	
		Maximum	Average
59	Standard conditions[1]	28	10
60	airflow: 0.0290 - 0.0690 $m^3 \cdot s^{-1} \cdot m^{-2}$	37	15
61	fan temperature rise: 0°C	28	11
62	fan temperature rise: 3°C	-19	9
63	fan temperature rise: 3°C; airflow: 0.0290 - 0.0690 $m^3 \cdot s^{-1} \cdot m^{-2}$	-18	14
64	ventilation time: 12:00 - 18:00	-76	17
65	grain layer thickness: 56.8 cm	18	7
66	Offset in the equilibrium relative humidity in the equilibrium model: 5%	-19	9
67	initial moisture content: 13%	60	16
68	initial grain temperature: 15°C	27	4
69	worst year: 1963	-8	5
70	worst year: 1963; airflow: 0.0290 - 0.0690 $m^3 \cdot s^{-1} \cdot m^{-2}$	-15	8
71	worst year: 1963; fan temperature rise: 0°C	15	6
72	worst year: 1963; fan temperature rise: 3°C	-23	7
73	same as Test 70 and fan temperature rise: 3°C	-34	13

[1]Standard conditions as given in Table 5.7 and airflow: 0.0059 - 0.0351 $m^3 \cdot s^{-1} \cdot m^{-2}$.

almost the same trend as shown for the linear airflow case. The deviations in ASTE, however, were different for the non-linear airflow because the air velocity range was higher than that used for linear airflow. The increased air velocity increased the drying or wetting rates according to the air conditions thus resulting in under or over prediction in ASTE especially in the bottom layers. The deviations in ASTE between the equilibrium and non-equilibrium models increased or decreased over the storage period depending on the conditions used for the simulations such as airflow, fan temperature rise, year of simulation, and initial grain conditions but the average absolute deviations in ASTE normally decreased over the storage period.

5.3.4. Effects of simulation conditions

5.3.4.1. Airflow and fan temperature rise

The maximum absolute deviations in ASTE normally increased and the average absolute deviations in ASTE always increased when the airflow was increased either for linear or non-linear airflows (Tables 5.7 and 5.8). The differences in grain moisture content and ASTE predicted by both models increased when the air velocity was increased. For example, the deviations in grain moisture content nearly doubled and the absolute deviations in ASTE almost tripled when the airflow was increased from 0.0057 to 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$ for linear airflow distribution (Tests 39 and 40, Table 5.7). The differences in the grain temperatures predicted by the models decreased slightly for most cases when the airflow was increased. The differences in ASTE predicted by the models, consequently, are caused by over drying or over wetting depending on the air conditions during the aeration period.

Decreasing the fan temperature rise from 1 to 0°C resulted in an over prediction of the maximum ASTE by the equilibrium model in comparison with the non-equilibrium model particularly when the airflow was increased (Tests 39 and 41, 40 and 43, 53 and 55, or 54 and 57, Table 5.7 and Tests 59 and 61 or 69 and 71, Table 5.8). Conversely, increasing the fan temperature rise from 1 to 3°C, resulted in an under prediction of the maximum ASTE by the equilibrium model (Tests 39 and 42, 40 and 44, 53 and 56, or 54 and 58, Table 5.7 and Tests 59 and 62, 60 and 63, 69 and 72, or 70 and 73, Table 5.8). The over prediction in ASTE was caused by an over prediction of wetting by the equilibrium model and the under prediction in ASTE was caused by an over prediction of drying. The average absolute deviations in ASTE for the same airflow, however, did not change when the fan temperature rise was changed (e.g. Tests 39, 41, and 42 or 40, 43, and 44, Table 5.7).

5.3.4.2. Ventilation period

The maximum deviations in ASTE between the two models were high for ventilation from 12:00 to 18:00 (Test 45, Table 5.7) indicating the trend of the equilibrium model in over predicting drying. The over prediction of drying increased for non-linear airflow because of the increased air velocity (Test 64, Table 5.8). Because of this, equilibrium mathematical models should not be used for grain drying simulations when the airflow rates for unheated drying are higher than 5 $L \cdot s^{-1} \cdot m^{-3}$. These results agree with the results of Metzger and Muir (1983b) for simulating ventilation of stored wheat. They observed that equilibrium was not a good assumption for airflow rates of 9.0 $L \cdot s^{-1} \cdot m^{-3}$ while relatively accurate moisture contents were predicted for airflow rates of 1.9 $L \cdot s^{-1} \cdot m^{-3}$.

5.3.4.3. Grain layer thickness and grain depth

The absolute deviations in ASTE increased when the grain layer thickness was increased for both linear and non-linear airflows (Tests 39 and 46, Table 5.7 and Tests 59 and 65, Table 5.8). The absolute deviations in ASTE also increased when the grain layer thickness was decreased for linear airflow distribution and no apparent trend was observed for these deviations (Tests 39 and 47, Table 5.7). The average absolute deviations in ASTE, however, increased when the grain layer thickness was increased. The absolute deviations in ASTE increased slightly when the grain depth was increased from 4 to 6 m (Tests 48 and 49, Table 5.7).

5.3.4.4. Initial moisture content and temperature of the grain

The deviations in ASTE increased when the initial moisture content was decreased from 15 to 12% (Tests 39 and 50, Table 5.7) or from 15 to 13% (Tests 59 and 67, Table 5.8). The deviations in ASTE increased because as the initial moisture content decreased the amount of wetting increased. Under prediction of ASTE (maximum deviation) was changed to over prediction when the initial grain temperature was decreased from 30 to 15°C for linear airflow but the average deviation in ASTE was not changed (Tests 39 and 51, Table 5.7). A change in the initial grain temperature affected only the average deviation in ASTE for non-linear airflow (Tests 59 and 68, Table 5.8).

5.3.4.5. Offset in the equilibrium relative humidity

A 5% offset in relative humidity in moisture adsorption did not change the deviations in ASTE for linear airflow (Test 52, Table 5.7) but the maximum absolute deviation in ASTE was reduced for non-linear airflow (Test 66, Table 5.8). Over prediction of wetting, however, changed to over prediction of drying when the offset in relative humidity was included.

The deviations in ASTE between the equilibrium model with and without a 5% offset in the equilibrium relative humidity were not important for airflows of 0.0057 and 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$ and fan temperature rises of 1 and 3°C. The maximum deviations in ASTE after 3 mo of storage were between 15 and 16% at 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$ and 1°C fan temperature rise. This shows that a simple inclusion of an offset in the equilibrium relative humidity is not sufficient to generate differences between the equilibrium model with and without the offset. The over prediction in

ASTE, however, was decreased for Test 66 when the offset in the equilibrium relative humidity was assumed, indicating that the offset improved the equilibrium model compared with the non-equilibrium model, especially at high airflow rates.

5.3.4.6. Year of simulation

The equilibrium model over predicted drying in the worst year, 1963, and over predicted wetting in the median year, 1979, because 1963 was drier and warmer than 1979 (Tests 53 to 58, Table 5.7 and Tests 69 to 73, Table 5.8). For example, the maximum deviation in ASTE changed from 26 to -12% for linear airflow when simulating at 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$ and 1°C fan temperature rise. The over prediction of drying by the equilibrium model, however, was observed only for airflows higher than 0.0057 $m^3 \cdot s^{-1} \cdot m^{-2}$.

5.4. Sensitivity Analysis of the Non-equilibrium Model for Brazilian Locations

5.4.1. Summary

The most important variables when simulating aeration of wheat stored in Curitiba for 1 year using linear airflow distribution, in decreasing order, were the fan temperature rise, thin-layer wetting equation, and thin-layer drying equation.

The accuracy of the equations used to calculate airflow rate, specific heat, and equilibrium moisture content for adsorption and desorption by wheat was not important to simulate aeration of wheat stored in Curitiba because the errors introduced by these equations were lower than the uncertainty in predicting allowable storage time elapsed.

The wheat bulk density can be a constant, the net heat of sorption can be neglected, and the ratio of bin diameter to bin height was not important in the mathematical model to simulate aeration of wheat stored in Curitiba.

The model's sensitivity was affected by the airflow distribution, fan temperature rise, airflow rate, geographical location, grain depth, grain layer thickness, and initial moisture content of the grain.

5.4.2. Sensitivity analysis using fixed uncertainties

Among all variables a change in fan temperature rise caused the highest maximum deviations of ASTE (Tables 5.9 to 5.11) when adding a fixed uncertainty and using linear airflow. Other variables which also caused high maximum deviations of ASTE were the thin-layer wetting equation (parameter K') and thin-layer drying equation (parameter K). The maximum deviations of ASTE caused by incremental changes in the EMC desorption and adsorption equations, specific heat of wheat, airflow, thin-layer drying equation (parameter N), thin-layer wetting equation (parameter N'), net heat of sorption, air velocity, and wheat bulk density were lower than the uncertainty in predicting ASTE and can be considered insignificant.

Subtracting 0.5°C from the fan temperature rise (T_{fan}) produced higher maximum deviations of ASTE than adding the same amount (Table 5.10). Adding 0.5°C caused a decrease in the grain moisture content and ASTE and an increase in the grain temperature across the grain bulk (Fig. 5.14). The deviations in moisture content and ASTE decreased from the bottom to the top while the deviations in temperature were almost constant. The results obtained for the fan temperature rise showed that the amount of heat delivered by the aeration fan may be decisive in

Table 5.9. Sensitivity of the non-equilibrium mathematical model to airflow, bulk density and specific heat of the grain, and EMC equations using a linear airflow distribution, as determined by the maximum deviations in ASTE, when simulating aeration of wheat stored in Curitiba, Brazil for 1 year[1]

Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Fan Temperature Rise (°C)	Variable Change (%)	Maximum Deviations in ASTE (%) Caused by Changes in Variables				
			Airflow	Grain Bulk Density	Grain Specific Heat	EMC Equations	
						Desorption	Adsorption
0.0056	1	+6	-5	0	-3	-20	-14
	1	-6	6	0	3	19	11
	3	+6	-2	0	-2	-12	-12
	3	-6	2	0	2	15	10
0.0278	1	+6	-9	0	8	-27	-22
	1	-6	12	0	9	20	22
	3	+6	3	2	-4	-16	-17
	3	-6	3	-2	3	18	14

[1]Aeration conditions — ventilation time: 6:00 - 12:00; location: Curitiba, Brazil; total grain depth: 1 m; grain layer thickness: 5 cm; initial grain moisture content: 13%; initial grain temperature: 30°C; storage period: 1 Dec. 1965 - 30 Nov. 1966.

Table 5.10. Sensitivity of the non-equilibrium mathematical model to fan temperature rise and thin-layer equations using a linear airflow distribution, as determined by the maximum deviations in ASTE, when simulating aeration of wheat stored in Curitiba, Brazil for 1 year[1]

Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Fan Temperature Rise (°C)	Maximum Deviations in ASTE Caused by Changes in Variables									
		Fan Temperature Rise		Thin-Layer Drying Equation				Thin-Layer Wetting Equation			
				Parameter K		Parameter N		Parameter K'		Parameter N'	
		Change (°C)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)
0.0056	1	+0.5	32	+50	13	+30	9	+90	-23	+10	-11
	1	-0.5	-61	-50	-28	-30	-11	-90	34	-10	10
	3	+0.5	10	+50	7	+30	6	+90	-22	+10	-7
	3	-0.5	-17	-50	-13	-30	-7	-90	31	-10	7
0.0278	1	+0.5	48	+50	19	+30	15	+90	-27	+10	-19
	1	-0.5	-150	-50	-45	-30	-15	-90	47	-10	19
	3	+0.5	13	+50	11	+30	9	+90	-26	+10	-8
	3	-0.5	-21	-50	-20	-30	-9	-90	41	-10	8

[1]See Table 5.9 for aeration conditions.

Table 5.11. Sensitivity of the non-equilibrium mathematical model to net heat of sorption and bin area using a linear airflow distribution, as determined by the maximum deviations in ASTE, when simulating aeration of wheat stored in Curitiba, Brazil for 1 year[1]

Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Fan Temperature Rise (°C)	Maximum Deviations in ASTE Caused by Changes in Variables			
		Net Heat of Sorption (NHS)		Bin Area (A)	
		Change	Deviation (%)	Change	Deviation (%)
0.0056	1	NHS=0	-5	2 A	8
0.0056	3	NHS=0	-1	2 A	5
0.0278	1	NHS=0	-12	2 A	15
0.0278	3	NHS=0	2	2 A	8

[1]See Table 5.9 for aeration conditions.

dictating the allowable storage time because the grain deterioration in the bottom layers (up to 30 cm above the perforated floor) was affected significantly by a variation of ±0.5°C in the fan temperature rise (Fig. 5.14).

As the storage time increased the maximum deviations of ASTE increased for all variables and the relative importance of some variables changed (Fig. 5.15). Except for the first month of storage the non-equilibrium model was more sensitive to the temperature rise over the fan than any other variable when simulating at standard conditions (Fig. 5.15).

Van Ee and Kline (1979a) determined that a slight change (+0.5%) in the EMC of shelled corn had an important effect on the calculated final grain moisture content and on the rate of movement of the drying front. Because of this, Sharp (1982) recommended caution on the selection of an accurate EMC equation when simulating drying of corn at near ambient

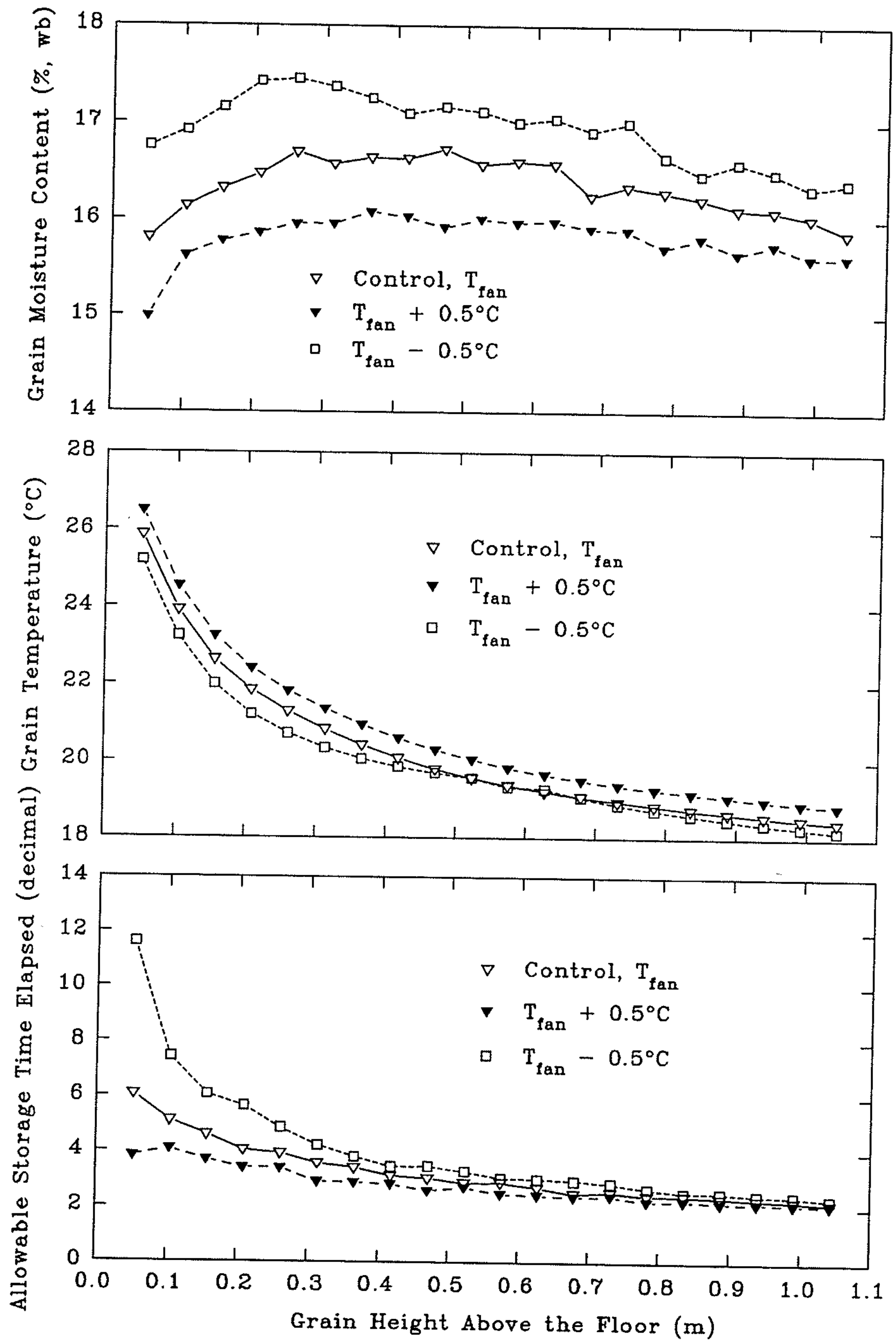

Fig. 5.14. Moisture content, temperature, and allowable storage time elapsed obtained when adding or subtracting 0.5°C from the fan temperature rise (T_{fan}) when simulating aeration of wheat stored in Curitiba, Brazil after 12 mo of storage using 1°C fan temperature rise, 0.1111 $m^3 \cdot s^{-1} \cdot m^{-2}$ airflow, linear airflow distribution, and aeration conditions given in Table 5.4

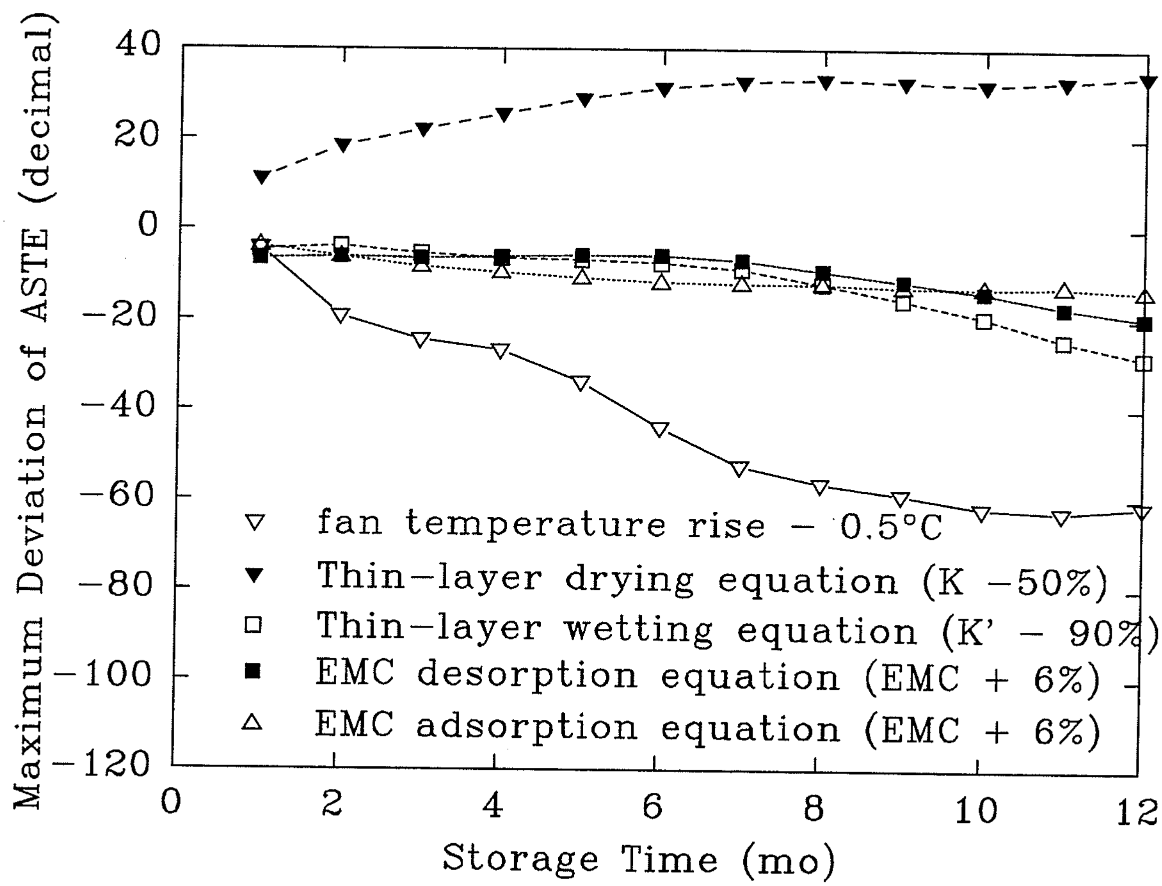

Fig. 5.15. Changes of maximum deviations of allowable storage time elapsed (ASTE) over 12 mo for the fan temperature rise, thin-layer drying equation, thin-layer wetting equation, EMC desorption and adsorption equations during the simulation of aeration of stored wheat in Curitiba, Brazil at standard conditions and using linear airflow distribution

temperatures. The uncertainty used in the EMC (±6% which corresponded to ±0.8 percentage points in the EMC at 13%) did not generate significant deviations in ASTE.

Neglecting the net heat of sorption caused no significant maximum deviations of ASTE (Table 5.11). Therefore, the net latent heat of vaporization equations for desorption and adsorption by wheat, which were used to calculate net heat of sorption are not necessary in the computer model.

Reducing the air velocity to one-half by doubling the bin area for a constant airflow per unit grain volume (1 and 5 $L \cdot s^{-1} \cdot m^{-3}$) caused no significant maximum deviations of ASTE (Table 5.11). Consequently, the ratio of bin diameter to bin height is not important when simulating the aeration of stored wheat.

Wheat bulk density caused the lowest maximum deviations of ASTE among all variables. The results for wheat bulk density were obtained assuming no change in the air velocity due to a variation in the bulk density. The maximum deviations of ASTE for wheat bulk density, when the air velocity was changed in proportion to the changes in grain volume, were practically the same as those obtained when the airflow was changed ±6% (Table 5.9). Therefore, these deviations were caused by a change in the airflow and not by a change in the bulk density. Consequently, a constant bulk density can be used in simulations of aeration of stored wheat without any significant error. The grain bulk density has a greater importance in drying processes compared with grain aeration because during drying bulk density varies across a greater range and also because the variation of bulk density affects the airflow due to a variation in the air resistance to airflow.

5.4.3. Effects of simulation conditions

5.4.3.1. Airflow distribution

The maximum deviations of ASTE for all variables were greater for non-linear airflow than for linear airflow. The maximum deviations of ASTE, when using non-linear airflow and 3°C fan temperature rise (Table 5.12), are only shown for the variables which caused the maximum deviations in ASTE. The deterioration was higher for the non-linear airflow because the higher air velocity in the bottom layers brought in more moisture to these layers (see Sec. 5.2.2). For example, with linear airflow distribution increasing the air velocity from 0.0056 to 0.4336 $m \cdot s^{-1}$ caused an increase in the maximum deviations of ASTE from 60 to 700% for a 1°C fan temperature rise and from 17 to 38% for a 3°C fan temperature rise. Therefore, it is important to simulate accurately the air velocity gradient in the bottom layers of large horizontal grain storages for determining the best airflow rates and fan-control methods for Brazilian locations.

5.4.3.2. Fan temperature rise and airflow

The mathematical model was less sensitive to the changes in all variables when the fan temperature rise was increased or the airflow was decreased (Tables 5.9 to 5.11). In addition, the relative importance of the variables was changed when the fan temperature rise was increased. For example, the fan temperature rise was more important than the parameter K' of the thin-layer wetting equation at 1°C but not at 3°C (Table 5.10). The relative importance of all variables did not change when the airflow was changed. Increasing the uncertainty in the measurement of airflow from ±6% to ±15% as determined by Metzger et al. (1981) would practically double the maximum absolute deviations in ASTE. The relative importance of the variables, however, would not be changed if the uncertainty in the measurement of airflow was increased from ±6% to ±15%.

Table 5.12. Sensitivity of the non-equilibrium mathematical model to fan temperature rise, thin-layer equations, and EMC equations using a non-linear airflow distribution, as determined by the maximum deviations of ASTE, when simulating aeration of wheat stored in Curitiba, Brazil for 1 year[1]

Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Maximum Deviations in ASTE Caused by Changes in Variables									
	Fan Temperature Rise		Thin-Layer Equations				EMC Equations			
			Drying-Parameter K		Wetting-Parameter K'		Desorption		Adsorption	
	Change (°C)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)
0.018 - 0.159	-0.5	-18	-50	-21	-90	48	+6	17	-6	-18
0.091 - 0.796	-0.5	-24	-50	-26	-90	56	+6	19	-6	-21

[1]Aeration conditions — fan temperature rise: 3°C; ventilation time: 6:00 - 12:00; location: Curitiba, Brazil; total grain depth: 6 m; grain layer thickness: 30 cm; initial grain moisture content: 13%; initial grain temperature: 30°C; storage period: 1 Dec. 1965 - 30 Nov. 1966.

5.4.3.3. Grain depth and grain layer thickness

The maximum deviations in ASTE for fan temperature rise were affected by both grain depth and grain layer thickness in the sensitivity analysis (Table 5.13). Grain depth and grain layer thickness had little effect on the maximum deviations for the EMC adsorption equation and parameter K' of the thin-layer wetting equation (Table 5.13). The maximum deviations in ASTE for the fan temperature rise increased when the grain layer thickness was decreased from 20 to 2.5 cm but no trend was observed when the grain depth was increased from 1 to 8 m. These results indicate that care should be taken to select the grain layer thickness when simulating grain aeration in warm and humid climates. Probably, the best choice for these climatic conditions is to use variable grain layer thicknesses, i.e. increase the grain layer thickness from the bottom to the top. The minimum grain layer thickness will depend on the maximum amount of spoiled grain that is acceptable.

5.4.3.4. Year of simulation and geographical location

The differences between the maximum deviations of ASTE for the median and worst years were not important when the results of the sensitivity analysis were compared for each variable at the standard conditions and using a linear aiflow distribution. Therefore, the year used for the simulations did not affect the model's sensitivity for Curitiba. The geographical location used for the simulations affected the model's sensitivity for the following variables: fan temperature rise, airflow, specific heat, EMC adsorption equation, thin-layer drying equation (parameter N), and thin-layer wetting equation (parameter N'). For standard conditions, the maximum deviations of ASTE for the fan temperature rise for Curitiba, Campo Grande, and Cuiabá were -61, -18, and -13%, respectively, during the year 1966. The maximum deviations of ASTE for Cuiabá, which

Table 5.13. Effect of grain depth and grain layer thickness on the sensitivity of the non-equilibrium mathematical model to fan temperature rise, EMC adsorption equation, and thin-layer wetting equation using a linear airflow distribution and at standard conditions, determined by the maximum deviation of ASTE, when simulating aeration of wheat stored in Curitiba, Brazil for 1 year[1]

Grain Depth (m)	Grain Layer Thickness (cm)	Maximum Deviations in ASTE Caused by Changes in Variables					
		Fan Temperature Rise		EMC Adsorption Equation		Parameter K' - Wetting Equation	
		Change (°C)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)
1	20	+0.5	19	+6	-12	+90	-23
1	20	-0.5	-24	-6	10	-90	32
4	20	+0.5	16	+6	-11	+90	-26
4	20	-0.5	-17	-6	9	-90	32
8	20	+0.5	21	+6	-12	+90	-22
8	20	-0.5	-32	-6	10	-90	32
1	10	+0.5	25	+6	-12	+90	-24
1	10	-0.5	-40	-6	12	-90	28
1	5	+0.5	32	+6	-14	+90	-23
1	5	-0.5	-61	-6	11	-90	34
1	2.5	+0.5	40	+6	-14	+90	-29
1	2.5	-0.5	-92	-6	16	-90	36

[1]Standard conditions — location: Curitiba; ventilation time: 6:00 - 12:00; airflow: 0.0056 $m^3 \cdot s^{-1} \cdot m^{-2}$; fan temperature rise: 1°C; total grain depth: 1 m; grain layer thickness: 5 cm; initial grain moisture content: 13%; initial grain temperature: 30°C; storage period: 1 Dec. 1965 - 30 Nov. 1966.

has the highest average temperature and lowest relative humidity, were lower than those for the other geographical locations for the fan temperature rise, airflow, specific heat, and thin-layer wetting equation (parameter N'). These deviations were lower for Cuiabá compared with the other geographical locations because the average relative humidity was the lowest for that location.

5.4.3.5. Initial moisture content and temperature of the grain

The effects of initial moisture content and temperature of the grain on the maximum deviations of ASTE were simulated at the standard conditions and using linear aiflow for the fan temperature rise, thin-layer wetting equation (parameter K'), and EMC adsorption equation. Decreasing the initial temperature from 30 to 15°C caused no significant effect while changing the initial moisture content from 13 to 15% affected only the thin-layer wetting equation (parameter K'). The maximum deviations of ASTE reduced from -34 to -20% for the thin-layer wetting equation (parameter K') when the wheat initial moisture content was increased from 13 to 15%, respectively.

5.4.4. Variable interaction using fixed uncertainties in the variables

Interaction among the variables may cause a change in the maximum deviations of ASTE. For instance, the maximum deviations of ASTE for the interaction of fan temperature rise (T_{fan} -0.5°C) and the thin-layer wetting equation (parameter K' - 90%) were -243 and -64%, at 1 and 3°C, respectively, at the standard conditions and using linear airflow. The maximum deviations of ASTE, however, were -231 and -42%, at 1 and 3°C, respectively, when the EMC adsorption (EMC + 6%) equation was added to that interaction. Therefore, one error introduced by one variable may balance the error introduced by another variable. The sensitivity analysis, when using fixed uncertainties in the variables, gave a good estimate of the maximum errors that could be introduced into the mathematical model by each variable and gave the relative importance of the variables.

5.4.5. Variable interaction using random variation in the increments

The maximum deviations of ASTE for all variables interacting with random variation in the increments varied from -7 to 4% for three repetitions of the simulations at standard conditions and using linear airflow. The wheat bulk density was not included in these simulations because it was not considered an important variable when simulating wheat aeration. Maximum deviations in ASTE between -7 and 3% were obtained when using a linear airflow of 0.0056 $m^3 \cdot s^{-1} \cdot m^{-2}$, initial moisture content of 13 or 15%, fan temperature rise of 1 or 3°C, and initial grain temperature of 15 or 30°C.

The sensitivity analysis, with random variation in the increments, indicated that in computer simulations the errors introduced in the mathematical model by the uncertainties in the thermal and physical properties of the grain and weather data will be much less than expected because the error introduced by one variable may balance the error of another variable.

5.5. Sensitivity Analysis of the Non-Equilibrium Model for Winnipeg

5.5.1. Summary

The most important variables for simulatong aeration of wheat stored in Winnipeg for 3 mo were the thin-layer drying equation followed by the EMC desorption equation, fan temperature rise, and thin-layer wetting equation, which were equally important.

The uncertainty in the calculation of allowable storage time elapsed was much higher than the uncertainties generated by all parameters tested in the computer program for simulating aeration of stored wheat.

The wheat bulk density can be a constant, the net heat of sorption can be neglected, and the ratio of bin diameter to bin height was not important in the mathematical model to simulate aeration of stored wheat.

The model's sensitivity was affected by the airflow distribution, fan temperature rise, airflow, year of simulation, grain layer thicknesses greater than 30 cm, and initial moisture content and temperature of the grain.

5.5.2. Sensitivity analysis using fixed uncertainties

Thin-layer drying equation (parameter N) was the variable which presented the highest maximum deviations in ASTE among all variables (Tables 5.14 to 5.16) when adding a fixed uncertainty. The maximum deviations in ASTE for all variables and tests were much lower than the uncertainty in predicting ASTE. Therefore, the mathematical model used to simulate aeration of stored grain can be simplified based on the results of sensitivity analyses.

The thin-layer drying equation (parameter N) caused a large variation in moisture content and ASTE when comparing adding and subtracting a fixed uncertainty (Fig. 5.16). Subtracting an uncertainty was more important than adding it because decreasing the drying front speed increased the grain deterioration.

The maximum deviations of ASTE were approximately constant over the storage period and the maximum difference among the maximum deviations of ASTE over the 3 mo storage period for each variable was less than 5%. The relative importance of most variables changed

Table 5.14. Sensitivity of the non-equilibrium mathematical model to airflow, grain specific heat, and EMC equations using linear airflow distribution, as determined by the maximum deviations in ASTE (%), to simulate aeration of stored wheat in Winnipeg, Canada for 3 mo[1]

Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Fan Temperature Rise (°C)	Variable Change (%)	Maximum Deviations in ASTE (%) Caused by Changes in Variables			
			Airflow	Grain Specific Heat	EMC Equations	
					Desorption	Adsorption
0.0057	1	+6	4	-4	-8	-2
	1	-6	-5	4	8	2
	3	+6	4	-4	-9	-1
	3	-6	-5	4	10	-1
0.0284	1	+6	-2	-4	-8	-3
	1	-6	-4	2	8	3
	3	+6	2	-2	-8	-2
	3	-6	-2	3	11	1

[1]Aeration conditions — ventilation time: 0:00 - 6:00; total grain depth: 5.7 m; grain layer thickness: 28.4 cm; initial moisture content: 15%; initial grain temperature: 30°C; storage period: 1 Sept. - 30 Nov. 1979.

Table 5.15. Sensitivity of the non-equilibrium mathematical model to fan temperature rise and thin-layer equations using linear airflow distribution, as determined by the maximum deviations in ASTE, when simulating aeration of wheat stored in Winnipeg, Canada for 3 mo[1]

Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Fan Temperature Rise (°C)	Maximum Deviations in ASTE (%) Caused by Changes in Variables									
		Fan Temperature Rise		Thin-Layer Drying Equation				Thin-Layer Wetting Equation			
				Parameter K		Parameter N		Parameter K'		Parameter N'	
		Change (°C)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)
0.0057	1	+0.5	-2	+20	4	+30	10	+90	-4	+10	-1
	1	-0.5	2	-20	-5	-30	-18	-90	4	-10	1
	3	+0.5	-3	+20	4	+30	11	+90	-2	+10	-1
	3	-0.5	3	-20	-5	-30	-18	-90	2	-10	0
0.0284	1	+0.5	7	+20	4	+30	10	+90	-8	+10	-3
	1	-0.5	-9	-20	-5	-30	-16	-90	8	-10	3
	3	+0.5	-3	+20	5	+30	10	+90	-3	+10	-1
	3	-0.5	4	-20	-5	-30	-16	-90	4	-10	-1

[1]See Table 5.14 for aeration conditions.

Table 5.16. Sensitivity of the non-equilibrium mathematical model to fan temperature rise, thin-layer equations, and EMC equations using non-linear airflow distribution, as determined by the maximum deviations in ASTE, when simulating aeration of wheat stored in Winnipeg, Canada for 3 mo[1]

Airflow ($m^3 \cdot s^{-1} \cdot m^{-2}$)	Maximum Deviations in ASTE (%) Caused by Changes in Variables									
	Fan Temperature Rise		Thin-Layer Equations				EMC Equations			
			Drying - Parameter N		Wetting - Parameter K'		Desorption		Adsorption	
	Change (°C)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)	Change (%)	Deviation (%)
0.0059-0.0351	+0.5	7	+30	11	+90	-8	+6	-8	+6	-4
0.0059-0.0351	-0.5	-11	-30	-18	-90	9	-6	8	-6	3
0.0290-0.0690	+0.5	6	+30	11	+90	-13	+6	-8	+6	-5
0.0290-0.0690	-0.5	-12	-30	-15	-90	13	-6	9	-6	4

[1]Aeration conditions — fan temperature rise: 1°C; ventilation time: 0:00 - 6:00; total grain depth: 5.7 m; grain layer thickness: 28.4 cm; initial moisture content: 15%; initial grain temperature: 30°C; storage period: 1 Sept. - 30 Nov. 1979.

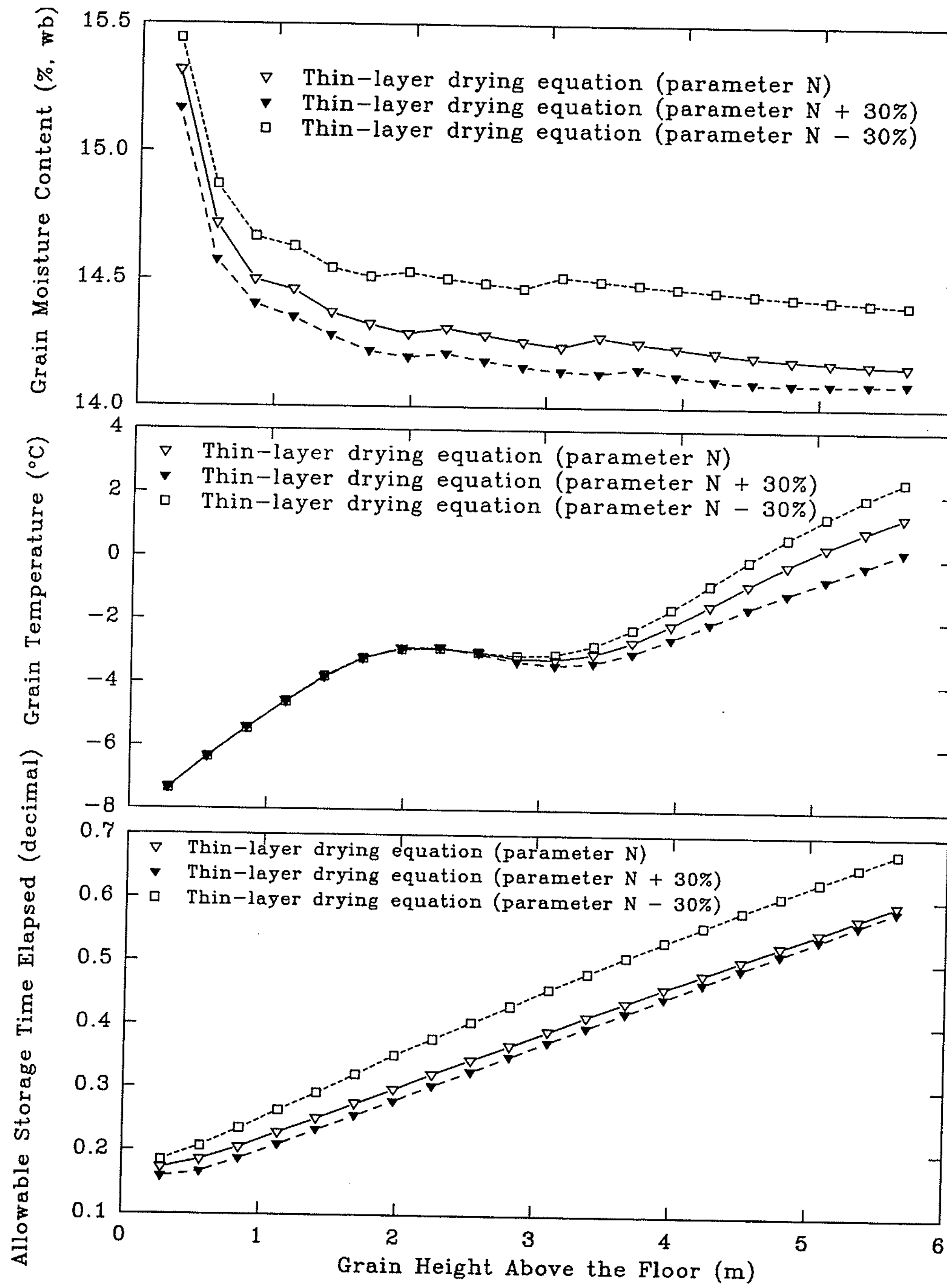

Fig. 5.16. Moisture content, temperature, and allowable storage time elapsed obtained when adding or subtracting 30% from the thin-layer drying equation (parameter N) to simulate aeration of stored wheat in Winnipeg, Canada after 3 mo of storage at standard conditions with linear airflow distribution

when the airflow or the fan temperature rise was changed. The relative importance of the thin-layer drying equation (parameter N), however, was not changed.

The uncertainty generated by equations which describe the resistance to airflow was not important for simulating aeration of stored wheat because the maximum deviations in ASTE resulting from changes in airflow were much lower than the uncertainty in predicting ASTE (Table 5.14). The relative importance of airflow, however, would be the same as of the EMC desorption equation if the uncertainty in the measurement of airflow was increased from ±6% to ±15% as determined by Metzger et al. (1981).

Changes in wheat bulk density caused no deviations in ASTE (maximum deviations in ASTE=0%). The results for wheat bulk density were obtained assuming no change in the air velocity due to a variation in the bulk density. The maximum deviations in ASTE for wheat bulk density, when the air velocity was changed in proportion to the changes in grain volume, were practically the same as those obtained for the airflow (Table 5.14). Therefore, these deviations were caused by a change in the airflow and not by a change in the bulk density. Consequently, a constant bulk density can be used in simulations of aerated wheat without any significant error.

Neglecting the net heat of sorption caused a maximum deviation in ASTE of -4% for airflows of 0.0057 and 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$ and fan temperature rises of 1 and 3°C with linear airflow distribution. Therefore, the latent heat of vaporization equations for desorption and adsorption by wheat, which were used to calculate net heat of sorption, are not necessary in the computer model.

Reducing the air velocity to one-half by doubling the bin area for a constant airflow per grain volume (1 and 5 $L \cdot s^{-1} \cdot m^{-3}$) for fan temperature rises of 1 and 3°C with linear airflow distribution caused a maximum deviation in ASTE of 3%. Consequently, the ratio of bin diameter to bin height is not important to simulate aeration of stored wheat when only forced convection is simulated.

5.5.3. Effects of simulation conditions

5.5.3.1. Airflow, fan temperature rise, and airflow distribution

Changing the airflow from 0.0057 to 0.0284 $m^3 \cdot s^{-1} \cdot m^{-2}$ or the fan temperature rise from 1 to 3°C (Tables 5.14 and 5.15) varied the deviations in ASTE for several variables. These variations depended on the variable being analyzed and on the airflow and fan temperature rise used in the simulation. These variations, however, were not significant when analyzed for the thin-layer drying equation and EMC desorption equation.

The maximum deviations in ASTE varied when non-linear airflow was used. There was no apparent trend in these variations. For most tests increasing the air velocity increased the over prediction of drying or wetting depending on the airflow and fan temperature rise. The maximum deviations in ASTE, when using non-linear airflow and 1°C fan temperature rise (Table 5.16), are only shown for the variables which caused the maximum deviations in ASTE.

5.5.3.2. Grain depth and grain layer thickness

The effect of grain depth and grain layer thickness on the model's sensitivity for the thin-layer drying equation (parameter N), thin-layer wetting equation (parameter K'), EMC desorption equation, and airflow were investigated for the median year at standard conditions with linear airflow distribution. Grain depths of 4 and 6 m and grain layer thickness less than 30 cm (thickness of 14.2 cm) did not affect the model's sensitivity. The maximum deviations in ASTE were 24% for the EMC desorption equation and 11% for the thin-layer equation (parameter N) when using 56.8 cm grain layer thickness. Therefore, excessively increasing the grain layer thickness increases the possibility of errors due to uncertainty in variables such as the EMC equation.

5.5.3.3. Year of simulation

The maximum deviations in ASTE for the median and the worst years were slightly changed when the results of the sensitivity analysis were compared for each variable. The maximum change in the deviation of ASTE, however, was 5% which occurred for both the EMC desorption equation and fan temperature rise. The relative importance of several variables changed when simulating for the worst year and median year. The relative importance of the thin-layer drying equation (parameter N) was not changed when using linear airflow distribution. The fan temperature rise, however, was as important as the thin-layer drying equation (parameter N) for the worst year when simulating with non-linear airflow distribution.

5.5.3.4. Initial moisture content and temperature of the grain

The effects of initial moisture content and temperature of the grain on the maximum deviations in ASTE were simulated for the median year at the standard conditions with linear airflow for all variables. The deviations in ASTE were increased 47 to 117% when the initial moisture content was decreased from 15 to 13% for the thin-layer wetting equation, EMC adsorption equation, and fan temperature rise. The deviations in ASTE decreased 49 to 65% when the initial temperature was decreased from 30 to 15°C for the thin-layer drying equation, airflow, and specific heat. The deviations in ASTE for the EMC desorption equation were not affected by the initial moisture content or temperature of the grain.

5.5.4. Variable interaction using fixed uncertainties in the variables

Different variables interacting may cause a significant change in the maximum deviations in ASTE. For instance, the maximum deviation in ASTE for the interaction of thin-layer drying equation (parameter N - 30%) and EMC desorption equation (EMC - 6%) was -11% at the standard conditions with linear airflow. Therefore, one error introduced by one variable may balance the error introduced by another variable. The maximum deviation in ASTE, however, was -14% when the airflow (airflow - 6%) was added to that interaction. The results of sensitivity analysis, with fixed uncertainties in the variables, give a good estimate of the maximum errors that could be introduced in the mathematical model by each variable and also about the relative importance of all variables.

5.5.5. Variable interaction using random variation in the increments

The maximum deviations in ASTE for all variables interacting with random variation in the increments varied from 4 to 5% for three repetitions of the simulations at standard conditions with linear airflow distribution. The wheat bulk density was not included in these simulations because it was not considered an important variable when simulating wheat aeration. Maximum deviations in ASTE between -3 and 7% were obtained when using linear airflow rates of 1 or 5 $L \cdot s^{-1} \cdot m^{-3}$, initial moisture content of 13 or 15%, fan temperature rise of 1 or 3°C, and initial grain temperature of 15 or 30°C temperature.

The results of sensitivity analysis, with random variation in the increments, indicated that in computer simulation the errors introduced in the mathematical model by the variations in the thermal and physical properties of the grain and fan temperature rise will be much lower than normally expected because the error introduced by one variable may balance the error of another variable.

5.6. Validation of the Mathematical Model of Forced Convection

The comparison of equilibrium and non-equilibrium mathematical models showed that the equilibrium model over predicts drying and wetting rates especially in the bottom layers and that the non-equilibrium model is more accurate because it is based on empirical thin-layer drying and wetting equations and equilibrium moisture content equations for adsorption and desorption.

The results of the sensitivity analyses suggest that validation of the non-equilibrium mathematical model developed here is not needed. For Winnipeg, for example, the uncertainty in predicting grain deterioration is much higher than the maximum deviations in ASTE for all variables within their expected range of uncertainty. Such a validation would be applicable only for a specific product and within the specific range of experimental conditions and the errors introduced in the mathematical model by several variables will be much less than expected. Validation of computer models to simulate aeration of stored grain would require long duration tests and demand great economical resources. The tests would have to be repeated for different grain varieties and experimental conditions due to the random nature of the errors associated with the determination of thermal and physical properties of the grain, making such efforts economically unfeasible.

5.7. Airflow Rates and Fan Control Methods for Brazilian Locations

5.7.1. Summary

The best fan-control method to aerate wheat stored in eight Brazilian locations was a differential-thermostat. The best differential-thermostat settings, airflow rates, and air-temperature increments with linear and non-linear airflow distributions were determined for all locations.

Simulated results using the best aeration conditions for the Brazilian locations indicated that the best locations for grain storage in Brazil, in descending order, were Curitiba (12 mo), Porto Alegre (11 mo), São Paulo (10 mo), Belo Horizonte (9 mo), Florianópolis (8 mo), Goiânia (8 mo), Campo Grande (7 mo), and Cuiabá (4 mo).

The maximum allowed storage time for aerated wheat in Brazilian locations correlated well with the annual average-time that the ambient air temperature was below 15°C.

5.7.2. Comparison of fan control methods

Simulations comparing costs to aerate, with linear airflow distribution, wheat stored in Curitiba and Goiânia for 1 year indicated that the best fan-control method was a differential-thermostat (Tests 88 and 89, Table 5.17 and Tests 104 and 105, Table 5.18). The second best method was based on the vapor-pressure-deficit (Test 86, Table 5.17 and Test 102, Table 5.18). The first and second best fan control methods are the only methods which take into account the actual temperature of the grain bulk and ambient air conditions to operate the fan. The differential-thermostat method resulted in acceptable costs of over drying, spoilage, and electricity for both Curitiba and Goiânia but it was not possible to store wheat in Goiânia for 1 year without some spoilage (maximum allowed storage time was 8 mo). Spoilage cost was the major cost dictating the feasibility of storage in these two locations followed by electricity and over drying costs.

Table 5.17. Comparison of fan control methods to aerate wheat stored in Curitiba for 1 year with linear airflow distribution[1]

Test #	Fan Control Method	ASTE (decimal) Maximum	ASTE (decimal) Average	Fan Time (h)	Costs ($\$\cdot t^{-1}$) Over Drying	Spoilage	Fan Electricity	Total
74	No ventilation	4.54	4.17	0	0	150.00	0	150.00
75	Continuous ventilation	2.69	2.41	8710	0	150.00	7.01	157.01
76	Time-clock: 0:00 - 6:00	6.62	2.16	2178	0	101.36	1.75	103.11
77	Time-clock: 6:00 - 12:00	3.03	1.88	2178	0	150.00	1.75	151.75
78	Time-clock: 12:00 - 18:00	1.93	1.84	2178	0.66	147.00	1.75	149.41
79	Time-clock: 18:00 - 24:00	4.53	2.22	2178	0	150.00	1.75	151.75
80	Humidistat: RH ≤ 80%	1.89	1.76	2353	1.31	147.00	1.89	150.20
81	Humidistat: RH ≤ 90%	1.86	1.80	3258	0.60	147.00	2.62	150.22
82	Humidistat: 70 ≤ RH ≤ 80%	2.16	1.91	818	0	150.00	0.66	150.66
83	Humidistat: 70 ≤ RH ≤ 90%	2.69	1.99	1723	0	150.00	1.39	151.39
84	Thermostat: $T_{gmax} \geq 30°C$ (warm season) or $T_{gmax} \geq 25°C$ (cold season) fan is on	2.86	2.45	65	0.38	147.00	0.05	147.43
85	Thermostat: $T_{gmax} \geq 25°C$ (warm season) or $T_{gmax} \geq 20°C$ (cold season) fan is on	2.39	1.90	2413	0	150.00	1.94	151.94
86	Vapor-pressure-deficit ≥ 0 and:							
	- air-temperature increment = 0°C	1.49	0.93	365	0.52	0	0.29	0.81
	- air-temperature increment = 1°C	1.42	0.85	253	0.41	0	0.20	0.61
	- air-temperature increment = 3°C	1.40	0.87	303	0.47	0	0.24	0.71
87	Differential-thermostat (TDIFF = -5°C) and humidistat (RH ≤ 90%)	1.73	1.27	176	0.47	39.86	0.14	40.47
88	Differential-thermostat (TDIFF = -5°C) and time-clock (8:00 pm - 8:00 am)	1.32	0.81	492	0	0	0.40	0.40
89	Differential-thermostat (TDIFF = -5°C)	1.24	0.78	534	0	0	0.43	0.43

[1]Aeration conditions — airflow rate: 2 $L\cdot s^{-1}\cdot m^{-3}$; temperature increment: 3°C; initial moisture content: 13%; initial grain temperature: 30°C; storage period: 1 Jan.-31 Dec. 1961. ASTE = Allowable storage time elapsed. RH = ambient air relative humidity. T_{gmax} = maximum grain temperature.

Table 5.18. Comparison of fan control methods to aerate wheat stored in Goiânia for 1 year with linear airflow distribution[1]

Test #	Fan Control Method	ASTE (decimal)		Fan Time (h)	Costs ($\$\cdot t^{-1}$)			
		Maximum	Average		Over Drying	Spoilage	Fan Electricity	Total
90	No ventilation	4.56	4.36	0	0	150.00	0	150.00
91	Continuous ventilation	2.12	2.02	8758	2.27	150.00	7.05	159.32
92	Time-clock: 0:00 - 6:00	3.56	2.35	2190	0	150.00	1.76	151.76
93	Time-clock: 6:00 - 12:00	2.62	2.19	2190	0.83	150.00	1.76	152.59
94	Time-clock: 12:00 - 18:00	2.57	2.23	2190	4.18	147.00	1.76	152.94
95	Time-clock: 18:00 - 24:00	2.61	2.40	2190	0.55	150.00	1.76	152.31
96	Humidistat: RH ≤ 80%	2.17	1.89	4683	4.45	147.00	3.77	155.22
97	Humidistat: RH ≤ 90%	2.14	1.89	6032	3.58	147.00	4.85	155.43
98	Humidistat: 70 ≤ RH ≤ 80%	2.50	2.34	1027	0	150.00	0.83	150.83
99	Humidistat: 70 ≤ RH ≤ 90%	3.00	2.47	2376	0	150.00	1.91	151.91
100	Thermostat: $T_{gmax} \geq 30°C$ (warm season) or $T_{gmax} \geq 25°C$ (cold season) fan is on	2.87	2.67	2085	3.04	150.00	1.68	154.72
101	Thermostat: $T_{gmax} \geq 25°C$ (warm season) or $T_{gmax} \geq 20°C$ (cold season) fan is on	2.12	2.03	8647	2.26	150.00	6.96	159.22
102	Vapor-pressure-deficit ≥ 0 and:							
	- air-temperature increment = 0°C	2.08	1.73	1986	1.55	147.00	1.60	150.15
	- air-temperature increment = 1°C	2.01	1.64	2404	2.61	110.14	1.93	114.68
	- air-temperature increment = 3°C	2.00	1.67	3441	3.08	136.50	2.77	142.35
103	Differential-thermostat (TDIFF = -5°C) and humidistat (RH ≤ 90%)	2.51	1.64	288	0.31	95.57	0.23	96.11
104	Differential-thermostat (TDIFF = -5°C) and time-clock (8:00 pm - 8:00 am)	2.15	1.34	534	0	15.00	0.43	15.43
105	Differential-thermostat (TDIFF = -5°C)	2.18	1.34	571	0	15.00	0.46	15.46

[1]Aeration conditions as given in Table 5.17.

Therefore, the maximum allowed storage time depended first on the spoilage costs and if no spoilage occurred then electricity and over drying costs became the major costs.

The differences of storability between Curitiba and Goiânia were due to the differences in ambient air temperatures between these locations since the average relative humidity for Curitiba was much higher than that for Goiânia (Table 4.2, Sec. 4.2). The method based on the vapor-pressure-deficit compared with the differential-thermostat method, however, did not succeed for Goiânia (Table 5.18) because the total costs of aeration using that method (Test 102) were about ten times higher than those for the differential-thermostat method (Tests 104 and 105) with a 3°C air-temperature increment.

Other fan control methods (Tests 74 to 85 and 87, Table 5.17 and Tests 90 to 101 and 103, Table 5.18), including the fan control method used traditionally in Brazil (Tests 84 and 85, Table 5.17 and Tests 100 and 101, Table 5.18), resulted in spoilage of all or almost all of the grain bulk and therefore they should not be recommended for the Brazilian climatic conditions considered. The differential-thermostat combined with a humidistat to turn the fan on only when the relative humidity was less than or equal to 90% (Test 87, Table 5.17 and Test 103, Table 5.18) indicated that preventing grain ventilation during periods of high relative humidity reduced the grain cooling because low ambient air temperatures were combined with high relative humidities.

The differential-thermostat method combined with a time-clock (Tests 88 and 104) resulted in practically the same aeration costs as the differential-thermostat alone (Tests 89 and 105) indicating that the fan was turned on mostly at night when the ambient air temperature was low. Therefore, grain storage managers in Brazil could decrease electricity costs for aeration because the costs of electrical energy are lower for night periods compared with daylight periods.

Combining the time-clock with the differential-thermostat method decreased the fan ventilation time by 8 and 6% for Curitiba and for Goiânia, respectively.

The method based on the vapor-pressure-deficit allowed fan operation at any time of the day resulting in higher over drying costs and higher average grain temperatures compared with the differential-thermostat method. Therefore, the grain bulk was not cooled properly and it would be difficult to change the fan control system from automatic to manual when using the method based on the vapor-pressure-deficit. The problem of over drying and reduced cooling was worse for Goiânia because the fan was turned on during periods of low relative humidities and high ambient air temperatures. For example, the method based on the vapor-pressure-deficit compared with the differential-thermostat method (Tests 102 and 105, respectively, Table 5.18), after 12 mo of storage in Goiânia with 3°C air-temperature increment, resulted in a decrease of 1.9% in the final average moisture content of the grain and an increase of 9.2°C in the final average grain temperature.

5.7.3. Differential-thermostat method

The simulated results using the differential-thermostat control of wheat aeration are the average of 10 years for eight Brazilian locations (Tables 5.19 to 5.30). The best differential-thermostat settings, airflow rates, and air-temperature increments for each geographical location were those which resulted in the longest maximum allowed storage times, no spoilage costs for any year, and lowest over drying and electricity costs. For Campo Grande, Curitiba, Goiânia, Florianópolis, and São Paulo, the best aeration conditions with linear airflow distribution at 13% initial grain moisture content (Table 5.31) were -5°C differential-thermostat setting, 3 $L \cdot s^{-1} \cdot m^{-3}$ airflow rate, and 3°C air-temperature increment (Tests 133, 264, 302, 310, and 394) but for Belo

Table 5.19. Differential-thermostat control of wheat aeration in Belo Horizonte[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
					Linear Airflow Distribution					
106	-4	1	1	4	14.9	0.67	585	0.02	0.47	0.49
107	-4	1	3	7	14.5	0.98	1274	0	1.03	1.03
108	-4	1	5	8	13.7	1.13	1819	0.13	1.46	1.59
109	-4	2	1	4	14.8	0.62	350	0	0.28	0.28
110	-4	2	3	7	14.4	0.91	827	0	0.66	0.66
111	-4	2	5	8	13.7	1.11	1523	0.01	1.22	1.23
112	-4	3	1	5	14.9	0.67	318	0	0.26	0.26
113	-4	3	3	7	14.4	0.87	621	0	0.50	0.50
114	-4	3	5	8	13.7	1.10	1368	0	1.10	1.10
115	-5	1	1	6	14.6	0.85	601	0.14	0.48	0.62
116	-5	1	3	8	14.1	1.01	841	0.15	0.68	0.83
117	-5	1	5	8	13.7	1.07	1108	0.24	0.89	1.13
118	-5	2	1	7	14.5	0.84	368	0.04	0.30	0.34
119	-5	2	3	8	14.0	0.93	505	0.05	0.41	0.46
120	-5	2	5	9	13.6	1.07	788	0.12	0.63	0.75
121	-5	3	1	8	14.4	0.85	263	0.01	0.21	0.22
122	-5	3	3	8	13.9	0.89	362	0.03	0.29	0.32
*123	-5	3	5	9	13.5	0.97	629	0.07	0.51	0.58

Table 5.19. Differential-thermostat control of wheat aeration in Belo Horizonte[1] (cont'd)

Test #	TDIFF (C°)	Airflow Rate ($L{\cdot}s^{-1}{\cdot}m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\${\cdot}t^{-1}$) Over Drying	Costs ($\${\cdot}t^{-1}$) Fan Electricity	Costs ($\${\cdot}t^{-1}$) Total
Non-Linear Airflow Distribution										
124	-5	0.6	5	6	13.7	1.03	1341	0.24	1.08	1.32
125	-5	0.9	5	7	13.8	1.07	1272	0.12	1.02	1.14
*126	-5	1.3	5	7	13.8	1.04	1121	0.08	0.90	0.98
127	-6	0.6	5	5	13.6	0.92	682	0.30	0.55	0.85
128	-6	0.9	5	6	13.6	0.96	665	0.26	0.54	0.80
129	-6	1.3	5	6	13.6	0.93	567	0.23	0.46	0.69

[1]Aeration conditions — values are the average of 10 years starting on 1 Jan. 1961; initial moisture content: 13%; initial grain temperature: 30°C; and final average moisture content: 12.8 - 13.2%. TDIFF is the difference between the average grain temperature and the ambient air temperature set for the differential-thermostat method. AST is the maximum allowed storage time. M. C. is the grain moisture content. ASTE is the average allowable storage time elapsed.

*Asterisks indicate the best combination of differential-thermostat setting, airflow rate, and air-temperature increment.

Table 5.20. Differential-thermostat control of wheat aeration in Campo Grande[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$) Over Drying	Fan Electricity	Total
				Linear Airflow Distribution						
130	-5	2	1	4	14.5	0.75	204	0.07	0.16	0.23
131	-5	2	3	7	14.1	1.03	420	0.11	0.34	0.45
132	-5	3	1	5	14.6	0.81	186	0.04	0.15	0.19
*133	-5	3	3	7	14.0	0.98	313	0.07	0.25	0.32
				Non-Linear Airflow Distribution						
134	-5	0.9	3	3	14.8	0.70	290	0	0.23	0.23
135	-5	0.9	5	4	13.7	0.95	690	0.08	0.56	0.64
136	-5	1.3	3	3	14.7	0.68	240	0	0.19	0.19
137	-5	1.3	5	4	13.7	0.93	605	0.07	0.49	0.56
138	-6	0.9	3	4	14.3	0.88	215	0.05	0.17	0.22
139	-6	0.9	5	4	13.6	0.91	323	0.18	0.26	0.44
*140	-6	1.3	3	4	14.3	0.86	179	0.05	0.15	0.20
141	-6	1.3	5	4	13.5	0.88	279	0.17	0.22	0.39

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.9 - 13.1%.

Table 5.21. Differential-thermostat control of wheat aeration in Campo Grande (12% initial moisture content)[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
142	-5	2	1	4	14.3	0.52	270	0	0.21	0.21
143	-5	2	3	8	13.9	0.78	579	0	0.46	0.46
144	-5	3	1	5	14.3	0.55	226	0	0.18	0.18
145	-5	3	3	9	13.7	0.77	416	0	0.33	0.33
146	-6	1	1	8	14.0	0.81	501	0.05	0.39	0.44
147	-6	1	3	9	13.4	0.89	615	0.06	0.48	0.54
148	-6	1	5	10	13.1	0.99	782	0.08	0.61	0.69
149	-6	2	1	9	14.0	0.77	298	0.01	0.23	0.24
150	-6	2	3	10	13.2	0.84	377	0.02	0.29	0.31
151	-6	2	5	10	12.9	0.90	518	0.04	0.40	0.44
152	-6	3	1	8	13.9	0.69	216	0	0.17	0.17
153	-6	3	3	10	13.1	0.79	274	0.01	0.22	0.23
154	-6	3	5	10	12.8	0.85	398	0.02	0.31	0.33
155	-7	1	1	9	13.5	0.89	373	0.18	0.29	0.47
156	-7	1	3	9	13.0	0.91	430	0.21	0.34	0.55
157	-7	1	5	9	12.7	0.94	514	0.24	0.40	0.64
158	-7	2	1	9	13.5	0.81	229	0.07	0.18	0.25
159	-7	2	3	9	12.9	0.83	270	0.10	0.21	0.31
160	-7	2	5	10	12.6	0.90	338	0.13	0.26	0.39
161	-7	3	1	9	13.4	0.77	168	0.03	0.13	0.16
*162	-7	3	3	10	12.8	0.83	204	0.05	0.16	0.21
163	-7	3	5	10	12.5	0.86	261	0.08	0.21	0.29

Table 5.21. Differential-thermostat control of wheat aeration in Campo Grande (12% initial moisture content) (cont'd)

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Non-Linear Airflow Distribution										
164	-6	0.9	1	2	15.5	0.33	124	0	0.10	0.10
165	-6	0.9	3	6	14.5	0.77	439	0	0.35	0.35
166	-6	0.9	5	8	13.5	0.95	808	0.01	0.64	0.65
167	-6	1.3	1	2	15.2	0.32	102	0	0.08	0.08
168	-6	1.3	3	7	14.4	0.79	403	0	0.32	0.32
169	-6	1.3	5	8	13.5	0.91	695	0	0.55	0.55
170	-7	0.6	1	3	14.7	0.51	119	0	0.10	0.10
171	-7	0.6	3	8	14.0	0.93	446	0.02	0.35	0.37
172	-7	0.6	5	8	13.2	0.96	593	0.09	0.47	0.56
173	-7	0.9	1	3	14.5	0.49	90	0	0.07	0.07
174	-7	0.9	3	8	13.9	0.88	344	0.01	0.27	0.28
175	-7	0.9	5	8	13.1	0.91	474	0.06	0.38	0.44
176	-7	1.3	1	3	14.5	0.48	76	0	0.06	0.06
177	-7	1.3	3	8	13.8	0.85	288	0.01	0.23	0.24
*178	-7	1.3	5	9	13.1	0.92	405	0.05	0.32	0.37

[1]Aeration conditions are given in the foot note toTable 5.19 except that final average moisture content was 11.9 - 12.3%. Over drying was calculated for moisture contents below 12%.

Table 5.22. Differential-thermostat control of wheat aeration in Cuiabá[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$) Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
179	-5	1	1	3	14.1	0.88	178	0.02	0.14	0.16
180	-5	1	3	3	13.8	0.90	219	0.02	0.18	0.20
181	-5	2	1	4	14.3	1.06	144	0.02	0.11	0.13
182	-5	2	3	4	13.8	1.10	196	0.02	0.16	0.18
*183	-5	3	1	4	14.3	1.03	109	0.01	0.09	0.10
184	-5	3	3	4	13.8	1.07	151	0.01	0.12	0.13
Non-Linear Airflow Distribution										
185	-5	0.6	1	2	15.5	0.63	123	0	0.10	0.10
186	-5	0.6	3	3	14.7	0.95	249	0	0.20	0.20
187	-5	0.9	1	2	15.4	0.61	94	0	0.08	0.08
188	-5	0.9	3	3	14.6	0.93	202	0	0.16	0.16
189	-5	1.3	1	2	15.2	0.60	76	0	0.06	0.06
190	-5	1.3	3	3	14.6	0.91	173	0	0.14	0.14
191	-6	0.6	1	3	14.7	0.95	77	0	0.06	0.06
192	-6	0.6	3	3	13.9	0.96	106	0.01	0.09	0.10
*193	-7	0.6	1	3	14.0	1.00	40	0	0.03	0.03
194	-7	0.6	3	3	13.4	1.01	47	0.03	0.04	0.07
195	-8	0.6	1	3	13.6	1.05	21	0.02	0.02	0.04
196	-8	0.6	3	3	13.2	1.05	23	0.04	0.02	0.06

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 13.0 - 13.1%.

Table 5.23. Differential-thermostat control of wheat aeration in Cuiabá (12% initial moisture content)[1]

Test #	TDIFF (C°)	Airflow Rate ($L{\cdot}s^{-1}{\cdot}m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\${\cdot}t^{-1}$) Over Drying	Fan Electricity	Total
				Linear Airflow Distribution						
197	-6	1	1	6	13.6	1.01	302	0.01	0.24	0.25
198	-6	1	3	6	13.2	1.04	365	0.01	0.29	0.30
199	-6	2	1	6	13.6	0.95	193	0	0.15	0.15
200	-6	2	3	7	13.1	1.06	271	0	0.21	0.21
201	-6	3	1	6	13.6	0.91	143	0	0.11	0.11
*202	-6	3	3	7	13.0	1.01	203	0	0.16	0.16
				Non-Linear Airflow Distribution						
203	-6	0.6	1	4	14.9	0.79	138	0	0.11	0.11
204	-6	0.6	3	5	14.1	0.97	290	0	0.23	0.23
205	-6	0.6	5	5	13.3	1.04	477	0	0.38	0.38
206	-6	0.9	1	4	14.7	0.77	106	0	0.08	0.08
207	-6	0.9	3	6	14.2	1.05	252	0	0.23	0.23
208	-6	0.9	5	6	13.4	1.13	497	0	0.39	0.39
209	-6	1.3	1	4	14.7	0.76	91	0	0.07	0.07
210	-6	1.3	3	6	14.1	1.02	247	0	0.20	0.20
211	-6	1.3	5	6	13.4	1.11	437	0	0.35	0.35
212	-7	0.6	3	5	13.1	0.97	149	0	0.12	0.12
213	-7	0.6	5	5	12.7	0.99	196	0.03	0.16	0.19
214	-7	0.9	3	5	13.1	0.95	126	0	0.10	0.10
215	-7	0.9	5	5	12.7	0.97	164	0.02	0.13	0.15
216	-7	1.3	3	5	13.1	0.93	110	0	0.09	0.09
*217	-7	1.3	5	6	12.8	1.06	197	0.02	0.15	0.17

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.0 - 12.2%. Over drying was calculated moisture contents below 12%.

Table 5.24. Differential-thermostat control of wheat aeration in Cuiabá (11% initial moisture content)[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
218	-5	1	1	4	14.7	0.58	581	0	0.47	0.47
219	-5	1	3	4	14.1	0.65	879	0	0.71	0.71
220	-5	2	1	4	14.4	0.53	324	0	0.26	0.26
221	-5	2	3	4	13.9	0.62	558	0	0.45	0.45
222	-5	3	1	5	14.3	0.58	264	0	0.21	0.21
223	-5	3	3	6	13.6	0.75	482	0	0.39	0.39
224	-6	1	1	8	13.7	0.82	491	0	0.40	0.40
225	-6	1	3	8	13.2	0.87	643	0	0.52	0.52
226	-6	2	1	8	13.6	0.75	298	0	0.23	0.23
227	-6	2	3	9	13.0	0.85	399	0	0.32	0.32
228	-6	3	1	9	13.4	0.75	205	0	0.17	0.17
229	-6	3	3	9	12.8	0.80	287	0	0.23	0.23
230	-7	1	1	10	12.6	0.91	309	0	0.24	0.24
231	-7	1	3	10	12.2	0.94	364	0	0.28	0.28
232	-7	2	1	10	12.7	0.84	190	0	0.15	0.15
233	-7	2	3	10	12.1	0.87	231	0	0.18	0.18
*234	-7	3	1	10	12.5	0.81	139	0	0.11	0.11
235	-7	3	3	9	12.1	0.83	173	0	0.13	0.13

Table 5.24. Differential-thermostat control of wheat aeration in Cuiabá (11% initial moisture content)[1] (cont'd)

Test #	TDIFF (C°)	Airflow Rate (L·s^{-1}·m^{-3})	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs (\$·t^{-1}) Over Drying	Costs (\$·t^{-1}) Fan Electricity	Costs (\$·t^{-1}) Total
					Linear Airflow Distribution					
236	-8	1	1	9	12.1	0.88	216	0.07	0.17	0.24
237	-8	1	3	9	11.8	0.89	242	0.08	0.18	0.26
238	-8	2	1	9	12.2	0.83	136	0	0.11	0.11
239	-8	2	3	9	11.7	0.84	156	0.01	0.12	0.13
240	-8	3	1	9	12.1	0.80	99	0	0.08	0.08
241	-8	3	3	9	11.7	0.81	118	0	0.09	0.09
					Non-Linear Airflow Distribution					
242	-7	0.6	1	7	14.6	0.77	245	0	0.19	0.19
243	-7	0.9	1	7	14.5	0.74	190	0	0.15	0.15
244	-7	1.3	1	7	14.3	0.72	158	0	0.12	0.12
245	-8	0.6	1	8	13.9	0.85	188	0	0.15	0.15
246	-8	0.9	1	8	13.6	0.82	145	0	0.11	0.11
*247	-8	1.3	1	8	13.6	0.80	123	0	0.10	0.10

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 11.0 - 11.9%. Over drying was calculated for moisture contents below 11%.

Table 5.25. Differential-thermostat control of wheat aeration in Curitiba[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
248	-4	1	1	4	15.7	0.46	664	0.03	0.54	0.57
249	-4	1	3	9	15.0	0.73	1375	0.01	1.11	1.12
250	-4	1	5	10	14.2	0.88	2074	0.03	1.67	1.70
251	-4	2	1	5	15.8	0.46	462	0.01	0.37	0.38
252	-4	2	3	10	14.7	0.67	814	0	0.65	0.65
253	-4	2	5	11	14.1	0.87	1561	0	1.26	1.26
254	-4	3	1	5	15.7	0.43	325	0.01	0.26	0.27
255	-4	3	3	11	14.5	0.64	590	0	0.48	0.48
256	-4	3	5	12	14.1	0.88	1302	0	1.05	1.05
257	-5	1	1	7	15.3	0.59	687	0.19	0.55	0.74
258	-5	1	3	11	14.4	0.76	909	0.20	0.73	0.93
259	-5	1	5	12	13.9	0.87	1254	0.26	1.01	1.27
260	-5	2	1	9	15.4	0.57	406	0.08	0.33	1.41
261	-5	2	3	12	14.1	0.69	529	0.11	0.43	0.54
262	-5	2	5	12	13.7	0.76	799	0.17	0.64	0.81
263	-5	3	1	9	15.2	0.53	289	0.04	0.23	0.27
*264	-5	3	3	12	14.0	0.64	382	0.07	0.31	0.38
265	-5	3	5	12	13.6	0.71	613	0.12	0.49	0.61

Table 5.25. Differential-thermostat control of wheat aeration in Curitiba[1] (cont'd)

Test #	TDIFF (C°)	Airflow Rate (L·s⁻¹·m⁻³)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($·t⁻¹) Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
266	-6	1	1	11	14.8	0.74	548	0.36	0.44	0.80
267	-6	1	3	12	14.0	0.80	658	0.39	0.53	0.92
268	-6	1	5	12	13.6	0.84	828	0.44	0.67	1.11
269	-6	2	1	11	14.8	0.65	318	0.23	0.25	0.48
270	-6	2	3	12	13.8	0.70	390	0.27	0.31	0.58
271	-6	2	5	12	13.5	0.74	515	0.34	0.41	0.75
272	-6	3	1	11	14.8	0.61	229	0.16	0.18	0.34
273	-6	3	3	12	13.7	0.65	284	0.21	0.23	0.44
274	-6	3	5	12	13.4	0.70	391	0.28	0.32	0.60
275	-7	1	1	12	14.4	0.81	435	0.48	0.35	0.83
276	-7	1	3	12	13.8	0.83	500	0.52	0.40	0.92
277	-7	1	5	12	13.4	0.86	596	0.56	0.48	1.04
278	-7	2	1	12	14.4	0.73	256	0.35	0.21	0.56
279	-7	2	3	12	13.6	0.74	302	0.39	0.24	0.63
280	-7	2	5	12	13.3	0.77	377	0.45	0.30	0.75
281	-7	3	1	12	14.4	0.68	188	0.27	0.15	0.42
282	-7	3	3	12	13.6	0.69	223	0.32	0.18	0.50
283	-7	3	5	12	13.3	0.72	283	0.38	0.23	0.61

Table 5.25. Differential-thermostat control of wheat aeration in Curitiba[1] (cont'd)

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Non-Linear Airflow Distribution										
284	-5	0.9	3	7	15.5	0.67	791	0	0.64	0.64
285	-5	0.9	5	11	14.2	0.91	1407	0.02	1.13	1.15
286	-5	1.3	3	8	15.4	0.67	666	0	0.54	0.54
287	-5	1.3	5	12	14.1	0.91	1190	0.01	0.96	0.97
288	-6	0.9	3	10	15.1	0.77	567	0.03	0.46	0.49
289	-6	0.9	5	12	13.9	0.88	840	0.21	0.68	0.89
290	-6	1.3	3	10	14.9	0.73	463	0.02	0.37	0.39
*291	-6	1.3	5	12	13.9	0.84	695	0.18	0.56	0.74

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.7 - 13.3%.

Table 5.26. Differential-thermostat control of wheat aeration in Florianópolis[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$) Over Drying	Fan Electricity	Total
					Linear Airflow Distribution					
292	-4	2	1	4	14.5	0.66	256	0.06	0.21	0.27
293	-4	2	3	6	14.0	0.88	542	0.10	0.43	0.53
294	-4	2	5	7	13.3	1.05	1032	0.25	0.83	1.08
295	-4	3	1	4	14.4	0.63	184	0.05	0.15	0.20
296	-4	3	3	7	14.0	0.89	441	0.06	0.36	0.42
297	-4	3	5	7	13.3	1.03	915	0.17	0.74	0.91
298	-5	2	1	7	14.4	0.90	293	0.17	0.24	0.41
299	-5	2	3	8	13.8	0.98	388	0.23	0.31	0.54
300	-5	2	5	8	13.2	1.04	551	0.38	0.44	0.82
301	-5	3	1	6	14.3	0.82	203	0.11	0.16	0.27
*302	-5	3	3	8	13.7	0.93	291	0.17	0.23	0.40
303	-5	3	5	8	13.2	0.99	446	0.33	0.36	0.69
					Non-Linear Airflow Distribution					
304	-5	0.9	3	5	14.5	0.91	423	0.07	0.34	0.41
305	-5	0.9	5	6	13.3	1.04	824	0.39	0.66	1.05
306	-5	1.3	3	5	14.5	0.88	354	0.07	0.28	0.35
*307	-5	1.3	5	6	13.3	1.01	714	0.36	0.57	0.93

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.8 - 13.0%.

Table 5.27. Differential-thermostat control of wheat aeration in Goiânia[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
				Linear Airflow Distribution						
308	-5	2	3	8	14.4	1.05	616	0	0.50	0.50
309	-5	2	5	7	14.0	1.10	997	0	0.80	0.80
*310	-5	3	3	8	14.2	1.00	438	0	0.35	0.35
311	-5	3	5	8	13.9	1.13	824	0	0.66	0.66
312	-6	1	3	7	14.1	1.07	645	0.20	0.52	0.72
313	-6	1	5	7	13.7	1.12	812	0.25	0.66	0.91
314	-6	2	3	8	14.0	1.06	397	0.08	0.32	0.40
315	-6	2	5	8	13.6	1.11	553	0.13	0.45	0.58
				Non-Linear Airflow Distribution						
316	-5	0.6	3	3	15.5	0.68	554	0	0.45	0.45
317	-5	0.6	5	4	14.2	0.93	1118	0	0.90	0.90
318	-5	0.9	3	3	15.3	0.65	419	0	0.34	0.34
319	-5	0.9	5	5	14.3	1.07	1235	0	0.99	0.99
320	-5	1.3	3	4	15.5	0.81	429	0	0.34	0.34
321	-5	1.3	5	5	14.3	1.06	1149	0	0.92	0.92
322	-6	0.6	3	5	15.2	0.99	523	0	0.42	0.42
323	-6	0.6	5	5	14.1	1.04	793	0.08	0.64	0.72
324	-6	0.9	3	5	15.0	0.95	411	0	0.33	0.33
325	-6	0.9	5	6	14.0	1.09	772	0.05	0.62	0.67
*326	-6	1.3	3	6	15.0	1.01	405	0	0.33	0.33
327	-6	1.3	5	6	14.0	1.06	662	0.03	0.53	0.56

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.8 - 13.3%.

Table 5.28. Differential-thermostat control of wheat aeration in Goiânia (12% initial moisture content)[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
328	-5	2	1	6	15.1	0.61	496	0	0.39	0.39
329	-5	2	3	8	14.3	0.77	790	0	0.62	0.62
330	-5	2	5	8	13.9	0.94	1143	0	1.13	1.13
331	-5	3	1	7	14.9	0.62	358	0	0.28	0.28
332	-5	3	3	9	14.0	0.77	560	0	0.44	0.44
333	-5	3	5	9	13.8	0.99	1193	0	0.94	0.94
334	-6	1	1	8	14.4	0.76	683	0	0.54	0.54
335	-6	1	3	10	13.8	0.90	844	0	0.66	0.66
336	-6	1	5	10	13.5	0.97	1144	0	0.90	0.90
337	-6	2	1	9	14.2	0.74	372	0	0.29	0.29
338	-6	2	3	11	13.6	0.86	490	0	0.39	0.39
339	-6	2	5	12	13.2	0.99	735	0	0.58	0.58
340	-6	3	1	9	14.2	0.70	257	0	0.20	0.20
*341	-6	3	3	12	13.4	0.86	341	0	0.27	0.27
342	-6	3	5	12	13.0	0.94	548	0	0.43	0.43
343	-7	1	1	11	13.7	0.93	486	0.01	0.38	0.39
344	-7	1	3	11	13.3	0.96	583	0.01	0.46	0.47
345	-7	2	1	11	13.7	0.86	274	0	0.22	0.22
346	-7	2	3	11	13.1	0.88	338	0	0.27	0.27
347	-7	3	1	11	13.6	0.83	189	0	0.15	0.15
348	-7	3	3	11	13.0	0.84	239	0	0.19	0.19
349	-7	3	5	11	12.7	0.87	326	0	0.26	0.26

Table 5.28. Differential-thermostat control of wheat aeration in Goiânia (12% initial moisture content)[1] (cont'd)

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
					Non-Linear Airflow Distribution					
350	-6	0.9	3	6	15.2	0.74	638	0	0.51	0.51
351	-6	0.9	5	8	13.9	0.95	1252	0	0.99	0.99
352	-6	1.3	3	7	15.1	0.77	576	0	0.46	0.46
353	-6	1.3	5	9	13.9	0.97	1051	0	0.83	0.83
354	-7	0.9	3	9	14.5	0.89	456	0	0.36	0.36
355	-7	0.9	5	10	13.5	0.98	699	0	0.55	0.55
356	-7	1.3	3	9	14.3	0.86	372	0	0.30	0.30
*357	-7	1.3	5	10	13.4	0.94	582	0	0.46	0.46

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.0 - 12.8%. Over drying was calculated for moisture contents below 12%.

Table 5.29. Differential-thermostat control of wheat aeration in Porto Alegre[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
358	-4	1	1	8	15.3	0.80	792	0.11	0.64	0.75
359	-4	1	3	10	14.3	0.93	1018	0.17	0.82	0.99
360	-4	1	5	10	13.5	1.00	1363	0.36	1.10	1.46
361	-4	2	1	9	15.2	0.72	473	0.01	0.38	0.39
362	-4	2	3	11	14.1	0.86	643	0.05	0.52	0.57
363	-4	2	5	11	13.5	0.95	1006	0.21	0.81	1.02
364	-4	3	1	9	15.1	0.67	345	0	0.28	0.28
365	-4	3	3	11	14.0	0.79	485	0.01	0.39	0.40
366	-4	3	5	11	13.5	0.91	849	0.12	0.68	0.80
367	-5	2	1	10	14.7	0.77	359	0.13	0.29	0.42
368	-5	2	3	10	13.8	0.81	456	0.20	0.37	0.57
369	-5	2	5	10	13.3	0.87	627	0.33	0.50	0.83
*370	-5	3	1	11	14.6	0.75	260	0.06	0.21	0.27
371	-5	3	3	11	13.8	0.79	344	0.12	0.28	0.40
372	-5	3	5	11	13.3	0.85	503	0.26	0.40	0.66

Table 5.29. Differential-thermostat control of wheat aeration in Porto Alegre[1] (cont'd)

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$) Over Drying	Fan Electricity	Total
Non-Linear Airflow Distribution										
373	-4	0.9	3	5	15.1	0.76	714	0	0.57	0.57
374	-4	0.9	5	9	13.7	1.03	1581	0.19	1.27	1.46
375	-4	1.3	3	6	15.2	0.78	721	0	0.58	0.58
*376	-4	1.3	5	10	13.7	1.10	1420	0.10	1.14	1.24
377	-5	0.9	1	3	15.6	0.53	195	0.01	0.16	0.17
378	-5	0.9	3	8	15.0	0.87	652	0.01	0.52	0.53
379	-5	0.9	5	8	13.6	0.92	974	0.31	0.78	1.09
380	-5	1.3	1	3	15.4	0.51	164	0.01	0.13	0.14
381	-5	1.3	3	8	14.9	0.83	550	0	0.44	0.44
382	-5	1.3	5	9	13.6	0.93	845	0.25	0.68	0.93

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.8 - 13.2%.

Table 5.30. Differential-thermostat control of wheat aeration in São Paulo[1]

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
								Over Drying	Fan Electricity	Total
Linear Airflow Distribution										
383	-4	1	1	6	14.9	0.71	707	0.08	0.57	0.65
384	-4	1	3	8	14.3	0.89	1146	0.06	0.92	0.98
385	-4	2	1	7	14.7	0.69	424	0.04	0.34	0.38
386	-4	2	3	9	14.1	0.86	689	0.05	0.55	0.60
387	-4	3	1	8	14.6	0.70	312	0.02	0.25	0.27
388	-4	3	3	10	13.9	0.86	499	0.03	0.40	0.43
389	-5	1	1	9	14.4	0.89	560	0.25	0.45	0.70
390	-5	1	3	10	13.9	0.99	724	0.27	0.58	0.85
391	-5	2	1	9	14.3	0.82	320	0.15	0.26	0.41
392	-5	2	3	10	12.9	0.90	427	0.18	0.34	0.52
393	-5	3	1	9	14.2	0.78	229	0.09	0.18	0.27
*394	-5	3	3	10	13.7	0.86	313	0.13	0.25	0.38

Table 5.30. Differential-thermostat control of wheat aeration in São Paulo[1] (cont'd)

Test #	TDIFF (C°)	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$) Over Drying	Fan Electricity	Total
Non-Linear Airflow Distribution										
395	-4	0.9	1	2	15.7	0.33	278	0	0.22	0.22
396	-4	0.9	3	5	15.1	0.75	929	0	0.75	0.75
397	-4	0.9	5	8	13.5	1.10	2503	0.07	2.01	2.08
398	-4	1.3	1	2	15.5	0.31	228	0	0.18	0.18
399	-4	1.3	3	5	15.0	0.72	768	0	0.62	0.62
400	-4	1.3	5	8	13.6	1.09	2318	0.02	1.87	1.89
401	-5	0.6	3	6	14.7	0.83	783	0.05	0.63	0.68
402	-5	0.6	5	8	13.5	1.04	1593	0.27	1.28	1.55
403	-5	0.9	3	7	14.7	0.85	640	0.03	0.51	0.54
404	-5	0.9	5	9	13.6	1.06	1295	0.20	1.04	1.24
405	-5	1.3	3	7	14.6	0.82	524	0.03	0.42	0.45
*406	-5	1.3	5	9	13.6	1.02	1096	0.18	0.88	1.06

[1]Aeration conditions are given in the foot note to Table 5.19 except that the final average moisture content was 12.8 - 13.2%.

Table 5.31. The best differential-thermostat settings (TDIFF), airflow rates[1], and air-temperature increments to aerate wheat stored at eight Brazilian locations with linear airflow distribution[2]

Location	Test #	Initial Moisture Content (%, wb)	TDIFF (°C)	Temperature Increment (C°)	Maximum AST (mo)	Total Operating Costs ($·t^{-1})
Belo Horizonte	123	13	-5	5	9	0.58
Campo Grande	133	13	-5	3	7	0.32
Campo Grande	162	12	-7	3	10	0.21
Cuiabá	183	13	-5	1	4	0.10
Cuiabá	202	12	-6	3	7	0.16
Cuiabá	234	11	-7	1	10	0.11
Curitiba	264	13	-5	3	12	0.38
Florianópolis	302	13	-5	3	8	0.40
Goiânia	310	13	-5	3	8	0.35
Goiânia	341	12	-6	3	12	0.27
Porto Alegre	370	13	-5	1	11	0.27
São Paulo	394	13	-5	3	10	0.38

[1]The best airflow rate for all locations was 3 L·s^{-1}·m^{-3}.
[2]Aeration conditions — values are the average of 10 years starting on 1 Jan. 1961; initial grain temperature: 30°C; AST is the maximum allowed storage time.

Horizonte, Cuiabá, and Porto Alegre the best air-temperature increments were 5, 1, and 1°C, respectively (Tests 123, 183, and 370). The best absolute differential-thermostat settings, however, were increased at all locations for lower initial moisture contents of the grain, but the air-temperature increment did not change except at Cuiabá with an initial moisture content of 12%.

Increasing the absolute difference between the ambient air temperature and the average grain temperature (TDIFF) reduced the ventilation time for the same airflow rate, temperature increment, and storage period (e.g. Tests 256, 265, 274, and 283, Table 5.25). Because of this, grain wetting was decreased especially in the bottom layers of grain. For the same reason, an increased absolute TDIFF increased the allowed storage time when ventilating grain at initial moisture contents lower than 13% (e.g. Tests 222, 228, and 234, Table 5.24 at 11% initial moisture content). Increasing the absolute TDIFF decreased the ventilation time for the same storage period because the average time that the ambient air temperature was below a selected temperature level decreased as that temperature level was lowered. Conversely, a low absolute TDIFF caused, for many cases, a reduced storage time and a high deterioration in the bottom layers due to excessive wetting, especially at 1°C air-temperature increment (e.g. Tests 248, 251, and 254, Table 5.25). Therefore, increasing the absolute TDIFF increased the probability of grain deterioration in the top layers due to lack of ventilation and decreasing the absolute TDIFF increased the probability of grain deterioration in the bottom layers due to excessive wetting. Consequently, when the temperature rise through the fans and ducts is low in a specific grain storage the first choice would be to select a high absolute TDIFF to prevent grain deterioration in the bottom layers. This choice is explained by the difficulty in monitoring grain deterioration in the bottom layers during the storage period. Increasing the absolute TDIFF excessively for the same airflow rate, temperature increment, and storage period (e.g. compare Tests 264 and 282, Table 5.25), however, increased the over drying costs although the electricity costs were reduced due to a reduction in the ventilation time. Therefore, the higher TDIFF would be the lower cost option if grain were marketed on a dry mass basis (which is not the case for Brazil).

The best aeration conditions as given in Table 5.31, however, might not be the optimum condition for a specific grain storage. For example, at Belo Horizonte, total costs of 0.75 and 0.58 $\$\cdot t^{-1}$ were obtained for airflow rates of 2 and 3 $L\cdot s^{-1}\cdot m^{-3}$, respectively, using the same differential-thermostat setting and air-temperature increment but the maximum allowed storage time did not change (Tests 120 and 123, respectively, Table 5.19). Therefore, it would be necessary to compare the increased capital costs to buy a higher capacity fan against the increased over drying and electricity costs when using a smaller aeration fan. Because of this, the results obtained for the various test conditions (Tables 5.19 to 5.30) are useful for engineers to find the optimum differential-thermostat settings, airflow rates, and air-temperature increments after the capital and operational costs for the fans and air heaters are known. In addition, if the expected storage time is known ahead of time then a less expensive combination of aeration conditions can be selected. For example, at Belo Horizonte, if the storage period is 7 mo then the aeration conditions of Test 118 (Table 5.19) would be preferred rather than those for Test 123 for 9 mo. Thus, there would be less fan electricity and heating costs and less capital costs to buy a lower capacity fan.

For most geographical locations, the best combinations of differential-thermostat settings and air-temperature increments were affected by the airflow distribution (Tables 5.31 and 5.32). The maximum allowed storage time was reduced by 0 to 3 mo when a non-linear airflow distribution was used instead of a linear distribution. The reduction in the maximum allowed storage time, however, varied from 1 to 8 mo and from 1 to 4 mo when using airflow rates of 0.9 and 1.3 $L\cdot s^{-1}\cdot m^{-3}$, respectively, and the best combinations of differential-thermostat settings and air-temperature increments determined for linear airflow distribution. Therefore, it is important that the airflow distribution in horizontal grain storages be as close as possible to a linear airflow distribution when designing aeration systems.

Table 5.32. The best differential-thermostat settings (TDIFF), airflow rates[1], and air-temperature increments to aerate wheat stored at eight Brazilian locations with non-linear airflow distribution[2]

Location	Test #	Initial Moisture Content (%, wb)	TDIFF (°C)	Temperature Increment (C°)	Maximum AST (mo)	Total Operating Costs ($·t^{-1})
Belo Horizonte	126	13	-5	5	7	0.98
Campo Grande	140	13	-6	5	4	0.20
Campo Grande	178	12	-7	5	9	0.37
Cuiabá	193	13	-7	1	3	0.03
Cuiabá	217	12	-7	5	6	0.17
Cuiabá	247	11	-8	1	8	0.10
Curitiba	291	13	-6	5	12	0.74
Florianópolis	307	13	-5	5	6	0.93
Goiânia	326	13	-6	3	6	0.33
Goiânia	357	12	-7	5	10	0.46
Porto Alegre	376	13	-4	5	10	1.24
São Paulo	406	13	-5	5	9	1.06

[1] The best airflow rate for all locations was 1.3 L·s^{-1}·m^{-3} except for Cuiabá at 13% initial moisture content where the best airflow rate was 0.6 L·s^{-1}·m^{-3}.
[2]Aeration conditions and variable definition as given in Table 5.31.

The aeration costs for the same storage period were much higher when changing from linear to non-linear distribution. For example, at Curitiba, the aeration costs with linear airflow distribution were 0.38 $·t^{-1} while with non-linear airflow they were 0.74 $·t^{-1} plus additional heating costs (Tests 264 and 291, Table 5.25). Modifying storages to have near linear airflow distribution may be quickly paid by the lower aeration costs and higher grain quality.

The reduction in the maximum allowed storage time when changing from linear to non-linear airflow distributions was caused by increased wetting in the bottom layers of grain and decreased cooling in the top layers. The increased wetting was caused by the high air velocities in the grain layers close to the air entrance and the decreased cooling was caused by the low air velocities in the top layers. An increase of 1°C in the absolute TDIFF and an increase of 2°C in the air-temperature increment were the most common changes to the aeration conditions required to maintain the allowed storage time as high as possible when changing from linear to non-linear airflow distribution. An increase in the absolute TDIFF and temperature increment when changing from linear to non-linear airflow was helpful because it reduced the ventilation time and the average relative humidity of the incoming air so that the bottom layers were not wetted as much. The reduced ventilation time and increased air temperature, however, caused an increase in the grain deterioration of the top layers which were aerated with much-smaller air-velocities compared with the linear airflow distribution.

When ventilating with non-linear airflow distribution the best airflow rate for all locations was 1.3 $L \cdot s^{-1} \cdot m^{-3}$ except for Cuiabá (Table 5.32). Cuiabá is the warmest location among the studied locations (Table 4.2) and an increased airflow rate for Cuiabá increased the wetting in the bottom layers of grain, therefore, accelerating the grain deterioration.

The maximum grain deterioration for the best aeration conditions always occurred in the top layer for both linear and non-linear airflow distributions and the main cause of deterioration was the heat transferred by convection from the head space air to the top grain layer since the grain moisture contents in this layer were always below 13%. Therefore, these results reinforce the use of head space ventilation and other strategies to decrease the net heat transfer between the roof and its surroundings. On the positive side, it is easier to monitor grain deterioration at the grain surface than within the bulk during the storage period.

An increased airflow rate resulted in a decreased fan energy input even though an increased airflow rate requires increased energy per unit volume of air passed through the grain (e.g. Tests 261 and 264, Table 5.25). In addition, increasing the airflow rate decreased the average grain deterioration and resulted in lower aeration costs when comparing the same storage period for both linear (e.g. Tests 267, 270, and 273, Table 5.25) and non-linear airflow distributions (Tests 171, 174, and 177, Table 5.21) because the average grain temperature was lowered. Conversely, the average grain deterioration and aeration costs were increased due to an increase in the air-temperature increment for both linear (e.g. Tests 275 to 277, Table 5.25) and non-linear airflow distributions (Tests 155 to 157, Table 5.21) and these increased costs do not include any additional heating costs required for increasing the air temperature. The maximum allowed storage time for many test conditions was increased when the air-temperature increment was increased because it decreased the wetting in the bottom layer (e.g. Tests 109 to 111, Table 5.19). Increasing the air-temperature increment from 1 to 3°C was more effective in reducing the allowable storage time elapsed for the bottom layer than increasing the increment from 3 to 5°C (grain depth of 0.4 m in Fig. 5.17). The allowable storage times elapsed for the other layers, however, were increased due to an increase in the air-temperature increment, therefore increasing the average grain deterioration (Fig. 5.17).

The effect of initial grain moisture content on the maximum allowed storage time was tested for Campo Grande, Cuiabá, and Goiânia (Tables 5.21, 5.23, 5.24, 5.28). Over drying costs were based on any decrease in final average moisture content below the initial moisture content. Therefore, extra over drying costs should be added to the costs for locations where trade

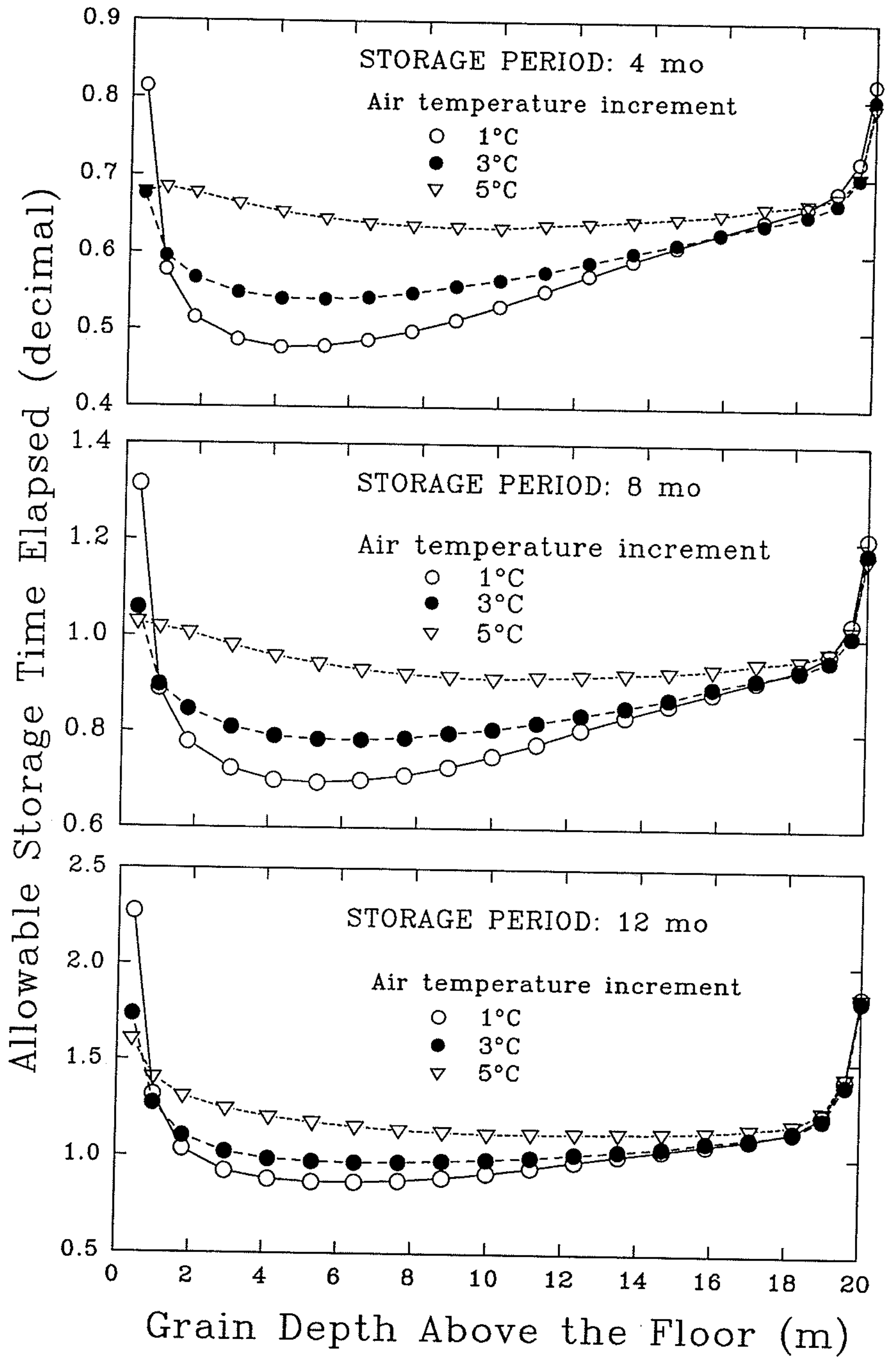

Fig. 5.17. Allowable storage time elapsed for different storage periods and air-temperature increments as a function of the grain depth above the floor (location: Belo Horizonte; differential-thermostat setting: -5°C; airflow rate: 3 $L \cdot s^{-1} \cdot m^{-3}$; and linear airflow distribution)

regulations set the maximum moisture content without penalty at a moisture content higher than the initial moisture contents used in these simulations. The added over drying costs when the final average moisture contents are 12 and 11% instead of 13% are 1.70 and 3.37 $\$\cdot t^{-1}$, respectively. For example, the total aeration costs for 10 mo at Campo Grande when adding the over drying costs for a final average moisture content of 12% is 1.91 $\$\cdot t^{-1}$ (Test 162, Table 5.21) while the total aeration costs for 12 mo at Curitiba is 0.38 $\$\cdot t^{-1}$, i.e. five times less than at Campo Grande. In addition, if a final average moisture content of 12% is not over dry then the total aeration costs at Campo Grande are less than at Curitiba and more dry matter can be stored in the same storage volume. By storing the grain at an initial moisture content of 12% the maximum allowed storage time was increased 43 to 75% and 67 to 125%, for linear and non-linear airflow distributions, respectively. For an initial moisture content of 11% the maximum allowed storage times were increased 43 and 33%, for linear and non-linear airflow distributions, respectively. The effect of initial moisture content was very important to extend the maximum allowed storage time but the increased over drying costs should be taken into account for a final decision. A change in the Brazilian marketing system that takes into account the dry mass instead of the wet mass for calculating the selling price, would eliminate the over drying costs and would encourage the use of storage conditions that improve the stored grain quality.

The average allowable storage time elapsed and total aeration costs for a differential-thermostat setting of -5°C, airflow rate of 3 $L\cdot s^{-1}\cdot m^{-3}$, and air-temperature increment of 3°C with linear airflow distribution indicated that the best geographical locations for grain storage in Brazil, in descending order, were Curitiba, Porto Alegre, São Paulo, Belo Horizonte, Florianópolis, Goiânia, Campo Grande, and Cuiabá (Tests 264, 371, 394, 122, 302, 310, 133, and 184, respectively, Tables 5.19 to 5.30 and Fig. 5.18). Curitiba was the only location where wheat at

13% initial moisture content could be stored for 12 mo without spoilage. The total aeration costs were practically the same up to 4 mo of storage although the average allowable storage time elapsed was much higher for Cuiabá compared with the other locations.

The differences in grain deterioration and aeration costs among the Brazilian locations could not be completely explained by the differences in annual average ambient temperature and relative humidity (Table 4.2, Sec. 4.2). For example, Porto Alegre and São Paulo had annual average ambient temperatures of 19.4 and 18.7°C and the same average relative humidity (80.4%) but Porto Alegre was better for grain storage than São Paulo. The annual average ambient temperature, however, was a practical indicator of the grain aeration potential. The maximum allowed storage time (AST) when using the differential-thermostat method (linear airflow distribution; -5°C differential-thermostat setting, 3 $L \cdot s^{-1} \cdot m^{-3}$ airflow rate, and 3°C air-temperature increment), was approximately a linear function of the annual average ambient air temperature (Eq. 5.10):

$$AST = 25 - 0.8\ T_{ave} \tag{5.10}$$

where: T_{ave} = annual average ambient air temperature (°C).

The standard error of AST (Eq. 5.10) is 0.7 mo and the coefficient of determination is 0.93.

The lower grain deterioration and total aeration costs at Belo Horizonte than at Florianópolis are probably caused by the lower average relative humidity at Belo Horizonte although Florianópolis had a slightly lower average ambient temperature (Table 4.2, Sec. 4.2). The prediction of AST, however, was not improved when the average relative humidity was included in Eq. 5.10. The differences in storability between Belo Horizonte and Florianópolis may also be explained by differences in the distribution of ambient temperature and relative humidity over the

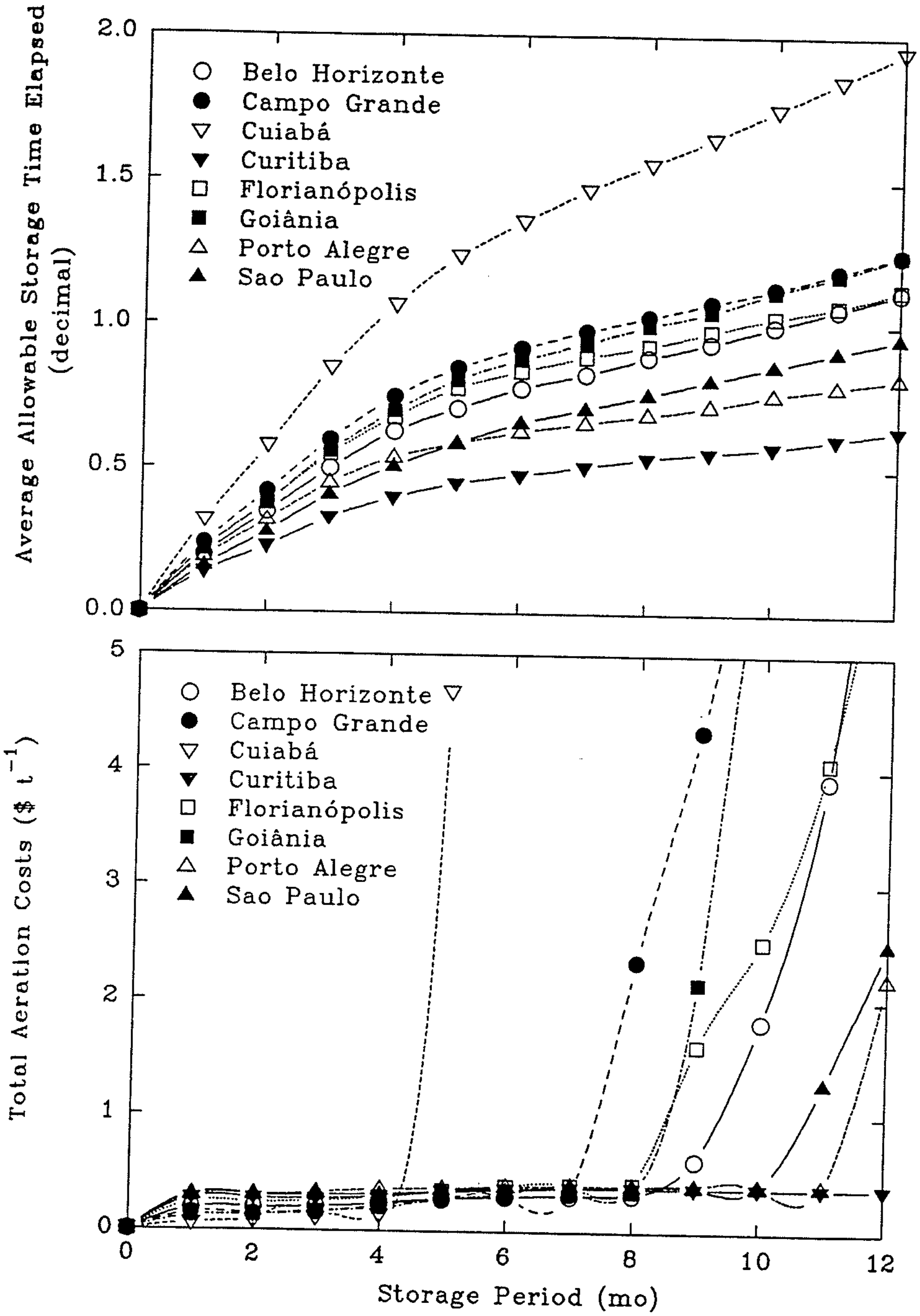

Fig. 5.18. Average allowable storage time elapsed and total aeration costs as a function of the storage period (average of 10 years for all Brazilian locations; differential-thermostat setting: -5°C; airflow rate: 3 L·s^{-1}·m^{-3}; air-temperature increment: 3°C; and linear airflow distribution)

day during the ventilation period.

The maximum allowed storage time and the maximum allowable storage time elapsed plotted against the annual average-time (averaged over 10 years and given as percentage) that the ambient air temperature is below 15°C (Fig. 5.19) was related to the grain aeration potential for the eight Brazilian locations when using the differential-thermostat method (linear airflow distribution; -5°C differential-thermostat setting, 3 $L \cdot s^{-1} \cdot m^{-3}$ airflow rate, and 3°C air-temperature increment). The proposed equation (Eq. 5.11) to predict AST is:

$$AST = 3.9\ \theta_{15}^{\ 0.32} \qquad \textbf{(5.11)}$$

where: θ_{15} = annual average-time that the ambient air temperature is below 15°C (%).

The standard error of AST (Eq. 5.11) is 0.3 mo and the coefficient of determination is 0.99. The annual average-times that the ambient air temperature was below other levels of ambient air temperature (5, 10, 20, and 25°C) (Fig. 5.20) were not useful to indicate the grain aeration potential because some Brazilian locations had only a few hours below 10°C. Ambient air temperatures above 15°C are not adequate for cooling the grain unless it is at the beginning of the storage period when the grain storage is loaded with warm grain from heated-air dryers.

5.7.4. Effects of simulation conditions on the differential-thermostat method

The effects of harvest date, grain depth, initial temperature of the grain, number of grain layers, and the difference between the bin attic temperature and the ambient air temperature were simulated for Curitiba and Goiânia (Tables 5.33 and 5.34).

A 10°C temperature rise of the bin attic above the ambient air temperature (Test 413, Table 5.33 and Test 420, Table 5.34) instead of 5°C used in all other simulations was the variable which caused the greatest effect on the predicted grain deterioration (ASTE) compared with the

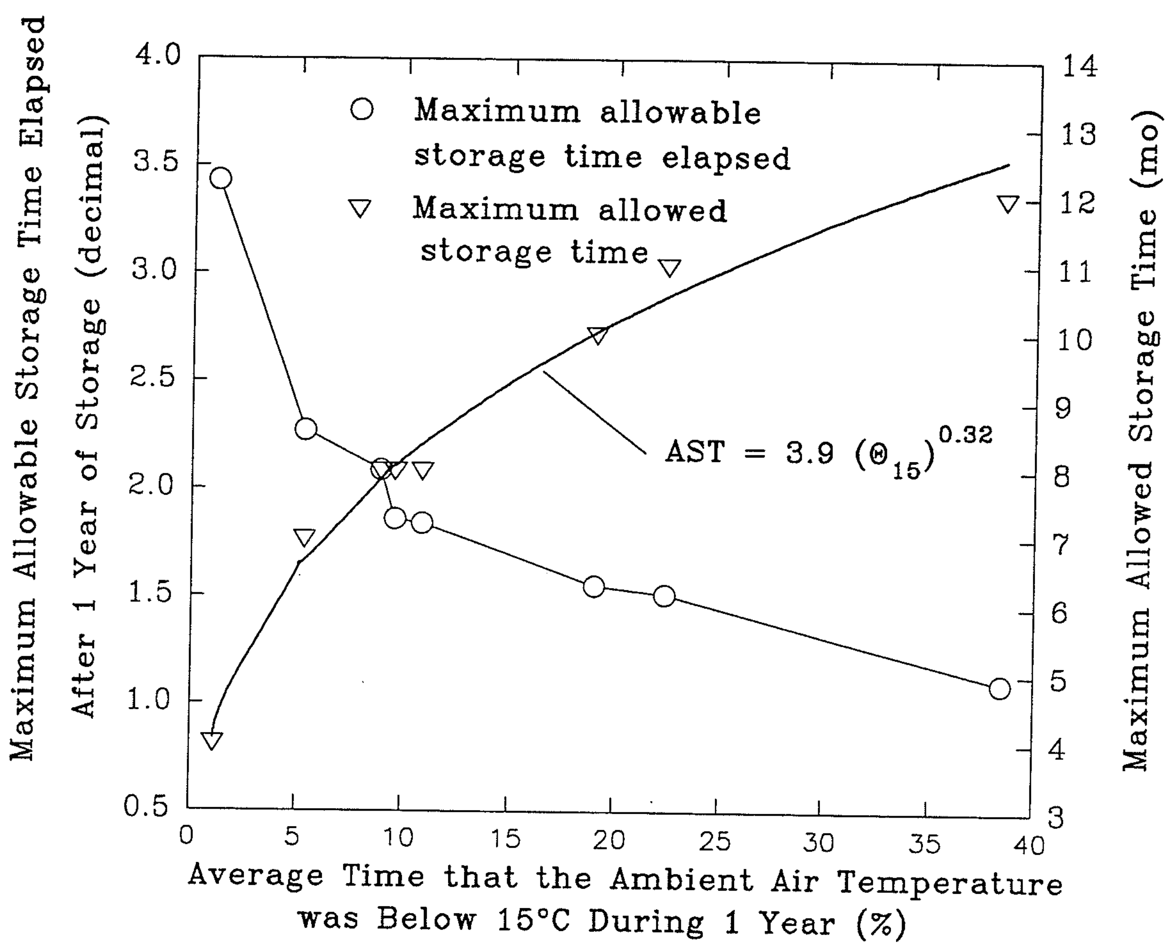

Fig. 5.19. Maximum allowable storage time elapsed and maximum allowed storage time as a function of the annual average-time that the ambient air temperature was below 15°C (all Brazilian locations; differential-thermostat setting: -5°C; airflow rate: 3 $L{\cdot}s^{-1}{\cdot}m^{-3}$; air-temperature increment: 3°C; and linear airflow distribution)

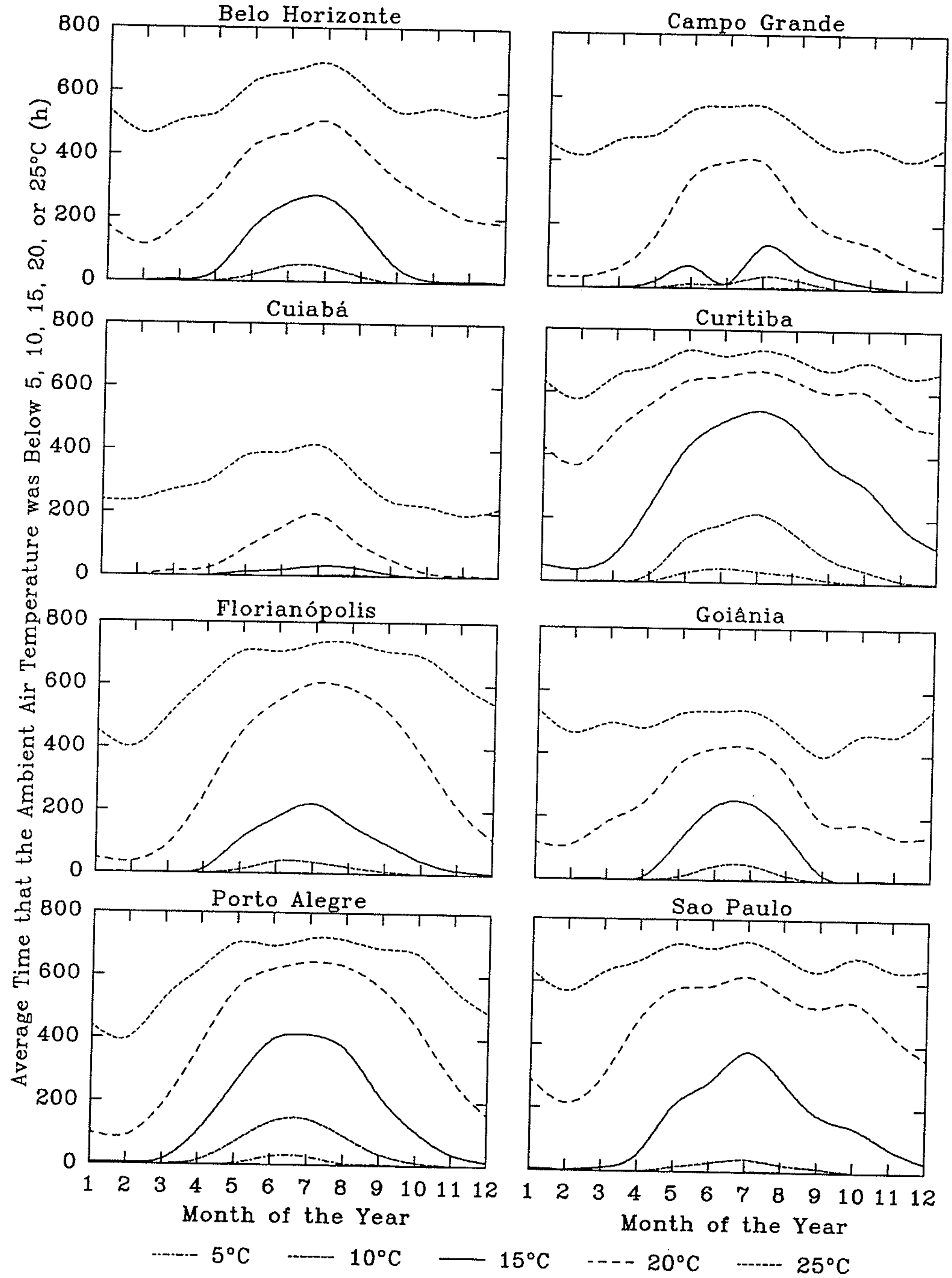

Fig. 5.20. Average time that the ambient air temperature was below 5, 10, 15, 20, or 25°C as a function of the month of the year

other test conditions. The maximum and average ASTE for Curitiba and Goiânia were increased by 28 and 3%, and 22 and 2%, respectively. The increase in the maximum and average ASTE were not significant because they were lower than the uncertainty in predicting the grain deterioration (±30%). These values reinforce the need for head space ventilation to decrease heat transfer by convection from the head space air to the grain surface. The computer model used for the simulation of heat transfer for periods of no ventilation, however, could be improved by including the prediction of the bin attic temperatures as a function of the physical and thermal properties of the head space ventilation, roof, solar radiation, and wind speed.

The grain depth and selected number of grain layers slightly affected the spoilage costs indicating that these variables must be specified according to each particular situation, i.e., using grain depths as close as possible to actual depths and using grain layer thicknesses small enough to detect spoilage of a selected maximum amount of grain. The grain layer thicknesses used for determining the best airflow rates and fan-control methods (Table 4.8) varied from 2 to 5.8% of the total grain depth. Grain layers of smaller thicknesses were used for strategic locations in the grain bulk (first three bottom layers and the last three top layers) where deterioration normally occurred first (Fig. 5.17). The average ASTE increased slightly as the grain depth decreased (Tests 89, 408, and 409, Table 5.33 and Tests 105, 415, and 416, Table 5.34), because the accuracy in predicting grain deterioration increases as the grain layer thicknesses are decreased. For example, the predicted wetting in the bottom layer normally increases when the grain layer thickness is decreased because the proportion of dry mass of air per dry mass of grain for each time interval increases as the grain layer thickness is decreased. The same logic applies to the heat conduction when predicting the grain temperatures especially for the top layer which is susceptible to deterioration due to heat transfered by convection from the bin attic. The grain deterioration,

Table 5.33. Effect of harvest date, grain depth, initial temperature of the grain, number of grain layers, and the difference between the bin attic temperature and the ambient air temperature (T_{roof}) on the maximum and average allowable storage time elapsed (ASTE), fan ventilation time, and costs of over drying, spoilage, and electricity to simulate aeration of wheat stored in Curitiba for 1 year using the differential-thermostat method

Test #	Variable Changed	ASTE (decimal)		Fan Time (h)	Costs ($\$\cdot t^{-1}$)			
		Maximum	Average		Over Drying	Spoilage	Fan Electricity	Total
89	Standard conditions[1]	1.24	0.78	534	0	0	0.43	0.43
407	Harvest date: 1 Feb./61 - 31 Jan./62	1.33	0.73	542	0	0	0.44	0.44
408	Grain depth: 10 m	1.28	0.80	548	0.02	0	0.11	0.13
409	Grain depth: 30 m	1.29	0.78	535	0	0	1.06	1.06
410	Initial temperature of the grain: 20°C	1.26	0.74	329	0	0	0.26	0.26
411	Number of grain layers: 10	1.16	0.80	536	0	0	0.43	0.43
412	Number of grain layers: 30	1.28	0.78	532	0	0	0.43	0.43
413	T_{roof}: 10°C	1.59	0.80	556	0	3.00	0.45	3.45

[1]Standard conditions — differential-thermostat setting: -5°C; T_{roof}: 5°C; grain depth: 20 m; number of grain layers: 10; linear airflow distribution, and same aeration conditions given in Table 5.17.

Table 5.34. Effect of harvest date, grain depth, initial temperature of the grain, number of grain layers, and the difference between the bin attic temperature and the ambient air temperature (T_{roof}) on the maximum and average allowable storage time elapsed (ASTE), fan ventilation time, and costs of over drying, spoilage, and electricity to simulate aeration of wheat stored in Goiânia for 1 year using the differential-thermostat method

Test #	Variable Changed	ASTE (decimal)		Fan Time (h)	Costs ($\$\cdot t^{-1}$)			
		Maximum	Average		Over Drying	Spoilage	Fan Electricity	Total
105	Standard conditions[1]	2.18	1.34	571	0	15.00	0.46	15.46
414	Harvest date: 1 Feb./61 - 31 Jan./62	2.17	1.24	564	0	15.00	0.45	15.45
415	Grain depth: 10 m	2.18	1.37	615	0	27.00	0.12	27.12
416	Grain depth: 30 m	2.20	1.33	558	0	15.00	1.10	16.10
417	Initial temperature of the grain: 20°C	2.14	1.07	248	0	7.50	0.20	7.70
418	Number of grain layers: 10	2.00	1.35	561	0	21.00	0.45	21.45
419	Number of grain layers: 30	2.33	1.33	562	0	18.00	0.45	18.45
420	T_{roof}: 10°C	2.66	1.37	604	0	21.00	0.49	21.49

[1]Standard conditions as given in Table 5.33.

consequently, increases as the grain moisture content and temperature are increased. The grain layer thicknesses for grain depths different than 20 m were calculated proportionally to the grain layer thicknesses used in the standard conditions (Table 4.8). The fan electricity costs were increased when the grain depth was increased because the fan power increases almost by the square of the grain depth. For example, when the grain depth was increased by three times (from 10 to 30 m) the fan electricity costs increased 9.6 times although the fan ventilation times were similar (Tests 408 and 409, Table 5.33).

Decreasing the initial temperature of the grain from 30 to 20°C decreased the aeration costs to nearly one-half (Tests 89 and 410, Table 5.33 and Tests 105 and 417, Table 5.34). Several factors might affect the initial grain temperature such as the ambient air temperature during harvest and first day of storage, effectiveness of grain cooling after drying operations, and grain shipments from other countries or regions. The aeration costs calculated for the best airflow rates and fan-control methods might be over predicted if the actual grain temperature is below 30°C. Delaying harvest by 1 mo did not affect the simulated results.

5.7.5. Method based on the vapor-pressure-deficit

The simulated results using the control method based on the vapor-pressure-deficit are the average of 10 years to aerate wheat stored in eight Brazilian locations with linear airflow distribution (Table 5.35). When using a control method based on the vapor pressure-deficit the maximum allowed storage times were 1 to 2 mo shorter for the four warmest locations and the

Table 5.35. Method based on the vapor-pressure-deficit to control wheat aeration in Brazilian locations[1]

Test #	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$) Over Drying	Costs ($\$ \cdot t^{-1}$) Fan Electricity	Costs ($\$ \cdot t^{-1}$) Total
Belo Horizonte (initial moisture content: 13%; final average moisture content: 12.6 - 12.8%)									
421	1	1	8	13.2	1.04	559	0.53	0.45	0.98
422	1	3	8	12.8	1.07	738	0.62	0.59	1.21
423	2	1	8	13.2	0.99	346	0.44	0.28	0.72
424	2	3	8	12.8	1.01	516	0.59	0.42	1.01
*425	3	1	8	13.2	0.96	262	0.41	0.21	0.62
426	3	3	8	12.8	0.98	446	0.60	0.36	0.96
Campo Grande (initial moisture content: 13%; final average moisture content: 12.6 - 12.7%)									
427	1	1	4	13.1	0.85	285	0.43	0.23	0.66
428	1	3	5	12.9	0.99	449	0.61	0.36	0.97
429	2	1	5	13.1	0.92	266	0.51	0.21	0.72
430	2	3	5	12.9	0.95	382	0.69	0.31	1.00
*431	3	1	5	13.1	0.89	229	0.52	0.19	0.71
432	3	3	5	12.8	0.93	369	0.75	0.30	1.05
Campo Grande (initial moisture content: 12%; final average moisture content: 11.7 - 11.8%)									
433	1	1	8	12.3	0.90	358	0.46	0.28	0.74
434	1	3	8	12.0	0.92	425	0.51	0.34	0.85
435	2	1	8	12.3	0.85	236	0.38	0.18	0.56
436	2	3	9	12.0	0.90	311	0.47	0.25	0.72
437	3	1	8	12.3	0.82	186	0.34	0.15	0.49
*438	3	3	9	12.0	0.88	261	0.45	0.21	0.66

Table 5.35. Method based on the vapor-pressure-deficit to control wheat aeration in Brazilian locations (cont'd)

Test #	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
							Over Drying	Fan Electricity	Total
Cuiabá (initial moisture content: 13%; final average moisture content: 12.6 - 12.9%)									
*439	1	1	3	12.9	0.88	199	0.26	0.16	0.42
440	1	3	3	12.9	0.90	245	0.31	0.20	0.51
441	2	1	3	12.9	0.85	180	0.32	0.15	0.47
442	2	3	3	12.9	0.89	289	0.49	0.24	0.73
443	3	1	3	13.0	0.84	184	0.39	0.15	0.54
444	3	3	3	12.8	0.87	340	0.68	0.27	0.95
Cuiabá (initial moisture content: 12%; final average moisture content: 11.6 - 11.8%)									
445	1	1	6	11.9	1.05	288	0.38	0.23	0.61
446	1	3	6	11.8	1.07	357	0.45	0.28	0.73
*447	2	1	6	12.0	1.02	240	0.40	0.19	0.59
448	2	3	6	11.8	1.05	344	0.56	0.27	0.83
449	3	1	6	12.0	1.00	227	0.43	0.18	0.61
450	3	3	6	11.8	1.02	346	0.63	0.27	0.90
Cuiabá (initial moisture content: 11%; final average moisture content: 10.5 - 10.9%)									
451	1	1	10	10.9	1.01	446	0.50	0.34	0.84
452	1	3	10	10.8	1.03	593	0.64	0.46	1.10
*453	2	1	11	10.8	1.04	479	0.68	0.37	1.05
454	2	3	11	10.7	1.09	796	1.03	0.61	1.64
455	3	1	11	10.7	1.03	532	0.81	0.41	1.22
456	3	3	11	10.5	1.08	907	1.22	0.70	1.92

Table 5.35. Method based on the vapor-pressure-deficit to control wheat aeration in Brazilian locations (cont'd)

Test #	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$)		
							Over Drying	Fan Electricity	Total
Curitiba (initial moisture content: 13%; final average moisture content: 12.6 - 12.7%)									
457	1	1	12	13.5	0.82	502	0.63	0.40	1.03
458	1	3	12	13.0	0.85	599	0.70	0.48	1.18
459	2	1	12	13.5	0.74	316	0.51	0.25	0.76
460	2	3	12	13.0	0.77	390	0.59	0.31	0.90
*461	3	1	12	13.6	0.71	237	0.44	0.19	0.63
462	3	3	12	12.9	0.73	302	0.54	0.24	0.78
Florianópolis (initial moisture content: 13%; final average moisture content: 12.6 - 12.7%)									
463	1	1	6	13.1	0.91	419	0.58	0.34	0.92
464	1	3	7	12.7	1.00	569	0.69	0.46	1.15
465	2	1	7	13.0	0.89	315	0.54	0.25	0.79
466	2	3	7	12.7	0.93	412	0.65	0.33	0.98
467	3	1	7	13.0	0.85	251	0.49	0.20	0.69
*468	3	3	8	12.7	0.95	381	0.66	0.31	0.97
Goiânia (initial moisture content: 13%; final average moisture content: 12.6 - 12.8%)									
469	1	1	6	13.2	1.07	474	0.50	0.38	0.88
470	1	3	6	12.9	1.09	582	0.57	0.47	1.04
471	2	1	6	13.2	1.02	303	0.43	0.25	0.68
472	2	3	7	12.9	1.12	478	0.59	0.38	0.97
*473	3	1	6	13.2	1.00	238	0.40	0.19	0.59
474	3	3	7	12.9	1.09	419	0.63	0.34	0.97

Table 5.35. Method based on the vapor-pressure-deficit to control wheat aeration in Brazilian locations (cont'd)

Test #	Airflow Rate ($L \cdot s^{-1} \cdot m^{-3}$)	Temperature Increment (C°)	Maximum AST (mo)	Maximum M. C. (%, wb)	Average ASTE (decimal)	Fan Time (h)	Costs ($\$ \cdot t^{-1}$) Over Drying	Costs Fan Electricity	Costs Total
Goiânia (initial moisture content: 12%; final average moisture content: 11.3 - 11.7%)									
*475	1	1	10	12.0	1.08	624	0.56	0.49	1.05
476	1	3	10	11.9	1.10	835	0.74	0.66	1.40
477	2	1	10	12.0	1.04	597	0.77	0.47	1.24
478	2	3	10	11.7	1.06	813	1.08	0.64	1.72
479	3	1	10	11.9	1.03	573	0.88	0.45	1.33
480	3	3	10	11.6	1.05	808	1.31	0.64	1.95
Porto Alegre (initial moisture content: 13%; final average moisture content: 12.5 - 12.7%)									
481	1	1	10	13.1	0.87	574	0.64	0.46	1.10
482	1	3	10	12.7	0.91	725	0.75	0.58	1.33
483	2	1	10	13.1	0.80	369	0.54	0.30	0.84
484	2	3	10	12.7	0.83	510	0.72	0.41	1.13
*485	3	1	11	13.0	0.81	292	0.50	0.24	0.74
486	3	3	11	12.7	0.84	436	0.72	0.35	1.07
São Paulo (initial moisture content: 13%; final average moisture content: 12.3 - 12.6%)									
487	1	1	10	12.8	1.03	695	0.69	0.56	1.25
488	1	3	10	12.6	1.06	914	0.84	0.74	1.58
*489	2	1	10	12.7	0.98	540	0.76	0.43	1.19
490	2	3	10	12.6	1.01	794	1.04	0.64	1.68
491	3	1	10	12.7	0.95	495	0.85	0.40	1.25
492	3	3	10	12.5	0.99	780	1.21	0.63	1.84

[1]Aeration conditions — values are the average of 10 years starting on 1 Jan. 1961; initial grain temperature of 30°C; and with linear airflow distribution. AST = allowed storage time. M. C. = grain moisture content. ASTE = allowable storage time elapsed.
*Asterisks indicate the best combination of airflow rate and air-temperature increment.

aeration costs were higher (all locations) than when using a control based on differential temperatures. The maximum allowed storage time at Cuiabá with an initial moisture content of 11% (Test 453), however, was increased by 1 mo compared with the differential-thermostat method (Test 234, Table 5.24) but that extra 1 mo storage increased the total aeration costs by about ten times.

The method based on the vapor-pressure-deficit is not advantageous for locations where regulations allow wheat to be traded at with moisture contents equal to or higher than 13%. The method based on the vapor-pressure-deficit, however, might be an alternative to the differential-thermostat method if the over drying costs are not important. For example, aerating wheat in Belo Horizonte for 8 mo, resulted in the same fan electricity costs for both control methods (Tests 121, Table 5.19 and 425, Table 5.35). The grain quality when using the differential-thermostat method, however, was higher than when using the method based on the vapor-pressure-deficit (average ASTE were 0.85 and 0.96, respectively).

The method based on the vapor-pressure-deficit allowed fan operation at any time of the day resulting in higher over drying costs and higher average grain temperatures compared with the differential-thermostat method. Therefore, the grain bulk was not cooled properly and this increased the average grain deterioration when comparing with the differential thermostat method. The problem of over drying and reduced cooling was worse for tropical locations because the fan was turned on during periods of low relative humidities and high ambient air temperatures.

Increasing the absolute TDIFF when using the differential-thermostat method resulted in similar aeration costs to using the method based on the vapor-pressure-deficit (e.g. compare Tests 278 and 279, Table 5.25 with Tests 459 and 460, Table 5.35). The increased absolute TDIFF caused a reduction in the ventilation time and increased the average vapor pressure difference between the grain and the aeration air causing over drying. Grain cooling, however, was more effective for the differential-thermostat method because the fan operated mainly at night and caused less over drying compared with the method based on the vapor-pressure-deficit.

The maximum allowed storage times were not affected by airflow rates and air-temperature increments when using the method based on the vapor-pressure-deficit (Table 5.35). The average ASTE, however, increased when the air-temperature increment was increased or when the airflow rate was decreased. Also, the aeration costs increased for increased air-temperature increments due to increased over drying but they decreased with increased airflow rates due to reduced ventilation time.

5.8. Evaluation of Hypotheses

5.8.1. Thin-layer drying and wetting equations for wheat

Assumption 1 (Sec. 1.3) was entirely true only for the thin-layer wetting equation (Eqs. 3.1, 5.6 and 5.7) because the effect of air velocity on the thin-layer drying equation was not significant. The major variables that affected the thin-layer drying of wheat were the difference between the initial moisture content and the desorption equilibrium moisture content, and air temperature and relative humidity (Eqs. 3.1, 5.4 and 5.5). The desorption equilibrium moisture content, however, was a function of the initial moisture content and air temperature and relative humidity. Taking into account the low standard errors determined for the thin-layer drying and wetting equations (Table 5.3) it can be inferred that Hypothesis 1 (Sec. 1.2) is true although Assumption 1 has not been entirely confirmed for the thin-layer drying equation.

5.8.2. Comparison of equilibrium and non-equilibrium mathematical models

The simulated results for the comparison of mathematical models to simulate aeration of wheat stored under tropical, subtropical, and temperate climates confirmed only partially Assumption 2 (Sec. 1.3). The equilibrium and non-equilibrium models were not considered different when using airflow rates and ventilation times recommended for the Canadian Prairies although it was observed that the equilibrium model had a tendency to over predict drying and wetting rates especially in the bottom layers of grain near the air entrance.

For Brazilian locations the equilibrium model over predicted wetting rates and grain deterioration in the bottom layers of grain causing significant errors in the prediction of allowable storage time elapsed. The over prediction of grain deterioration by the equilibrium model, however, was decreased when air velocities were increased for both linear and non-linear airflow distributions. Assumption 2 was partially contradicted because, as the air velocity increased, the grain moisture contents predicted by the non-equilibrium model approached the same equilibrium moisture contents that were calculated by the equilibrium model. Therefore, it can be inferred that Hypothesis 2 (Sec. 1.2) is true although Assumption 2 was not entirely confirmed.

5.8.3. Sensitivity analysis of the non-equilibrium mathematical model

The mathematical model used to determine the best airflow rates and fan-control methods for Brazilian locations was simplified based on the results of the sensitivity analyses for the non-equilibrium model to simulate aeration of wheat stored under tropical and subtropical climatic conditions.

The results of the sensitivity analyses for Winnipeg permitted to conclude that the deterioration model needs to be improved before more research is conducted for improving equations which describe physical and thermal properties of wheat. In addition, the knowledge about the most important variables to simulate aeration of wheat stored in Curitiba (fan temperature rise, thin-layer wetting equation, and thin-layer drying equation) is important to direct future research towards the measurement of those variables. Therefore, it can be inferred that Hypothesis 3 (Sec. 1.2) is true.

5.8.4. Airflow rates and fan control methods for tropical and subtropical climates

The computer model developed to simulate intermittent aeration of stored wheat was sucessfully used to determine the best airflow rates and fan-control methods for eight Brazilian locations based on 10 years of weather data confirming Assumption 4 (Sec. 1.3). The knowledge obtained in this research can be extended to other grain types and geographical regions. Therefore, it can be inferred that Hypothesis 4 (Sec. 1.2) is true.

6. SUMMARY OF RESULTS

6.1. Thin-Layer Drying and Wetting Equations

The equilibrium moisture content equations with four parameters that best fit the data were the modified Chung-Pfost equation for desorption and the modified Halsey equation for adsorption (standard errors of 0.19 and 0.39% moisture content, respectively). The modified Chung-Pfost equation with three parameters predicted reasonably well the equilibrium moisture content for both desorption and adsorption (standard errors of 0.59 and 0.80% moisture content, respectively). Thin-layer drying of wheat was affected by air temperature, relative humidity, and initial moisture content while thin-layer wetting also depended slightly on air velocity. The thin-layer equation for drying and wetting of wheat that best fit the data was the semi-empirical equation of Page with six parameters (standard errors of 0.12 and 0.24% moisture content, respectively). The equation of Page with five parameters and using the same variables to define the coefficients K'' and N'' predicted well for both drying and wetting (standard errors of 0.13 and 0.37% moisture content, respectively). The diffusion equation, with the diffusion coefficient dependent on temperature only, had the highest errors for both drying and wetting (standard errors of 0.77 and 1.33% moisture content).

6.2. Comparison of Equilibrium and Non-equilibrium Models

The results produced by the equilibrium and non-equilibrium models were significantly different (α=0.05) when simulating aeration of wheat stored in Curitiba, Brazil for 1 year for most test conditions. The differences in predicted grain deterioration were due to over prediction of wetting rates by the equilibrium model especially in the bottom layers of grain near the air entrance. For Winnipeg, Canada, however, the results were not different (α=0.05) when simulating aeration of wheat stored from September to November for most test conditions including the aeration conditions recommended for the Canadian Prairies (1 $L \cdot s^{-1} \cdot m^{-3}$ airflow rate and 0:00-6:00 ventilation time) although it was observed that the equilibrium model had a tendency to over predict drying and wetting rates.

The differences between the equilibrium and non-equilibrium models, when simulating for Curitiba, were affected by airflow rate, fan temperature rise, airflow distribution, grain layer thickness, grain depth, geographical location, ventilation time, and assuming a 5% offset in the equilibrium relative humidity in moisture adsorption calculated by the equilibrium model. The initial grain moisture content and temperature, year of simulation, or grain layer thickness less than 20 cm slightly affected the differences between the models. The differences between both models for Winnipeg, however, were also affected by the initial moisture content and temperature of the grain, and year of simulation but they were not affected by the grain depth.

The non-equilibrium model developed here is recommended to simulate aeration of stored wheat because it is based on empirical thin-layer drying and wetting equations and equilibrium moisture content equations for adsorption and desorption and because the equilibrium model over predicts drying and wetting rates especially in the bottom layers.

6.3. Sensitivity Analyses

The most important variables to simulate aeration of wheat stored in Curitiba for 1 year using linear airflow distribution, in decreasing order, were the fan temperature rise, thin-layer wetting equation, and thin-layer drying equation, at airflows of 0.0056 and 0.0278 $m^3\ s^{-1}\ m^{-2}$ and fan temperature rises of 1 and 3°C.

The most important variables to simulate aeration of wheat stored in Winnipeg for 3 mo were the thin-layer drying equation followed by the EMC desorption equation, fan temperature rise, and thin-layer wetting equation, which were equally important.

The accuracy of equations to describe specific heat and equilibrium moisture content for adsorption and desorption by wheat was not important to simulate aeration of wheat stored in Curitiba because the errors introduced by these equations were lower than the uncertainty in predicting allowable storage time elapsed. This conclusion can also be extrapolated for the equation which describes the air resistance to airflow because the uncertainties in airflow did not introduce significant errors in the allowable storage time elapsed. Therefore, the deterioration model must be improved before any of these equations are improved. The deterioration model must be improved especially for Winnipeg because the uncertainty in the calculation of wheat deterioration was much higher than the uncertainty generated by all equations tested in the computer program for simulating aeration of stored wheat.

The wheat bulk density can be a constant, the net heat of sorption can be neglected, and the ratio of bin diameter to bin height was not important in the mathematical model to simulate aeration of wheat stored in Curitiba or Winnipeg.

The model's sensitivity was affected by the airflow distribution, fan temperature rise, airflow rate, geographical location, grain depth, grain layer thickness, and initial moisture content of the grain but it was not affected by the year used for the simulation and initial temperature of the grain. The model's sensitivity for Winnipeg, however, was also affected by the year of simulation and initial temperature of the grain but it was not affected by the grain depth.

6.4. Airflow Rates and Fan Control Methods for Brazilian Locations

The best fan-control method to aerate wheat stored in Brazilian locations was a differential-thermostat and the second best method was based on the vapor-pressure-deficit. The best aeration conditions for all geographical locations with linear airflow distribution at 13% initial grain moisture content were -5°C differential-thermostat setting, 3 $L{\cdot}s^{-1}{\cdot}m^{-3}$ airflow rate, and 3°C air-temperature increment but for Belo Horizonte, Cuiabá, and Porto Alegre the best air-temperature increments were 5, 1, and 1°C, respectively.

For non-linear airflow distribution, when using the differential-thermostat setting and air-temperature increment determined to be the best for linear airflow distribution, the maximum allowed storage time was reduced by 1 to 4 mo (airflow rate of 1.3 $L{\cdot}s^{-1}{\cdot}m^{-3}$ and static pressure of 3500 Pa in the aeration duct). When changing from linear to non-linear airflow distribution, an increase of 1°C in the differential thermostat setting and an increase of 2°C in the air-temperature increment were the most common changes to the aeration conditions required to maintain the maximum allowed storage time as high as possible.

The simulation results indicated that the best locations for grain storage in Brazil, in descending order, were Curitiba (12 mo), Porto Alegre (11 mo), São Paulo (10 mo), Belo Horizonte (9 mo), Florianópolis (8 mo), Goiânia (8 mo), Campo Grande (7 mo), and Cuiabá (4 mo).

The maximum allowed storage time for aerated wheat in Brazilian locations correlated well with the annual average-time (averaged over 10 years) that the ambient air temperature was below 15°C.

7. CONCLUSIONS

1. The semi-empirical equation of Page was a more accurate model of the data than the theoretical diffusion equation with the diffusion coefficient dependent on temperature only.

2. The results produced by the equilibrium and non-equilibrium models were significantly different (α=0.05) when simulating aeration of wheat stored in Curitiba, Brazil. For Winnipeg, Canada, however, the results were not different (α=0.05) for most test conditions including the aeration conditions recommended for the Canadian Prairies.

3. The deterioration model must be improved because the uncertainty in the calculation of wheat deterioration was much higher than the uncertainty generated by many of the other variables for the Brazilian climate and by all the other variables for the Winnipeg climate when simulating aeration of stored wheat.

4. The best fan-control method to aerate wheat stored in the Brazilian locations was a differential-thermostat.

5. The maximum allowed storage time for aerated wheat stored at the Brazilian locations correlated well with the annual average-time that the ambient air temperature was below 15°C.

8. SUGGESTIONS FOR FUTURE RESEARCH

1. The design of the experimental equipment used for the thin-layer drying and wetting tests should be improved to facilitate the measurement of air velocity and to distribute the air uniformly through each tray section. In addition, automatic weighing of the sample holders should be used when testing at air temperatures higher than 35°C to prevent exposing the grain samples to the external environment.

2. The diffusion equations used for thin-layer drying and wetting of wheat (Eqs. 3.2 and 3.3) might be improved by determining the dependence of the diffusion coefficient on the temperature and moisture content of the grain.

3. The mathematical model used for predicting wheat deterioration needs to be improved to decrease its high uncertainty (±30%).

4. The best airflow rates and fan-control methods to aerate grain stored in tropical and subtropical climates should be determined for other grain types. Also, experiments should be conducted to determine under practical conditions the reduction in aeration costs (due to decrease in grain spoilage, over drying, and electricity costs) when changing from the traditional fan-control method used in Brazil to the differential-thermostat method.

5. The finite element program used to calculate the pressure gradients inside the grain bulk should be validated against actual pressure data measured in large horizontal grain storages of

different shapes and aeration designs. In addition, measured and predicted air velocities at the grain surface should be compared.

6. The heat transfer model should be improved to simulate the bin attic temperatures as a function of roof design, thermal and physical properties of the roof, solar radiation, and wind speed. In addition, this model should be able to predict the effects of head space ventilation.

7. The air-temperature increments existing in aeration ducts should be measured and compared with predicted values for different static pressures and duct designs.

9. REFERENCES

Abbouda, S. K., D. S. Chung, P. A. Seib, and A. Song. 1992a. Heat and mass transfer in stored milo. Part I. Heat transfer model. Trans. ASAE (Am. Soc. Agric. Eng.) 35:1569-1573.

Abbouda, S. K., D. S. Chung, P. A. Seib, and A. Song. 1992b. Heat and mass transfer in stored milo. Part II. Mass transfer model. Trans. ASAE (Am. Soc. Agric. Eng.) 35:1569-1573.

Abe, T., C. E. Ofoche, Y. Hikida, and D. H. Han. 1993. Development and evaluation of in-bin storage system with aeration cooling and humidity control units. Paper 93-6020. Am. Soc. Agric. Eng., St. Joseph, MI. 12 p.

Alagusunduram, K., D. S. Jayas, N. D. G. White, and W. E. Muir. 1990. Three-dimensional finite element, heat transfer model of temperature distribution in grain storage bins. Trans. ASAE (Am. Soc. Agric. Eng.) 33:577-584.

Anderson, M. E. and G. L. Kline. 1986. Field comparison of FALDRY -a low-temperature, corn drying model. Paper 86-6505. Am. Soc. Agric. Eng., St. Joseph, MI. 16 p.

Armitage, D. M. 1986. Pest control by cooling and ambient air drying. Pages 22:13-20 in: Spoilage and mycotoxins of cereals and other stored products. B. Flanningan (ed.). Int. Biodeterioration Supp. 22:13-20.

Armitage, D. M. and N. J. Burrell. 1978. The use of aeration spears for cooling infested grain. J. Stored Prod. Res. 14:223-226.

Armitage, D. M. and B. E. Llewellin. 1987. The survival of Oryzaephilus surinamensis (L.) (Coleoptera: Curculionidae) in aerated bins of wheat during British winters. Bull. Ent. Res. 77: 457-466.

ASAE, 1993a. Moisture measurement - unground grain and seeds. ASAE S352.2 DEC92. Page 449 in: Standards 1993. Am. Soc. Agric. Eng., St. Joseph, MI.

ASAE. 1993b. Moisture relationship of grains. ASAE D245.4 DEC92. Pages 412-416 in: Standards 1993. Am. Soc. Agric. Eng., St. Joseph, MI.

ASAE. 1993c. Psychrometric data. ASAE D271.2 DEC92. Pages 48-55 in: Standards 1993. Am. Soc. Agric. Eng., St. Joseph, MI.

ASAE. 1993d. Resistance to airflow of grains, seeds, other agricultural products, and perforated metal sheets. ASAE D272.2 DEC92. Pages 432-436 in: Standards 1993. Am. Soc. Agric. Eng., St. Joseph, MI.

Bailey, S. W. 1968. Air temperatures in the Australian wheat belt and their relationship to the aeration of stored grain. Division of Entomology CSIRO. Technical Paper No. 9. Canberra, Australia. 24 p.

Bailey, P. H. and E. A. Smith. 1982. Strategies for control of near-ambient grain driers - simulation using 1968 Turnhouse (Edinburgh) weather. Dep. Note SIN/300, Scot. Inst. Agric. Eng., Penicuik. (Unpublished).

Bakshi, A. S. and A. Bhatnagar. 1972. Studies on the storage of wheat grains in outdoor metal bins. Punjab Agric. Univ. J. Res. 9:598-609.

Bakker-Arkema, F. W. and C. W. Hall. 1965. Static versus dynamic moisture equilibria in the drying of biological products. J. Agric. Eng. Res. 10:308-311.

Bakker-Arkema, F. W. 1986. Modelling of forced convection in-store grain drying: the state of the art. Pages 89-85 in: Preserving grain quality by aeration and in-store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

Bakker-Arkema, F. W., L. E. Lerew, S. E. De Boer, and M. G. Roth. 1974. Grain dryer simulation. Research Report No. 224. Michigan State University, Michigan, MI.

Bala, B. K., N. N. Sarker, M. A. Basunia, and M. M. Alam. 1990. Simulation of temperature changes during storage of wheat and rough rice. J. Stored Prod. Res. 26:1-6.

Banaszek, M. M. and T. J. Siebenmorgen. 1990. Moisture adsorption rates of rough rice. Trans. ASAE (Am. Soc. Agric. Eng.) 33:1257-1262.

Barret, J. R. Jr., M. R. Okos, and J. B. Stenvens. 1981. Simulation of low temperature wheat drying. Trans. ASAE (Am. Soc. Agric. Eng.) 24:1042-1046.

Beard, J. T. and J. H. Arthur. 1985. Ventilation concepts for insect control in grain storage and agricultural warehousing. Paper 85-3517. Am. Soc. Agric. Eng., St. Joseph, MI. 20 p.

Bell, R. A. 1978. A simulation model of temperatures in grain bins. Pages 99-102 in: Proc. SIMSIG-78 Simulation Conf. Aust. Nat. Univ. Sept 1978. Canberra, Australia.

Benedict, R. P. 1984. Fundamentals of temperature, pressure, and flow measurements. John Wiley and Sons, New York, NY. 532 p.

Bhatnagar, A. P. and A. P. Bakshi. 1975. Aeration studies on the storage of wheat grains in a 50-t outdoor metal bin. Punjab Agric. Univ. J. Res. 12:189-199.

Biondi, P., M. Biscarini, and G. Farina. 1988. Simulation of low temperature corn drying in three locations in Italy. J. Agric. Eng. Res. 40:103-111.

Bloome, P. D. and G. C. Shove. 1971. Near equilibrium simulation of shelled corn drying. Trans. ASAE (Am. Soc. Agric. Eng.) 14:709-712.

Bloome, P. D. and G. C. Shove. 1972. Simulation of low temperature drying of shelled corn leading to optimization. Trans. ASAE (Am. Soc. Agric. Eng.) 15:310-316.

Bloome, P. D. and G. W. Cuperus. 1984. Aeration for management of stored grain insects in wheat. Paper 84-3517. Am. Soc. Agric. Eng., St. Joseph, MI. 12 p.

Bournas, L. 1988. Heat and moisture transfer in grains - consequences for aeration and storage. Pages 160-169 in: Preservation and storage of grains, seeds and their by-products, J. L. Multon (ed.). Lavoisier Pub., New York, NY.

Bowden, P. J., W. J. Lamond, and E. A. Smith. 1983. Simulation of near-ambient drying. I. Comparison of simulations with experimental results. J. Agric. Eng. Res. 28:279-300.

Boyce, D. S. 1965. Grain moisture and temperature changes with positions and time during through drying. J. Agric. Eng. Res. 10:333-341.

Boyce, D. S. 1966. Heat and moisture transfer in ventilated grain. J. Agri. Eng. Res. 11:255-265.

Bronzatti, L. S., M. Sagrilo, and S. V. dos Santos Gazzo. 1992. Letter of 1992 11 27 from L. S. Bronzatti, Grain Storage Manager, M. Sagrilo, Supervisor, and S. V. dos Santos Gazzo, Agronomist, COAMO-Cooperativa Agropecuária Mourãoense Ltda, Campo Mourão, PR, Brazil.

Brook, R. C. 1987. Modelling grain spoilage during near-ambient grain drying. AFRC Institute of Eng. Res. Div. Note DN.1388, Silsoe, Bedford. 20 p.

Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1974. Drying Cereal Grains. The AVI Publishing Company Inc., Westport, CT. 265 p.

Brooker, D. B. and A. K. Duggal. 1982. Allowable storage time of corn as affected by heat buildup, natural convection and aeration. Trans. ASAE (Am. Soc. Agric. Eng.) 25:806-810.

Browne D. A. 1962. Variation of the bulk density of cereals with moisture content. J. Agric. Eng. Res. 7:288-290.

Bunn, J. M. and C. A. DeWitt. 1990. Simulated ambient air drying in South Carolina. Paper 90-6051. Am. Soc. Agric. Eng., St. Joseph, MI. 14 p.

Bunn, J. M. and C. A. Krueger Wishert. 1991. Adding a wetting routine to Thompson's model. Trans. ASAE (Am. Soc. Agric. Eng.) 34:1892-1899.

Buschermohle, M. J., J. M. Bunn, and R. A. Spray. 1988. Moisture migration in stored grain. Paper 88-6508. Am. Soc. Agric. Eng., St. Joseph, MI. 12 p.

Buschermohle, M. J., J. M. Bunn, and R. A. Spray. 1989. Temperature and moisture distribution in stored grains in southeastern climates. Paper 89-6542. Am. Soc. Agric. Eng., St. Joseph, MI. 21 p.

Busta, F. F., L. B. Smith, and C. M. Christensen. 1980. Microbiology of controlled atmospheric storage of grains - an overview. Pages 121-132 in: Controlled atmosphere storage of grains, J. Shejbal (ed.). Elsevier Scientific Publ. Co., Castelgandolfo, Italy, Rome.

Calderon, M. 1972. Aeration of grains - Benefits and limitations. Pages 83-94 in: Grain Storage Seminar Jul 1971. OEPP/EPPO Bull. no 6. Ibadan, Nigeria.

Calderon, M. 1974. The possible role of aeration in the control of stored product insects in warm climates. Pages 1:77-84 in: Proc. First Int. Work. Conf. Stored-Prod. Entomol.

Calderon, M., E. Donahaye, S. Navarro, and R. Davis. 1989. Wheat storage in a semi-desert region. Trop. Sci. 29:91-110.

Calderwood, D. L., R. R. Cogburn, B. D. Webb, and M. A. Marchetti. 1983. Aeration of rough rice in long-term storage. Trans. ASAE (Am. Soc. Agric. Eng.) 27:1579-1585.

Canada Grains Council. 1994. Canadian grains industry statistical handbook 93. Canada Grains Council, Winnipeg, MB. 267 p.

Cenkowski S., D. S. Jayas, and D. Hao. 1992. Latent heat of vaporization for selected foods and crops. Can. Agric. Eng. 34:280-285.

Chang, C. S., H. H. Converse, and J. L. Steele. 1993. Modeling of temperature of grain during storage with aeration. Trans. ASAE (Am. Soc. Agric. Eng.) 36:509:519.

Chen, C. and R. V. Morey. 1989a. Comparison of four EMC/ERH equations. Trans. ASAE (Am. Soc. Agric. Eng.) 32:983-990.

Chen, C. and R. V. Morey. 1989b. Equilibrium relative humidity (ERH) relationships for yellow-dent corn. Trans. ASAE (Am. Soc. Agric. Eng.) 32:999-1006.

Chrinstensen, C. M. and D. B. Sauer. 1982. Microflora. Pages 219-240 in: Storage of cereal grains and their products, C. M. Christensen (ed.). Am. Assoc. Cereal Chem., Inc., St. Paul, MN.

Chung, D. S. and H. B. Pfost. 1967. Adsorption and desorption of water vapor by cereal grains and their products. Part III. Trans. ASAE (Am. Soc. Agric. Eng.) 10:556-557.

Chung, D. S., B. Kanuyoso, L. Ericksonand, and C-H. Lee. 1986. Grain aeration and in-store drying in the USA. Pages 224-238 in: Preserving grain quality by aeration and in-store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

CONAB 1994a. Companhia Nacional de Abastecimento (National Supply Company). Previsão e acompanhamento de safras. Ano 18 No. 4. Brasília, Brazil. (In Portuguese)

CONAB 1994b. Companhia Nacional de Abastecimento (National Supply Company). Sistema de cadastramento de armazéns. Page 1 in: Mapa dos totais de capacidade estática dos armazéns cadastrados por unidates da federação. Brasília, Brazil. (In Portuguese)

Converse, H. H., A. H. Graves, and D. S. Chung. 1973. Transient heat transfer within wheat stored in a cylindrical bin. Paper 69-855. Am. Soc. Agric. Eng., St. Joseph, MI. 24 p.

Cordeiro, L. A. M. 1993. Letter of 1993 04 29 from L. A. M. Cordeiro, Agronomist, CONAB-Companhia Nacional de Abastecimento, Ponta Grossa, PR, Brazil.

Cotton, R. T. and D. Wilbur. 1982. Insects. Pages 281-318 in: Storage of cereal grains and their products, C. M. Christensen (ed.). Am. Assoc. Cereal Chem., Inc., St. Paul, MN.

Covanich, A. 1988. Some engineering considerations for bulk storage in the humid tropics. Pages 272-273 in: Bulk handling and storage of grain in the humid tropics, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 22, Canberra, Australia.

Cuperus, G. W., C. K. Prickett, P. D. Bloome, and J. T. Pitts. 1986. Insect populations in aerated and unaerated wheat in Oklahoma. J. Kansas Ent. Soc. 59:620-627.

Dona, C. L. G and W. E. Stewart Jr. 1988. Numerical analysis of natural convection heat transfer in stored high moisture corn. J. Agric. Eng. Res. 40:275-284.

Donahaye, E., S. Navarro, and M. Calderon. 1974. Studies on aeration with refrigerated air. III. Chilling of wheat with a modified chilling unit. J. Stored Prod. Res. 10:1-8.

Driscoll, R. H. 1986. The application of psychrometrics to grain aeration. Pages 67-80 in: Preserving grain quality by aeration and in-store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

Duggal, A. K., W. E. Muir, and D. B. Brooker. 1982. Thin-layer rewetting of wheat straw and heads. Can. Agric. Eng. 24:11-14.

Epperly, D. R., R. T. Noyes, G. W. Cuperus, and B. L. Clary. 1987. Control stored grain insects by grain temperature management. Paper 87-6035. Am. Soc. Agric. Eng., St. Joseph, MI. 21 p.

Ferreira, W. A. and W. E. Muir. 1981. Aeração de graos de milho armazenados sob condições climáticas do Estado de São Paulo. (Aeration of corn stored at climatic conditions of São Paulo State). São Paulo, Brazil, Científica 9:197-205. (In Portuguese)

Ferreira, W. , W. E. Muir, and B. M. Fraser. 1979. Aeration of corn in Brazil. A feasibility study. Paper 79-5063, Am. Soc. Agric. Eng., St. Joseph, MI. 7 p.

Flood, C. A. Jr., M. A. Sabbah, D. Meeker, and R. M. Peart. 1972. Simulation of a natural-air corn drying system. Trans. ASAE (Am. Soc. Agric. Eng.) 15:156-159,162.

Foster, G. H. and J. Tuite. 1982. Aeration and stored grain management. Pages 117-143 in: Storage of cereal grains and their products, C. M. Christensen (ed.). Am. Assoc. Cereal Chem., Inc., St. Paul, MN.

Fraser, B. M. and W. E. Muir. 1977. Feasibility of solar energy for grain drying in Western Canada. Paper 77-1007. Am. Soc. Agric. Eng., St. Joseph, MI. 10 p.

Fraser, B. M. and W. E. Muir. 1981. Airflow requirements for drying grain with ambient air and solar heated air in Canada. Trans. ASAE (Am. Soc. Agric. Eng.) 24:208-210.

Freer, M. W., T. J. Siebenmorgen, R.J. Couvillion, and O. L. Loewer. 1990. Modelling temperature and moisture content changes in bunker-stored rice. Trans. ASAE (Am. Soc. Agric. Eng.) 33:211-220.

Ghaly, T. F. 1978. An aeration trial of bulk stored peanuts for the control of insect infestation and quality loss. J. Stored Prod. Res. 14:45-51.

Ghaly, T. F. 1984. Aeration trial of farm-stored wheat for the control of insect infestation and quality loss. J. Stored Prod. Res. 20:125-131.

Gonçalves, V. A. 1992. Desenvolvimento de um sistema computacional para o controle automático do processo de aeração de grãos de milho. (Development of a computational system for the automatic control of corn aeration process). Universidade Estadual Paulista, Faculdade de Ciências Agronômicas, Botucatu, Brazil. (Unpublished Ph. D. Thesis). (In Portuguese)

Gough, M. C. and J. A. McFarlene. 1984. Aeration of stored grains: some psychrometric considerations. Trop. Stored Prod. Inf. 50:32-35.

Gough, M. C., C. B. S. Uiso, and C. J. Stigter. 1987a. Convection currents in bulk grain. Trop. Sci. 27:29-37.

Gough, M. C., H. S. Cheigh, S. K. Kim, and T. W. Kwon. 1987b. Physical changes in stored bulk rice. J. Agric. Eng. Res. 37:59-71.

Gough, M. C., C. B. S. Uiso, and C. J. Stigter. 1990. Air convection currents in metal silos storing maize grain. Trop. Sci. 30:217-222.

Griffiths, H. J. 1981. Moisture migration in grain. Pages 281-286 in: Proc. Austr. Dev. Asst. Course on Preservation of Stored Cereals. Victoria, Australia.

Haghighi, K. and L. J. Segerlind. 1988. Modelling simultaneous heat and mass transfer in an isotropic sphere - a finite element approach. Trans. ASAE (Am. Soc. Agric. Eng.) 31:629-637.

Haghighi, K., J. Irudayaraj, R. L. Stroshine, and S. Sokhansanj. 1990. Grain kernel drying simulation using the finite element method. Trans. ASAE (Am. Soc. Agric. Eng.) 33:1957-1965.

Haines, C. P. 1994. Grain storage in the tropics. Pages 55-99 in: Stored-grain ecosystems, D. S. Jayas, N. D. G. White, and W. E. Muir (eds.). Marcel Dekker, Inc., New York, NY. 757 p.

Halderson, J. L. 1985. Results of a grain storage study in Idaho. Trans. ASAE (Am. Soc. Agric. Eng.) 28:246-250,254.

Hall, D. W. 1970. Handling and storage of food grains in tropical and subtropical areas. FAO Agricultural Development. Paper 90. Food and Agric. Org. of the United Nations, Rome, Italy.

Henderson, S. 1987. A mean moisture content-equilibrium relative humidity relationship for nine varieties of wheat. J. Stored Prod. Res. 23:143-147.

Henderson, S. M. and S. Pabis. 1962. Grain drying theory. VI. The effect of airflow rate on the drying index. J. Agric. Eng. Res. 7:85-89.

Holman, L. E. and D. G. Carter. 1952. Soybean storage in farm-type bins. Pages 451-496 in: A research report. Bulletin 553 Univ. of Illinois, Agric. Exp. Stn. and United States Dept. Agric.

Huggins L. F. 1991. Analysis and interpretation. Pages 15-01:15-13 in: Instrumentation and measurement for environmental sciences, Z. A. Henry, G. C. Zoerb, and G. S. Birth (eds.). Am. Soc. Agric. Eng., St. Joseph, MI.

Hunter, A. J. 1986. Traverse times for gas flow through porous media for some particular geometries. J. Agric. Eng. Res. 35:11-23.

Hunter, A. J. and P. A. Taylor. 1980. Refrigerated aeration for the preservation of bulk grain. J. Stored Prod. Res. 16:123-131.

Iglesias, H. A. and J. Chirife. 1976. Prediction of effect of temperature on water sorption isotherms of food materials. J. Food Technol. 11:109-116.

Iglesias, H. A. and J. Chirife. 1982. Handbook of food isotherms: water sorption parameters for food and food components. Academic Press, Inc., New York, NY. 347 p.

Incropera, F. P. and D. P. DeWitt. 1990. Fundamentals of heat and mass transfer. John Wiley and Sons, New York, NY. 919 p.

Ingram, G. W. 1976. Deep-bed drier simulation with intra particle moisture diffusion. J. Agric. Eng. Res. 21:263-272.

Ingram, G. W. 1979. Solution of grain cooling and drying problems by the method of characteristics in comparison with finite difference solutions. J. Agric. Eng. Res. 24:219-232.

Irudayaraj, J., K. Haghighi, and R. L. Stroshine. 1992. Finite element analysis of drying with application to cereal grains. J. Agric. Eng. Res. 53:209-229.

ISO. 1983. ISO 5167-1980(E). Measurement of fluid flow by means of orifice plates, nozzles and venturi tubes inserted in circular cross-section conduits running full. Pages 265-357 in: Measurement of Fluid Flow in Closed Conduits. vol. 15. International Organization for Standardization, Geneva, Switzerland.

Jayas, D. S. and S. Sokhansanj. 1986. Thin-layer drying of wheat at low temperatures. Pages 844-847 in: Drying'86, A. S. Mujumdar (ed.). Hemisphere Publishing Corporation, New York, NY.

Jayas, D. S., S. Sokhansanj, E. B. Moysey, and E. M. Barber. 1987. The effect of airflow direction on the resistance of canola (rapeseed) to airflow. Can. Agric. Eng. 29:189-192.

Jayas, D. S., S. Cenkowski, and W. E. Muir. 1988. A discussion of the thin-layer drying equation. Paper 88-6557. Am. Soc. Agric. Eng., St. Joseph, MI. 7 p.

Jayas, D. S., S. Cenkowski, S. Pabis, and W. E. Muir. 1991. Review of thin-layer drying and wetting equations. Drying Technol. 9:551-558.

Jayas D. S., N. D. G. White, M. G. Britton, and J. T. Mills. 1992. Effect of oil used for dust control on engineering properties of stored wheat. Trans. ASAE (Am. Soc. Agric. Eng.) 35:659-664.

Jiang, Q. and R. K. N. D. Rajapakse. 1991. A boundary integral equation formulation for coupled-heat moisture transfer in porous media. Int. J. Eng. Sci. 29:889-900.

Kay, R. L., C. J. Bern, and C. R. Hurburgh, Jr. 1989. Horizontal and vertical airflow resistance of shelled corn at various bulk densities. Trans. ASAE (Am. Soc. Agric. Eng.) 32:733-736.

Khankari, K. K., S. V. Patankar, and R. V. Morey. 1993. A mathematical model for natural convection moisture migration in stored grain. Paper 93-6017. Am. Soc. Agric. Eng., St. Joseph, MI. 29 p.

Kline, S. J. and F. A. McClintock. 1953. Describing uncertainties in single-sample experiments. Mech. Eng. 75:3-8.

Kreith, F. and M. S. Bohn. 1993. Principles of heat transfer. West Publishing Company, St. Paul, MN. 720 p.

Krueger, C. A. and J. M. Bunn. 1985. Selection of rewetting model for shelled corn. Paper 85-3511. Am. Soc. Agric. Eng., St. Joseph, MI. 20 p.

Kumar, A. and W. E. Muir. 1986. Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. Trans. ASAE (Am. Soc. Agric. Eng.) 29:1423-1426.

Labuza, T. P. 1984. Moisture sorption: practical aspects of isotherm measurement and use. Am. Assoc. Cereal Chem., Inc., St. Paul, MN. 150 p.

Lamond, W. J. and E. A. Smith. 1982. Modelling low temperature drying of grain in anisotropic beds. Proc. Third Int. Drying Symp. 12 p.

Lasseran, J. C. 1988. The aeration of grains and the measurement of grain temperature in storage bins (silo-thermometry). Pages 664-748 in: Preservation and storage of grains, seeds and their by-products, J. L. Multon (ed.). Lavoisier Pub., New York, NY.

Lee, S. M., L. J. Moore, and B. W. Taylor III. 1985. Management Science. Wm. C. Brown Publishers, Dubuque, IA. 910 p.

Lissik, E. A. 1986. A model for the removal of heat in respiring grain. Paper 86-6509. Am. Soc. Agric. Eng., St. Joseph, MI. 23 p.

Lissik, E. A. and N. Latif. 1986. A model for the movement of heat and moisture in stored grain as a result of mold respiration. Pages 218-226 in: Drying'86, A. S. Mujumdar (ed.). Hemisphere Publishing Corporation, New York, NY.

Liu, J. Y. and S. Cheng. 1991. Solutions of Luikov equations of heat and mass transfer in capillary-porous bodies. Int. J. Heat Mass Transfer 34:1747-1754.

Lo, K. M., C. S. Chen, J. T. Clayton, and D. D. Adrian. 1975. Simulation of temperature and moisture changes in wheat storage due to weather variability. J. Agric. Eng. Res. 20:47-53.

Longstaff, R. A. and H. J. Banks. 1987. Simulations of temperature fluctuations near the surface of grain bulks. J. Stored Prod. Res. 23:21-30.

Lu, F. and P. Chen. 1985. Forced aeration to control paddy temperature in warehouse. Paper 85-3553. Am. Soc. Agric. Eng., St. Joseph, MI. 21 p.

Lu, F., T. Rumsey, and P. Chen. 1987. Simulation model for aeration of rice in warehouses. Paper 87-6548. Am. Soc. Agric. Eng., St. Joseph, MI. 26 p.

Lynch, B. E. and R. V. Morey. 1989. Control strategies for ambient air corn drying. Trans. ASAE (Am. Soc. Agric. Eng.) 32:1727-1736.

Lydolph, P. E. 1985. The climate of the earth. Rowman and Allenheld Pub., Totowa, NJ. 386 p.

Maier, D. E., R. E. Kelley, and F. W. Bakker-Arkema. 1989. Long-term chilled grain storage. Paper 89-6541. Am. Soc. Agric. Eng., St. Joseph, MI. 17 p.

Manitoba Agriculture. 1987. Grain Aeration and Unheated Air Drying. Agdex 732-1. Manitoba Agriculture, Winnipeg, MB. 30 p.

Metzger J. F., P. D. Terry, and W. E. Muir. 1981. Performance of several axial-flow fans for grain bin ventilation. Can. Agric. Eng. 23:11-16.

Metzger J. F. and W. E. Muir. 1983a. Computer model of two-dimensional conduction and forced convection in stored grain. Can. Agric. Eng. 25:119-125.

Metzger, J. F. and W. E. Muir. 1983b. Aeration of stored wheat in the Canadian Prairies. Can. Agric. Eng. 25:127-137.

Mills, J. T. 1990. Protection of farm-stored grains and oilseeds from insects, mites, and molds. Publication 1851/E. Agriculture Canada. 45p.

Misra, M. K. and D. B. Brooker. 1980. Thin-layer drying and rewetting equations for shelled yellow corn. Trans. ASAE (Am. Soc. Agric. Eng.) 23:1254-1260.

Mittal, G. S. and L. Otten. 1980. Simulation of low-temperature drying of corn for Ontario conditions. Paper 80-3519. Am. Soc. Agric. Eng., St. Joseph, MI. 38 p.

Mittal, G. S. and L. Otten. 1982. Simulation of low temperature corn drying. Can. Agric. Eng. 24:111-118.

Mohsenin N. N. 1980. Thermal properties of foods and agricultural materials. Gordon and Breach, Science Publishers, Inc., New York, NY. 891 p.

Morey, R. V., H. A. Cloud, R. J. Gustafson, and D. W. Petersen. 1979. Evaluation of the feasibility of solar energy grain drying. Trans. ASAE (Am. Soc. Agric. Eng.) 22:409-417.

Morey R. V., H. A. Cloud, and D. J. Hansen. 1981. Ambient air wheat drying. Trans. ASAE (Am. Soc. Agric. Eng.) 24:1312-1316.

Mühlbauer, W., T. Stahl, W. Hofacker, and G. Reisinger. 1982. Comparison of low-temperature wheat drying management procedures. Paper 82-3006. Am. Soc. Agric. Eng., St. Joseph, MI. 26 p.

Muir, W. E. 1970. Temperatures in grain bins. Can. Agric. Eng. 12:21-24.

Muir, W. E. 1973. Temperature and moisture in grain storages. Pages 49-70 in: Grain storage: part of a system, R. N. Sinha and W. E. Muir (eds.). AVI Publ. Co., Westport, CT.

Muir, W. E., B. M. Fraser, and R. N. Sinha. 1980. Simulation model of two-dimensional heat transfer in controlled-atmosphere grain bins. Pages 385-398 in: Controlled atmosphere storage of grains, J. Shejbal (ed.). Elsevier Scientific Publ. Co., Castelgandolfo, Italy, Rome.

Muir, W. E., D. S. Jayas, M. G. Britton, R. N. Sinha, and N. D. G. White. 1989. Interdisciplinary grain storage research at the University of Manitoba and Agriculture Canada. Powder Handling and Processing 1:281-295.

Muir, W. E. and R. N. Sinha. 1988. Physical properties of cereal and oilseed cultivars grown in western Canada. Can. Agric. Eng. 30:51-55.

Muir, W. E. and S. Viravanichai. 1972. Specific heat of wheat. J. Agric. Eng. Res. 17:338-342.

Nash, M. J. 1978. Crop conservation and storage in cool temperate climates. Willian Clowes and Sons Ltd., Great Britain. 393 p.

Navarro, S. 1974. Aeration of grain as a non-chemical method for the control of insects in the grain bulk. Pages 1:341-353 in: Proc. First Int. Work. Conf. Stored-Prod. Entomol.

Navarro, S. 1982. Aeration of grain in subtropical climates. Agric. Services Bulletin, Food and Agric. Org. of the United Nations, FAO, Rome. 119 p.

Navarro, S., E. Donahaye, and M. Calderon. 1973a. Studies on aeration with refrigerated air - I. Chilling of wheat in a concrete elevator. J. Stored Prod. Res. 9:253-259.

Navarro, S., E. Donahaye, and M. Calderon. 1973b. Studies on aeration with refrigerated air - II. Chilling of soybeans undergoing spontaneous heating. J. Stored Prod. Res. 9:261-268.

Nellist, M. E. 1988. Near-ambient grain drying. Agric. Eng. 43:93-101.

Nelson S. O. 1980. Moisture-dependent kernel-and bulk-density relationships for wheat and corn. Trans. ASAE (Am. Soc. Agric. Eng.) 23:139-143.

Nguyen, T. V. 1986. Modelling temperatures and moisture changes resulting from natural convection in grain stores. Pages 81-88 in: Preserving grain quality by aeration and in-store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

Nour/Jantan, D. B. M., T. I. Check, and R. Abdullah. 1988. Bulk storage paddy aeration in concrete silos: a Malaysian experience. Pages 182-188 in: Bulk handling and storage of grain in the humid tropics, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 22, Canberra, Australia.

Noyes, R. T. 1990. Aeration of grain storage. Pages 139-171 in: Proc. III Nat. Stored Grain Pest Management. Training Conf. Minnesota Ext. Service, Univ. of Minnesota, St. Paul, MN.

Obaldo, L. G., J. P. Harner, and H. H. Converse. 1991. Prediction of moisture changes in stored corn. Trans. ASAE (Am. Soc. Agric. Eng.) 34:1851-1858.

O'Callaghan, J. R., D. J. Menzies, and P. H. Bailey. 1971. Digital simulation of agricultural drier performance. J. Agric. Eng. Res. 16:223-244.

Oliveira, M. I. 1994. Electronic mail sent on 94 06 29 by M. I. Oliveira, Secretary, Centro de Ensino e Extensão,Universidade Federal de Viçosa, Viçosa, MG, Brazil.

Omega. 1986. The 1986 Temperature measurement and control handbook. Omega Engineering Inc., Stamford, CT.

Osborn, G. S., G. M. White, and L. R. Walton. 1991. Thin-layer moisture adsorption equations for soybeans. Trans. ASAE (Am. Soc. Agric. Eng.) 34:201-206.

Pabis, S. and S. M. Henderson. 1961. Grain drying theory: II. A Critical analysis of the drying curve of shelled maize. J. Agric. Eng. Res. 6:272:277.

Page, G. 1949. Factors influencing the maximum rates of air drying shelled corn in thin layers. Purdue University, West Lafayette, IN. (Unpublished MSc. Thesis).

Parry, J. L. 1985. Mathematical modelling and computer simulation of heat and mass transfer in agricultural grain drying: a review. J. Agric. Eng. Res. 32:1-29.

Parti, M. 1990. A theoretical model for thin-layer grain drying. Drying Technol. 8:101-122.

Parti, M. 1993. Selection of mathematical models for drying grain in thin-layers. J. Agric. Eng. Res. 54:339-352.

Pascoali, I. 1993. Letter of 1993 02 26 from I. Pascoali, Director-President, Cooperativa Agrícola Consolata Ltda, Cafelândia, PR, Brazil.

Persson, G. W. and R. W. Churchill. 1983. Automatic computer control of grain drying and aeration. Pages 692-700 in: Agricultural electronics - 1983 and beyond. Proc. Nat. Conf. Agric. Electronics Applications. Am. Soc. Agric. Eng., St. Joseph, MI.

Persson, G. W. and R. W. Churchill. 1987. Centralized quality control system. Paper 87-3505. Am. Soc. Agric. Eng., St. Joseph, MI. 14 p.

Pfost, H. B., G. E. Rengifo, and D. B. Sauer. 1976a. High temperature, high humidity grain storage. Paper 76-3521. Am. Soc. Agric. Eng., St. Joseph, MI. 7 p.

Pfost, H. B., S. G. Maurer, D. S. Chung, and G. A. Milliken. 1976b. Summarizing and reporting equilibrium moisture data for grains. Paper 76-3520. Am. Soc. Agric. Eng., St. Joseph, MI. 11 p.

Pixton, S. W. and H. J. Griffiths. 1971. Diffusion of moisture through grain. J. Stored Prod. Res. 7:133-152.

Pixton, S. W. and S. Henderson. 1981. The moisture content-equilibrium relative humidity relationships of five varieties of Canadian wheat and of candle rapeseed at different temperatures. J. Stored Prod. Res. 17:187-190.

Pixton, S. W. and S. Warburton. 1973. The influence of the method used for moisture adjustment on the equilibrium relative humidity of stored products. J. Stored Prod. Res. 9:189-197.

Press W. H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling. 1989. Numerical recipes: the art of scientific computing (FORTRAN version). Cambridge University Press, Cambridge, England. 702 p.

Puzzi D. 1986. Abastecimento e Armazenagem de Grãos. (Supplies and Storage of Grains). Instituto Campineiro de Ensino Agrícola. Campinas, SP, Brazil. 603 p. (In Portuguese)

Pym, G. R. and T. Adamczak. 1986. Control for the aeration and drying of grain. Pages 118-128 in: Preserving grain quality by aeration and in-store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

Reed, C., J. Harner, and J. Petersen. 1993. Automatically-controlled aeration in Kansas farm-stored wheat. Paper 93-6604. Am. Soc. Agric. Eng., St. Joseph, MI. 6 p.

Roa, G., R. Fioreze, S. J. Rossi, and L. G. Villa. 1977. Dynamic estimation of thin-layer drying parameters. Paper 77-3530. Am. Soc. Agric. Eng., St. Joseph, MI. 7 p.

Sabbah, M. A., H. M. Keener, and G. E. Meyer. 1979. Simulation of solar drying of shelled corn using the logarithmic model. Trans. ASAE (Am. Soc. Agric. Eng.) 22:637-643.

Sanderson, D. B., W. E. Muir, R. N. Sinha, D. Tuma, and C. I. Kitson. 1989. Evaluation of a model of drying and deterioration of stored wheat at near-ambient conditions. J. Agric. Eng. Res. 42:219-233.

Sartori, M. R., C. R. D'amico, S. I. Costa, M. F. Leitão, B. A. Jordão, and D. B. Ortolani. 1976. Preservação de soja armazenada a granel, mediante emprego de aeração mecânica para melhoria das condições de armazenamento. (Preservation of stored soybeans through the use of mechanical aeration for the improvement of the storage conditions). Boletim do Instituto de Tecnologia de Alimentos, Campinas, Brazil 47:75-110. (In Portuguese)

SAS. 1985. SAS user's guide: Statistics. Statistical Analysis System Inc., Cary, NC. 584 p.

Saul, R. A. 1970. Deterioration rate of moist shelled corn at low temperatures. Paper 70-302. Am. Soc. Agric. Eng., St. Joseph, MI. 4 p.

Saul, R. A. and E. F. Lind. 1958. Maximum time for safe drying of grain with unheated air. Trans. ASAE (Am. Soc. Agric. Eng.) 1: 29-33.

Schultz, L. J., M. L. Stone, and P. D. Bloome. 1984. A comparison of simulation techniques for wheat aeration. Paper 84-3012. Am. Soc. Agric. Eng., St. Joseph, MI. 11 p.

Sharma, S. C. and W. E. Muir. 1974. Simulation of heat and mass transfer during ventilation of wheat and rapeseed bulks. Can. Agric. Eng. 16:41-44.

Sharp J. R. 1982. A review of low temperature drying simulation. J. Agric. Eng. Res. 27:169-190.

Sharp, J. R. 1984. The design and management of low temperature grain driers in England - a simulation study. J. Agric. Eng. Res. 29:123-131.

Simmonds, M. A., G. T. Ward, and E. McEwen. 1953. The drying of wheat grain. I. The mechanisms of drying. Trans. Inst. Chem. Eng. 31:265-278.

Singh R. P. 1988. Thermal properties of agricultural materials. Pages 193-202 in: CRC Handbook of Engineering in Agriculture. Vol. III: Environmental Systems Engineering, R. H. Brow (ed.). CRC Press, Inc., Boca Raton, FL.

Singh, A. K. and G. R. Thorpe. 1993. A solution procedure for three-dimensional free convective flow in peaked bulks of grain. J. Stored Prod. Res. 29:221-235.

Singh, A. K., E. Leonardi, and G. R. Thorpe. 1993. A solution procedure for the equations that govern three-dimensional free convection in bulk stored grains. Trans. ASAE (Am. Soc. Agric. Eng.) 36:1159-1173.

Sinha, R. N. and F. L. Watters. 1985. Insect pests of flour mills, grain elevators, and feed mills and their control. Publication 1776. Agriculture Canada, Ottawa, ON. 290 p.

Sinha, R. N., W. E. Muir, D. B. Sanderson, and D. Tuma. 1991. Ventilation of bin-stored moist wheat for quality preservation. Can. Agric. Eng. 33:55-65.

Sinicio, R. and G. Roa. 1979. Curvas e equações de equilíbrio higroscópico para 15 produtos agrícolas (Equilibrium moisture content curves and equations for 15 agricultural products). Rev. Bras. de Armaz. 4:45-55. (In Portuguese)

Sinicio, R., J. B. Pinheiro Filho, M. Fortes, and V. A. Dalpasquale. 1984/1985. Equacão de secagem de milho em camadas finas, para condições variáveis de temperatura e umidade do ar (Thin-layer drying equation for corn under variable conditions of air temperature and relative humidity). Rev. Bras. de Armaz. 9,10:37-41. (In Portuguese)

Sinicio, R., J. B. Pinheiro Filho, M. Fortes, and V. A. Daspasquale. 1986/1987. Comparação de modelos matemáticos para a simulação de secagem de milho a baixas temperatures (Comparison of mathematical models for corn drying simulation at low temperatures). Rev. Bras. de Armaz. 11, 12:36-42. (In Portuguese)

Sinicio, R., W. E. Muir, D. B. Sanderson, and D. S. Jayas. 1991. Simulated fan control systems for aerated corn and wheat in Sorocaba, Brazil. Sciences des Aliments 11:141-153.

Sinicio, R., D. S. Jayas, W. E. Muir, and D. B. Sanderson. 1992. Finite-element prediction of non-uniform airflow in fixed beds of wheat. Posharvest Biol. Tech. 2:51-59.

Sinicio, R., W. E. Muir, D. S. Jayas, and S. Cenkowski. 1994. Thin-layer drying and wetting of wheat. Postharvest Biol. Tech. In Press.

Smith, E. A. 1982. Simulation of grain drying when air-flow is non-parallel. J. Agric. Eng. Res. 27:21-33.

Smith, E. A. 1984a. Interactive computer program for evaluating the control options for near-ambient grain driers. Agric. Eng. 39:105-111.

Smith, E. A. 1984b. Maximum safe depth for barley in near-ambient temperature grain driers. Agric. Eng. 39:3-9.

Smith, E. A. and P. H. Bailey. 1983. Simulation of near-ambient grain drying. II. Control strategies for drying barley in Northern Britain. J. Agric. Eng. Res. 28:301-317.

Smith, E. A. and S. Sokhansanj. 1990a. Moisture transport caused by natural convection in grain stores. J. Agric. Eng. Res. 47:23-34.

Smith, E. A. and S. Sokhansanj. 1990b. Natural convection and temperature of store produce - a theoretical analysis. Can. Agric. Eng. 32:91-97.

Smith, E. A., D. S. Jayas, W. E. Muir, K. Alagusundaram, and V. H. Kalbande. 1992a. Simulation of grain drying in bins with partially perforated floors, Part I: Isotraverse lines. Trans. ASAE (Am. Soc. Agric. Eng.) 35:909-915.

Smith, E. A., D. S. Jayas, W. E. Muir, K. Alagusundaram, and V. H. Kalbande. 1992b. Simulation of grain drying in bins with partially perforated floors, Part II: Calculation of moisture content. Trans. ASAE (Am. Soc. Agric. Eng.) 35:917-922.

Sokhansanj, S., D. Singh, and P. Gebhardt. 1983. Low temperature system design and analysis using desktop computers. Pages 682-691 in: Agricultural electronics - 1983 and beyond. Proc. Nat. Conf. Agric. Electronics Applications. Am. Soc. Agric. Eng., St. Joseph, MI.

Sokhansanj S. and D. S. Jayas. 1990. Stochastic grain simulation. Pages 208-210 in: Drying of Solids, A. S. Mujumdar, (ed.). Sarita Prakashan, New Delhi, India.

Stewart, J. A. 1975. Moisture migration during storage of preserved, high moisture grains. Trans. ASAE (Am. Soc. Agric. Eng.) 18:387-393,400.

Steele, J. L., R. A. Saul, and W. V. Hukill. 1969. Deterioration of shelled corn as measured by carbon dioxiode production. Trans. ASAE (Am. Soc. Agric. Eng.) 12:685-689.

Strohman, R. D. and R. R. Yoerger. 1967. A new equilibrium moisture content equation. Trans. ASAE (Am. Soc. Agric. Eng.) 10:675-677.

Sun, Da-Wen and J. L. Woods. 1993. The moisture content/relative humidity equilibrium relationship of wheat - a review. Drying Technol. 11:1523-1551.

Sutherland, J. W. 1968. Control of insects in a wheat store with an experimental aeration system. J. Agric. Eng. Res. 13:210-219.

Sutherland, J. W. 1986. Grain aeration in Australia. Pages 206-218 in: Preserving grain quality by aeration and in-store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

Sutherland, J. W., P. J. Banks, and H. J. Griffiths. 1971. Equilibrium heat and moisture transfer in air flow through grain. J. Agric. Eng. Res. 16:368-386.

Sutherland, J. W., P. J. Banks, and W. B. Elder. 1983. Interaction between successive temperature or moisture fronts during aeration of deep grain beds. J. Agric. Eng. Res. 28:1-19.

Teter, N. C. 1986. Design parameters for storage and handling systems for grain. Pages 99-107 in: Preserving grain quality by aeration and in-store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

Thompson T. L. 1972. Temporary storage of high-moisture shelled corn using continuous aeration. Trans. ASAE (Am. Soc. Agric. Eng.) 15:333-337.

Thompson, T. L., R. M. Peart, and G. H. Foster. 1968. Mathematical simulation of corn drying - a new model. Trans. ASAE (Am. Soc. Agric. Eng.) 11:582-586.

Thompson, T. L., L. G. Villa, and O. E. Cross. 1971. Simulated and experimental performance of temperature-control systems for chilled high-moisture grain storage. Trans. ASAE (Am. Soc. Agric. Eng.) 14:554-559.

Thorpe, G. R. 1981. Moisture diffusion through bulk grain. J. Stored Prod. Res. 17:39-42.

Thorpe, G. R. 1982. Moisture diffusion through bulk grain subjected to a temperature gradient. J. Stored Prod. Res. 18:9-12.

Thorpe, G. R. 1986. Some fundamentals principles and benefits of aeration of stored grain. Pages 31-44 in: Preserving grain quality by aeration and in store drying, B. R. Champ and E. Highley (eds.). ACIAR Proceedings No. 15, Canberra, Australia.

Thorpe, G R. and W. B. Elder. 1982. Modelling the effects of aeration on the persistence of chemical pesticides applied to stored bulk grain. J. Stored Prod. Res. 18:103-114.

Thorpe, G. R., J. A. O. Tapia, and S. Whitaker. 1991a. The diffusion of moisture in food grains - I. The development of a mass transport equation. J. Stored Prod. Res. 27:1-9.

Thorpe, G. R., J. A. O. Tapia, and S. Whitaker. 1991b. The diffusion of moisture in food grains - II. Estimation of the effective diffusivity. J. Stored Prod. Res. 27:11-30.

Thorpe, G. R. and S. Whitaker. 1992a. Local mass and thermal equilibria in ventilated grain bulks. Part I: The development of heat and mass conservation equations. J. Stored Prod. Res. 28:15-27.

Thorpe, G. R. and S. Whitaker. 1992b. Local mass and thermal equilibria in ventilated grain bulks. Part II: The development of constraints. J. Stored Prod. Res. 28:29-54.

Trisvyatskii, L. A. 1969. Storage of grain. 3:553-839. Translated from the Russian by D. M. Keane. National Lending Library for Science and Technology, Boston, MA.

Uiso, C. B. S., M. C. Gough, and C. J. Stigter. 1990. Detection, causes and consequences of convection currents in bulk stored grain. J. Agric. Sci. 38:195-199.

USDA 1960. United States Department of Agriculture. Aeration of grain in commercial storages. Marketing Res. Rep. No. 178. 46 p.

Van Ee G. R. and G. L. Kline 1979a. FALDRY - a model for low temperature corn drying systems. Paper 79-3524. Am. Soc. Agric. Eng., St. Joseph, MI. 57 p.

Van Ee, G. R. and G. L. Kline. 1979b. Management strategies for corn production and low temperature drying. Paper 79-3032. Am. Soc. Agric. Eng., St. Joseph. 51 p.

Ward, N. and D. J. B. Calverly. 1972. A literature survey on the climate relationships in stores. Trop. Stored Prod. Inf. 23:35-44.

Watson, E. L. and V. K. Bhargava. 1974. Thin-layer drying studies on wheat. Can. Agric. Eng. 16:18-22.

Westerman, P. W., G. M. White, and I. J. Ross. 1973. Relative humidity effect on the high temperature drying of shelled corn. Trans. ASAE (Am. Soc. Agric. Eng.) 16:1136-1139.

White, G. G. 1988. Temperature changes in bulk stored wheat in sub-tropical Australia. J. Stored Prod. Res. 24:5-11.

Willian, H. A., L. J. Mason, D. E. Maier, and J. L. Obermeyer. 1993. Comparison of stored-insect management techniques - a progress report. ASAE Paper 93-6513, Am. Soc. Agric. Eng., St. Joseph, MI. 10 p.

Wilson, S. G. 1987. A theoretical transient model for the study of thermal and moisture boundary-layers during aeration of paddy in a cylindrical silo. Australia: Commonwealth Scientific and Ind. Res. Org., Division of Entomology. Report No. 39. 27 p.

Wilson, S. G. 1988. Simulation of thermal and moisture boundary-layers during aeration of cereal grain. Math. Comput. Simul. 30:181-188.

Yaciuk, G., W. E. Muir, and R. N. Sinha. 1975. A simulation model of temperatures in stored grain. J. Agric. Eng. Res. 20:245-258.

Young, J. H. and G. L. Nelson. 1967. Research of hysteresis between sorption and desorption isotherms of wheat. Trans. ASAE (Am. Soc. Agric. Eng.) 10:756-761.

APPENDICES

1. Experimental Data of Thin-layer Drying and Wetting of Wheat

Test 1

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.099	0.100	0.148	0.149	0.201	0.201	0.100	0.149	0.202
20	0.098	0.098	0.142	0.142	0.186	0.184	0.098	0.142	0.186
57	0.098	0.098	0.136	0.136	0.170	0.169	0.097	0.137	0.170
119	0.097	0.097	0.130	0.130	0.154	0.153	0.097	0.130	0.154
218	0.097	0.097	0.124	0.124	0.140	0.139	0.097	0.124	0.140
368	0.096	0.096	0.117	0.118	0.128	0.127	0.095	0.117	0.128
547	0.096	0.095	0.112	0.112	0.120	0.119	0.095	0.113	0.120
797	0.094	0.094	0.107	0.108	0.112	0.112	0.094	0.107	0.113
1386	0.094	0.093	0.101	0.101	0.104	0.103	0.093	0.101	0.104
1575	0.093	0.093	0.100	0.100	0.102	0.101	0.092	0.100	0.102
1815	0.093	0.092	0.098	0.098	0.100	0.099	0.091	0.098	0.101
T_c (°C)	35.1	35.2	35.2	35.2	35.2	35.2	35.2	35.2	34.9
RH (%)	27.0	26.8	26.8	26.8	26.9	26.9	26.9	26.9	27.3
V ($m \cdot s^{-1}$)	0.04	0.10	0.07	0.18	0.05	0.22	0.19	0.20	0.24

Test 2

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.099	0.099	0.146	0.149	0.200	0.200	0.100	0.148	0.200
20	0.098	0.098	0.141	0.142	0.185	0.184	0.099	0.142	0.185
57	0.098	0.098	0.135	0.136	0.169	0.168	0.098	0.136	0.169
119	0.098	0.097	0.129	0.131	0.154	0.153	0.098	0.130	0.154
218	0.097	0.097	0.123	0.124	0.140	0.139	0.097	0.123	0.140
368	0.097	0.096	0.117	0.118	0.128	0.127	0.097	0.117	0.128
547	0.096	0.095	0.112	0.113	0.120	0.119	0.096	0.112	0.120
797	0.095	0.094	0.107	0.108	0.113	0.112	0.095	0.108	0.113
1386	0.094	0.093	0.101	0.102	0.104	0.104	0.094	0.101	0.104
1575	0.094	0.093	0.100	0.101	0.103	0.102	0.094	0.100	0.103
1815	0.094	0.092	0.098	0.099	0.101	0.101	0.093	0.099	0.101
T_c (°C)	35.1	35.3	35.3	35.2	35.2	35.2	35.1	35.2	34.9
RH (%)	28.4	28.2	28.2	28.2	28.3	28.4	28.4	28.4	28.7
V ($m \cdot s^{-1}$)	0.05	0.10	0.07	0.18	0.06	0.19	0.21	0.22	0.22

Test 3

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.102	0.151	0.103	0.152	0.203	0.204	0.103	0.151	0.203
25	0.109	0.155	0.107	0.154	0.203	0.206	0.111	0.156	0.206
59	0.114	0.160	0.111	0.157	0.204	0.208	0.116	0.160	0.207
169	0.125	0.168	0.119	0.163	0.206	0.211	0.127	0.167	0.210
358	0.139	0.176	0.130	0.169	0.207	0.213	0.140	0.175	0.213
598	0.153	0.185	0.142	0.175	0.209	0.216	0.155	0.183	0.214
807	0.165	0.191	0.151	0.180	0.209	0.217	0.166	0.189	0.215
1437	0.190	0.205	0.175	0.191	0.211	0.219	0.192	0.203	0.217
1856	0.202	0.212	0.185	0.196	0.212	0.220	0.203	0.209	0.218
2876	0.218	0.223	0.203	0.206	0.213	0.222	0.219	0.218	0.219
4555	0.229	0.231	0.216	0.213	0.214	0.225	0.229	0.226	0.221
5965	0.232	0.234	0.220	0.216	0.214	0.226	0.232	0.228	0.221
7464	0.234	0.235	0.222	0.218	0.215	0.227	0.234	0.230	0.222
8729	0.235	0.236	0.224	0.220	0.216	0.228	0.235	0.231	0.223
T_c (°C)	7.4	7.4	7.4	7.5	7.6	7.6	7.6	7.6	7.8
RH (%)	87.5	87.5	87.3	86.7	86.1	86.4	86.2	86.3	85.3
V ($m \cdot s^{-1}$)	0.10	0.11	0.05	0.05	0.04	0.10	0.22	0.27	0.23

Test 4

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.101	0.150	0.103	0.151	0.201	0.202	0.103	0.150	0.204
25	0.108	0.155	0.106	0.153	0.202	0.204	0.111	0.155	0.206
59	0.114	0.160	0.110	0.155	0.203	0.206	0.116	0.159	0.207
169	0.125	0.168	0.119	0.162	0.205	0.209	0.127	0.167	0.210
358	0.138	0.177	0.130	0.168	0.207	0.213	0.140	0.175	0.212
598	0.153	0.185	0.142	0.175	0.208	0.215	0.155	0.183	0.214
807	0.164	0.192	0.151	0.179	0.209	0.216	0.167	0.189	0.215
1437	0.190	0.206	0.175	0.191	0.212	0.219	0.192	0.202	0.217
1856	0.202	0.213	0.186	0.196	0.212	0.220	0.204	0.208	0.218
2876	0.218	0.223	0.203	0.206	0.213	0.221	0.219	0.218	0.219
4555	0.228	0.232	0.215	0.213	0.213	0.224	0.229	0.226	0.220
5965	0.232	0.235	0.220	0.216	0.214	0.226	0.233	0.229	0.221
7464	0.235	0.238	0.222	0.219	0.214	0.227	0.236	0.231	0.222
8729	0.236	0.239	0.223	0.220	0.214	0.228	0.236	0.232	0.223
T_c (°C)	7.4	7.4	7.4	7.5	7.6	7.6	7.6	7.6	7.8
RH (%)	87.5	87.5	87.3	86.7	86.1	86.4	86.2	86.3	85.3
V ($m \cdot s^{-1}$)	0.09	0.11	0.05	0.05	0.05	0.10	0.27	0.23	0.21

Test 5

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.100	0.147	0.099	0.149	0.200	0.200	0.100	0.150	0.201
20	0.100	0.144	0.099	0.146	0.192	0.191	0.100	0.146	0.192
49	0.100	0.142	0.099	0.144	0.185	0.184	0.100	0.144	0.184
99	0.101	0.140	0.099	0.141	0.177	0.175	0.100	0.142	0.175
208	0.101	0.136	0.100	0.137	0.164	0.162	0.100	0.138	0.162
307	0.101	0.133	0.100	0.135	0.157	0.155	0.101	0.135	0.155
427	0.102	0.131	0.100	0.132	0.150	0.148	0.101	0.132	0.148
776	0.102	0.126	0.101	0.127	0.138	0.137	0.102	0.127	0.137
1437	0.103	0.121	0.102	0.123	0.128	0.127	0.103	0.122	0.127
1855	0.104	0.119	0.103	0.121	0.124	0.123	0.103	0.120	0.123
2884	0.105	0.117	0.104	0.118	0.120	0.119	0.105	0.118	0.119
4504	0.106	0.115	0.104	0.116	0.116	0.116	0.105	0.116	0.116
5663	0.106	0.113	0.105	0.115	0.115	0.115	0.105	0.115	0.115
T_c (°C)	25.1	25.1	25.0	25.0	25.0	25.0	25.0	25.0	25.0
RH (%)	37.4	37.4	37.5	37.5	37.6	37.5	37.5	37.5	37.6
V ($m \cdot s^{-1}$)	0.12	0.11	0.03	0.03	0.03	0.11	0.28	0.28	0.30

Test 6

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.098	0.145	0.098	0.147	0.200	0.199	0.098	0.147	0.200
30	0.099	0.145	0.099	0.147	0.195	0.194	0.099	0.147	0.194
159	0.101	0.145	0.101	0.146	0.185	0.184	0.101	0.145	0.183
299	0.103	0.145	0.102	0.145	0.178	0.177	0.102	0.145	0.176
468	0.105	0.144	0.104	0.144	0.172	0.171	0.104	0.144	0.171
778	0.107	0.143	0.106	0.143	0.165	0.165	0.107	0.143	0.164
1437	0.112	0.142	0.111	0.142	0.158	0.157	0.112	0.142	0.157
1797	0.114	0.142	0.113	0.142	0.155	0.155	0.114	0.142	0.154
2926	0.120	0.142	0.118	0.142	0.151	0.152	0.119	0.142	0.151
4616	0.124	0.142	0.123	0.142	0.148	0.149	0.123	0.141	0.148
T_c (°C)	15.0	15.0	15.0	15.1	15.1	15.1	15.1	15.1	15.1
RH (%)	52.2	52.1	52.0	51.8	51.8	51.8	51.8	51.7	51.7
V ($m \cdot s^{-1}$)	0.10	0.11	0.04	0.04	0.04	0.11	0.27	0.27	0.30

Test 7

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.201	0.151	0.202	0.150	0.104	0.104	0.202	0.149	0.103
25	0.203	0.155	0.203	0.152	0.107	0.110	0.205	0.154	0.110
59	0.205	0.160	0.204	0.155	0.110	0.115	0.207	0.158	0.115
169	0.209	0.167	0.206	0.161	0.119	0.126	0.211	0.166	0.126
358	0.213	0.176	0.209	0.168	0.129	0.140	0.214	0.175	0.139
598	0.215	0.185	0.211	0.175	0.141	0.154	0.216	0.183	0.153
807	0.216	0.191	0.212	0.180	0.150	0.165	0.217	0.189	0.163
1437	0.220	0.206	0.214	0.192	0.173	0.191	0.220	0.203	0.188
1856	0.221	0.213	0.215	0.197	0.184	0.202	0.221	0.209	0.199
2876	0.223	0.224	0.217	0.207	0.201	0.219	0.224	0.220	0.214
4533	0.226	0.233	0.218	0.215	0.213	0.229	0.226	0.227	0.223
5971	0.228	0.236	0.218	0.218	0.217	0.232	0.228	0.230	0.226
7464	0.230	0.239	0.219	0.220	0.219	0.236	0.230	0.232	0.228
8729	0.231	0.239	0.220	0.221	0.220	0.236	0.230	0.233	0.229
T_c (°C)	7.4	7.4	7.5	7.5	7.7	7.6	7.6	7.6	7.8
RH (%)	87.3	87.3	87.0	86.6	85.8	86.2	86.1	86.1	85.0
V ($m \cdot s^{-1}$)	0.10	0.11	0.06	0.05	0.05	0.11	0.23	0.25	0.24

Test 8

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.105	0.199	0.105	0.201	0.151	0.151	0.103	0.203	0.151
20	0.120	0.208	0.114	0.206	0.157	0.164	0.120	0.212	0.165
59	0.136	0.218	0.126	0.212	0.167	0.177	0.139	0.221	0.178
149	0.163	0.231	0.147	0.222	0.181	0.197	0.167	0.234	0.199
308	0.201	0.247	0.177	0.234	0.202	0.223	0.205	0.250	0.226
478	0.228	0.258	0.200	0.244	0.218	0.242	0.232	0.261	0.244
818	0.258	0.271	0.233	0.258	0.242	0.264	0.262	0.273	0.265
1437	0.280	0.283	0.263	0.273	0.264	0.281	0.282	0.284	0.282
1917	0.287	0.287	0.274	0.279	0.273	0.286	0.288	0.287	0.286
2876	0.288	0.287	0.282	0.283	0.281	0.288	0.289	0.287	0.288
4522	0.292	0.290	0.290	0.289	0.290	0.292	0.293	0.292	0.294
6008	0.292	0.291	0.291	0.289	0.288	0.292	0.293	0.291	0.291
T_c (°C)	25.1	25.1	25.0	25.0	25.0	25.0	25.0	25.0	25.0
RH (%)	91.5	91.5	91.5	91.5	91.5	91.5	91.6	91.5	91.5
V ($m \cdot s^{-1}$)	0.10	0.12	0.03	0.03	0.03	0.11	0.26	0.26	0.23

Test 9

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.147	0.201	0.149	0.201	0.102	0.102	0.149	0.201	0.102
30	0.148	0.200	0.149	0.199	0.103	0.104	0.150	0.200	0.104
89	0.150	0.199	0.150	0.198	0.105	0.107	0.151	0.199	0.106
239	0.152	0.196	0.152	0.195	0.109	0.111	0.153	0.196	0.111
478	0.155	0.193	0.154	0.192	0.114	0.117	0.156	0.193	0.116
758	0.156	0.191	0.156	0.190	0.119	0.122	0.157	0.191	0.122
1451	0.158	0.188	0.157	0.187	0.128	0.133	0.159	0.188	0.132
1897	0.159	0.188	0.158	0.185	0.133	0.139	0.160	0.187	0.138
2876	0.160	0.187	0.159	0.185	0.143	0.149	0.161	0.186	0.148
4316	0.161	0.187	0.160	0.184	0.153	0.158	0.162	0.186	0.156
5927	0.161	0.186	0.161	0.184	0.158	0.162	0.162	0.185	0.161
7697	0.162	0.186	0.161	0.184	0.160	0.165	0.163	0.185	0.163
8575	0.162	0.186	0.161	0.183	0.161	0.165	0.163	0.185	0.164
T_c (°C)	7.5	7.5	7.6	7.6	7.7	7.7	7.7	7.7	7.8
RH (%)	69.7	69.7	69.4	69.1	68.7	68.9	68.8	68.8	68.2
V ($m \cdot s^{-1}$)	0.12	0.13	0.05	0.05	0.05	0.12	0.23	0.24	0.26

Test 10

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.199	0.104	0.199	0.103	0.150	0.150	0.201	0.102	0.150
30	0.200	0.108	0.199	0.106	0.152	0.153	0.202	0.107	0.153
89	0.201	0.113	0.200	0.110	0.154	0.156	0.203	0.112	0.156
239	0.202	0.122	0.201	0.118	0.159	0.161	0.204	0.121	0.161
448	0.203	0.131	0.201	0.125	0.162	0.166	0.204	0.130	0.166
725	0.203	0.143	0.201	0.136	0.167	0.170	0.204	0.142	0.170
1437	0.204	0.166	0.202	0.156	0.173	0.178	0.205	0.164	0.177
2922	0.204	0.189	0.201	0.180	0.181	0.187	0.205	0.188	0.185
4401	0.204	0.198	0.202	0.190	0.184	0.192	0.205	0.196	0.189
5969	0.204	0.202	0.202	0.194	0.187	0.195	0.205	0.199	0.192
7557	0.205	0.203	0.202	0.196	0.189	0.196	0.205	0.201	0.194
8571	0.205	0.204	0.203	0.197	0.189	0.197	0.205	0.201	0.194
T_c (°C)	7.6	7.6	7.6	7.7	7.8	7.7	7.8	7.8	7.9
RH (%)	80.9	81.0	80.7	80.2	79.7	80.1	79.8	79.8	79.2
V ($m \cdot s^{-1}$)	0.10	0.12	0.04	0.04	0.04	0.11	0.26	0.24	0.23

Test 11

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.148	0.102	0.149	0.102	0.200	0.201	0.150	0.102	0.201
30	0.150	0.106	0.151	0.106	0.198	0.200	0.152	0.107	0.200
89	0.153	0.112	0.153	0.110	0.196	0.198	0.155	0.112	0.198
240	0.157	0.121	0.157	0.118	0.193	0.196	0.159	0.121	0.195
448	0.160	0.131	0.160	0.127	0.191	0.194	0.162	0.131	0.192
714	0.163	0.142	0.162	0.137	0.189	0.192	0.164	0.142	0.191
1437	0.168	0.162	0.166	0.156	0.187	0.191	0.168	0.161	0.190
1930	0.169	0.169	0.168	0.163	0.187	0.191	0.170	0.168	0.189
3058	0.172	0.176	0.170	0.172	0.187	0.190	0.172	0.175	0.189
4426	0.174	0.178	0.172	0.175	0.186	0.190	0.174	0.178	0.188
5942	0.175	0.180	0.173	0.176	0.186	0.190	0.175	0.179	0.188
7498	0.175	0.180	0.174	0.177	0.186	0.190	0.176	0.179	0.188
8580	0.176	0.181	0.174	0.177	0.186	0.189	0.176	0.180	0.188
T_c (°C)	14.9	14.9	15.0	15.1	15.1	15.1	15.1	15.1	15.2
RH (%)	75.7	75.9	75.5	75.0	74.8	75.0	74.9	74.9	74.4
V ($m \cdot s^{-1}$)	0.11	0.13	0.05	0.04	0.04	0.11	0.23	0.24	0.23

Test 12

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.150	0.106	0.199	0.150	0.104	0.201	0.152	0.103	0.201
30	0.160	0.119	0.202	0.156	0.111	0.206	0.162	0.117	0.207
90	0.170	0.132	0.206	0.163	0.120	0.212	0.172	0.130	0.212
239	0.185	0.155	0.213	0.176	0.138	0.220	0.187	0.153	0.219
479	0.203	0.183	0.219	0.189	0.160	0.228	0.205	0.181	0.225
726	0.216	0.205	0.224	0.201	0.178	0.234	0.218	0.202	0.230
1438	0.240	0.240	0.235	0.224	0.213	0.245	0.240	0.236	0.240
1823	0.246	0.249	0.238	0.231	0.223	0.249	0.247	0.245	0.243
2905	0.255	0.262	0.245	0.242	0.238	0.254	0.255	0.256	0.248
4339	0.259	0.267	0.250	0.249	0.246	0.257	0.258	0.259	0.250
5959	0.261	0.268	0.251	0.249	0.247	0.258	0.259	0.261	0.251
7408	0.261	0.269	0.252	0.251	0.249	0.259	0.260	0.261	0.252
8544	0.262	0.269	0.252	0.251	0.249	0.259	0.260	0.262	0.252
T_c (°C)	14.9	14.9	15.0	15.0	15.1	15.1	15.1	15.1	15.2
RH (%)	90.7	90.8	90.6	90.2	89.5	89.9	89.8	89.8	89.2
V ($m \cdot s^{-1}$)	0.11	0.13	0.04	0.04	0.04	0.10	0.24	0.23	0.23

Test 13

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.196	0.101	0.147	0.197	0.101	0.147	0.198	0.100	0.147
30	0.192	0.106	0.148	0.194	0.104	0.149	0.194	0.105	0.149
90	0.188	0.111	0.150	0.189	0.109	0.150	0.189	0.111	0.151
219	0.182	0.120	0.152	0.183	0.118	0.153	0.183	0.120	0.153
479	0.176	0.132	0.154	0.177	0.130	0.154	0.177	0.133	0.155
730	0.174	0.141	0.155	0.175	0.138	0.155	0.175	0.141	0.156
1438	0.172	0.153	0.156	0.172	0.151	0.157	0.172	0.153	0.157
1969	0.171	0.156	0.157	0.171	0.155	0.157	0.171	0.156	0.157
2951	0.170	0.157	0.157	0.170	0.156	0.158	0.170	0.158	0.158
4644	0.169	0.158	0.158	0.169	0.158	0.158	0.170	0.159	0.158
6240	0.169	0.158	0.158	0.169	0.159	0.158	0.169	0.159	0.159
7548	0.169	0.159	0.158	0.169	0.159	0.158	0.169	0.159	0.159
8626	0.169	0.159	0.158	0.169	0.159	0.159	0.169	0.159	0.159
T_c (°C)	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1	25.1
RH (%)	69.7	69.7	69.7	69.7	69.6	69.7	69.7	69.7	69.6
V ($m \cdot s^{-1}$)	0.11	0.12	0.03	0.03	0.03	0.12	0.25	0.22	0.26

Test 14

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.149	0.199	0.197	0.100	0.148	0.100	0.197	0.099	0.147
30	0.148	0.188	0.191	0.106	0.149	0.106	0.188	0.105	0.148
89	0.148	0.177	0.181	0.111	0.149	0.112	0.177	0.112	0.148
209	0.147	0.167	0.170	0.120	0.149	0.120	0.166	0.120	0.148
464	0.147	0.158	0.161	0.131	0.149	0.131	0.158	0.131	0.148
704	0.147	0.155	0.158	0.137	0.149	0.137	0.155	0.137	0.148
1430	0.146	0.153	0.154	0.142	0.149	0.142	0.153	0.142	0.148
1937	0.146	0.152	0.154	0.144	0.149	0.142	0.152	0.143	0.147
2952	0.146	0.151	0.153	0.144	0.148	0.143	0.151	0.143	0.147
4418	0.146	0.150	0.152	0.144	0.148	0.143	0.150	0.143	0.147
5969	0.145	0.150	0.152	0.144	0.148	0.143	0.149	0.143	0.147
7553	0.145	0.149	0.151	0.144	0.148	0.143	0.149	0.143	0.147
8577	0.145	0.149	0.151	0.144	0.148	0.142	0.149	0.142	0.146
T_c (°C)	35.1	35.1	35.0	34.9	34.8	34.9	34.9	34.9	34.8
RH (%)	65.2	65.2	65.4	65.8	66.0	65.9	65.9	66.0	66.3
V ($m \cdot s^{-1}$)	0.09	0.12	0.02	0.02	0.01	0.11	0.27	0.26	0.28

Test 15

Time (min)	Grain Moisture Content for Different Tray Positions (db, decimal)								
	1	2	3	4	5	6	7	8	9
0	0.199	0.151	0.150	0.103	0.200	0.102	0.150	0.103	0.202
30	0.209	0.169	0.164	0.122	0.211	0.128	0.170	0.130	0.214
90	0.216	0.184	0.178	0.142	0.217	0.153	0.187	0.155	0.223
179	0.223	0.201	0.194	0.167	0.225	0.180	0.204	0.183	0.231
379	0.230	0.220	0.215	0.201	0.236	0.214	0.224	0.217	0.240
582	0.234	0.228	0.227	0.221	0.242	0.229	0.232	0.232	0.244
1243	0.237	0.235	0.255	0.245	0.252	0.240	0.240	0.242	0.249
3130	0.237	0.236	0.244	0.245	0.249	0.241	0.240	0.242	0.246
T_c (°C)	35.2	35.2	35.1	35.1	35.1	35.1	35.1	35.1	34.9
RH (%)	84.4	84.4	84.7	84.5	85.0	85.0	84.9	85.1	85.8
V ($m \cdot s^{-1}$)	0.11	0.12	0.02	0.02	0.01	0.11	0.27	0.24	0.26

where: T_c = air temperature (°C),

RH = air relative humidity (%),

V = air velocity ($m \cdot s^{-1}$).

2. Error Analysis of the Deterioration Model

The deterioration model of Fraser and Muir (1981) was used to predict the allowable storage time elapsed (ASTE) as follows:

$$ASTE = \sum_{i=1}^{N} \frac{\Delta\theta}{\theta_{MAX}} \qquad \textbf{(1-1)}$$

$$\log_{10} \theta_{MAX} = a + bM + cT_c \qquad \textbf{(1-2)}$$

where: $\Delta\theta$ = time interval used for the simulation (h),

θ_{MAX} = Maximum allowed storage times before seed germination drops by 5% or visible mould appears (Fraser and Muir 1981) (h),

M = grain moisture content (%, wb),

T_c = grain temperature (°C), and

a = 6.2347 b = -0.21175 c = -0.05267 for $12 \leq M \leq 19\%$

a = 4.1286 b = -0.09972 c = -0.05762 for $19 \leq M \leq 24\%$

The probable uncertainty (U_{ASTE}) to predict the allowable storage time elapsed when using the deterioration model (Eq. 1-2) was determined based on the estimated uncertainties for each variable and coefficient (Kline and McClintock 1953, Huggins 1991). The magnitude of U_{ASTE}, with the same odds as the individual variables and coefficients, is calculated as follows:

$$U_{ASTE} = [(\frac{\partial U}{\partial M}.U_M)^2 + (\frac{\partial U}{\partial T_c}.U_T)^2 + (\frac{\partial U}{\partial a}.U_a)^2 + (\frac{\partial U}{\partial b}.U_b)^2 + (\frac{\partial U}{\partial c}.U_c)^2]^{1/2} \qquad \textbf{(1-3)}$$

where: U_M = uncertainty associated with measurement of grain moisture content (%, wb),

U_T = uncertainty associated with measurement of grain temperature (°C),

U_a, U_b, U_c = uncertainties in estimating the coefficients of the deterioration model

The uncertainty to predict ASTE in percentage is:

$$U_{ASTE}\% = \frac{U_{ASTE}}{\theta_{MAX}} 100\% \tag{1-4}$$

$$U_{ASTE}\% = \ln 10 \; [(U_a)^2 + (M \; U_b)^2 + (T_c \; U_c)^2 + (b \; U_M)^2 + (c \; U_T)^2]^{1/2} \; 100 \tag{1-5}$$

The uncertainties of the variables and coefficients of the deterioration model (Eq. 1-2) used in the error analysis are given in Table 1-1. The uncertainties in determining the coefficients a, b, and c of Eq. 1-2 correspond to moisture contents between 12 and 19%.

Table 1-1. Uncertainties (95% confidence level) in the measurement of grain moisture content and temperature, and in determining the coefficients a, b, and c of the deterioration model (Eq. 1-2)

Variable	Uncertainty
Grain moisture content (%, wb)	±0.2
Grain temperature (°C)	±0.5
Coefficient a (%)	±1.7
Coefficient b (%)	±3.3
Coefficient c (%)	±4.4

3. Equilibrium moisture content equations for desorption and adsorption by wheat

Equation	Application	References
$EMC = b_1 - b_2 \cdot \ln(-(T_c + b_3) \cdot \ln(RH))$ $b_1 = 0.35616$ $b_2 = 0.056788$ $b_3 = 50.998$ Me = [decimal, db]	Average data for adsorption and desorption of hard wheat	Chung equation (ASAE 1993b)
$EMC = (\ln(1 - RH)/(a_1(T_c + a_2)))^{(1/2.11)}$ $a_1 = -4.53x10-5$ $a_2 = 55.8$ EMC = [%, db]	Adsorption of Wheat	Morey et al. (1981)
$EMC = \ln(\ln(1/RH)/c_1)/\ln(c_2)$ $c_1 = 5.1552$ $c_2 = 0.8551$ EMC = [%, db]	Adsorption of wheat ('Capelle') T_c = 25°C $0.25 \leq RH \leq 0.85$	Iglesias and Chirife (1982)
$EMC = (\ln(1-RH)/(d_1(Tc+d_2)))^{(1/2.29)}$ $d_1 = -2.3x10^{-5}$ $d_2 = 55.8$ EMC = [%, db]	Desorption of Wheat	Pfost et al. (1976b)
$EMC = \{\ln(1 - RH)/(f_1 T^{-2.034})\}^{[1/A]}$ $A = f_3 T^{-1.255}$ $f_1 = -3.113x10^6$	Desorption of wheat ('Neepawa')	Sinicio et al. (1991)

where: EMC = equilibrium moisture content (decimal or %, db),
T = air temperature (K),
T_c = air temperature (°C),
RH = air relative humidity (decimal).

4. Thin-layer drying and wetting equations for wheat and shelled corn

Equation	Application	Reference
$MR = \exp(-Kt^N)$	Drying of wheat	Jayas and
$K = g_1 + g_2 T_c^2 + g_3 RH$	$5 \le T_c \le 35°C$	Sokhansanj
$N = 1$	$0.35 \le RH \le 0.80$	(1986)
$g_1 = 0.003537$	$0.3 \le V \le 0.6$ m/s	
$g_2 = 5.7005 \times 10^{-6}$	Mo = 18.5% wb	
$g_3 = -2.39126 \times 10^{-3}$		
t=[min]		
$K = \exp(h_1 + h_2 \cdot \ln(1.8T_c + 32) + h_3 V)$	Drying of shelled corn	Misra and
$N = h_4 \cdot \ln(100 \cdot RH) + h_5 Mo$	$0.03 \le RH \le 0.83$	Brooker (1980)
$h_1 = -7.1735$	$2.2 \le T_c \le 71.1°C$	
$h_2 = 1.2793$	$0.025 \le V \le 2.33$m/s	
$h_3 = 0.1378$	$0.18 \le Mo \le 0.60$ kg/kg db	
$h_4 = 0.0811$		
$h_5 = 0.78$		
t=[h]		
$K = \exp(i_1 + i_2 \cdot \ln(1.8T_c + 32) + i_3 Mo)$ $N = i_4 + i_5 RH$	Wetting of shelled corn	Misra and
$i_1 = -8.5122$	$0.9 \le RH \le 1$	Brooker (1980)
$i_2 = 1.2178$	$10 \le T_c \le 43.3°C$	
$i_3 = 8.64$	$0.025 \le V \le 0.382$ m/s	
$i_4 = 2.1876$	$0.08 \le Mo \le 0.25$ kg/kg db	
$i_5 = -1.67$		
t=[h]		

where: Mo = initial moisture content of the grain (decimal or %, db),
MR = moisture ratio (decimal),
RH = air relative humidity (decimal),
t = time (min or h),
T = air temperature (K),
T_c = air temperature (°C),
V = air velocity ($m \cdot s^{-1}$).