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**MATHEMATICAL MODELLING
OF BULK STORED ONIONS IN
TRANSPORT CONTAINERS**

A thesis
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of the requirements for the degree

of

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ABSTRACT

Export onion bulbs are predominantly transported from New Zealand loose in sacks which are bulk loaded into intermodal transport containers. Product respiratory heat, water vapour, and volatiles are dispensed of by a fan unit installed in the end of the container, ventilating the stow by forcing ambient air from a false floor up through the crop and exhausting the air from a head space.

The objective of this study was to mathematically model this system with respect to onion bulb temperature and weight loss, and internal container air temperature and relative humidity. These product and flowfield variables were predicted at different locations within the transport vessel. Bulb temperature and weight loss were simulated as dynamic variables using ordinary differential equations, and air temperature and relative humidity were simulated as quasi steady state variables using algebraic equations.

A validation experiment was conducted to evaluate the simulation model by placing temperature and humidity sensors throughout the product and flowfield space measuring the respective properties. Onion and air temperatures were predicted with satisfactory accuracy in almost all measured locations of the container. Prediction of relative humidity varied considerably throughout the container, although excessive sensor errors were identified casting suspicion on some validation measurements. Simulated relative humidity could not therefore be fully verified. Bulb weight loss was predicted with variable levels of accuracy. Significant variability in the validation data was evident in the upper and lower regions of the container preventing complete model validation. Central regions of the container were simulated with satisfactory accuracy.

A model sensitivity analysis revealed that container ventilation rate strongly influenced model performance with respect to temperature and relative humidity. The mass transfer coefficient, as expected, was most influential over product weight loss.

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TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF SYMBOLS	xi
CHAPTER 1	
INTRODUCTION	1
1.1 ONION STORAGE POTENTIAL	1
1.2 THERMOPHYSICAL VARIATION WITHIN PRODUCT STOWS	3
1.3 PREDICTING PRODUCT TEMPERATURE AND WEIGHT LOSS ...	3
CHAPTER 2	
LITERATURE REVIEW	4
2.1 PRINCIPLES OF MATHEMATICAL MODELLING	4
2.1.1 Model Classification and Infrastructure	4
2.1.2 Model Development Strategy	5
2.1.2.1 Time domain	6
2.1.2.2 Space domain	6
2.2 ISO INTERMODAL TRANSPORT CONTAINERS	7
2.2.1 Ventilated Containers	8
2.2.1.1 Refrigerated containers	8
2.2.1.2 Insulated containers	9
2.2.1.3 Purpose built Containers	9
2.2.1.4 Temporarily modified containers	9
2.2.2 Container Performance	10
2.2.2.1 Internal air circulation	11
2.2.2.2 Internal temperature distribution	13

2.3	MATHEMATICAL MODELS OF TRANSPORT CONTAINERS	15
2.3.1	Steady State Models	15
2.3.2	Dynamic Models	17
2.4	PRODUCT HEAT AND MASS TRANSFER	17
2.4.1	Modelling Heat Transfer	18
2.4.1.1	Single product	18
2.4.1.2	Bulk stacked product	19
2.4.2	Modelling Mass Transfer	23
2.4.2.1	Single product	24
2.4.2.2	Bulk stacked product	26
2.5	PHYSIOLOGY OF ONION BULB STORAGE	27
2.5.1	Product Respiration	27
2.5.1.1	Carbon weight loss	28
2.5.1.2	Effect of temperature on respiration	28
2.5.2	Product Transpiration	30
2.5.2.1	Moisture weight loss	30
2.5.2.2	Effect of relative humidity and temperature on weight loss	31

CHAPTER 3

	RESEARCH OBJECTIVES	35
3.1	JUSTIFICATION OF THE RESEARCH	35
3.2	OBJECTIVES OF THE RESEARCH	35

CHAPTER 4

	MEASURING THE ENVIRONMENTAL AND PRODUCT STATUS IN A TRANSPORT CONTAINER	36
4.1	PRODUCT SPECIFICATIONS	36
4.2	CONTAINER SPECIFICATIONS	37
4.2.1	False Floor Design	37
4.2.2	Plenum and Duct Design	39
4.2.3	False Door Design	41
4.2.4	Fan Unit	42

4.3 ENVIRONMENTAL AND PRODUCT MEASUREMENTS	42
4.3.1 Measurement Localities	42
4.3.2 Equipment and Instrumentation	44
4.3.3 Measurement Methodology	44
4.3.3.1 Temperature	46
4.3.3.2 Relative humidity	46
4.3.3.3 Weight loss	48
4.3.3.4 Ventilation rate	48
4.3.3.5 Air pressure	49
CHAPTER 5	
THERMOPHYSICAL PROPERTIES AND PARAMETERS	50
5.1 ONION BULB	50
5.1.1 Specific Heat Capacity	50
5.1.2 Thermal Conductivity	51
5.1.3 Convective Heat Transfer	52
5.1.4 Surface Area and Volume	53
5.1.4.1 Experiment introduction	53
5.1.4.2 Method and materials	53
5.1.4.3 Results and discussion	54
5.1.5 Respiration	56
5.1.5.1 Experiment introduction	56
5.1.5.2 Method and materials	57
5.1.5.3 Results and discussion	58
5.1.6 Transpiration	60
5.1.6.1 Experiment introduction	61
5.1.6.2 Method and materials	62
5.1.6.3 Results and discussion	63
5.1.7 Water Content	67
5.2 FLOWFIELD	67
5.2.1 Saturated Water Vapour Pressure	68
5.2.2 Absolute Humidity	68

5.2.3	Air Density	69
5.2.4	Latent Heat of Vaporization	69
5.3	PARAMETER VALUES	69

CHAPTER 6

MODEL DEVELOPMENT	72
6.1 HEAT AND MASS TRANSFER PATHWAYS	72
6.1.1 Convection Between Flowfield and Walls	72
6.1.2 Conduction Between Onions	73
6.1.3 Conduction Within Onions	74
6.1.4 Forced and Free Convection	75
6.1.5 Remaining Pathways	77
6.2 ONION AND FLOWFIELD MODEL FORMULATION	78
6.2.1 Methodology	78
6.2.2 Onion Temperature	80
6.2.3 Onion Weight Loss	81
6.2.4 Air Temperature	82
6.2.5 Air Humidity	83
6.2.6 Model Programming	85
6.2.7 Model Operational Details	85
6.2.7.1 Input parameter requirements	85
6.2.7.2 Initialization parameter requirements	86

CHAPTER 7

MODEL EVALUATION AND DISCUSSION	87
7.1 EVALUATION PROCEDURE	87
7.2 STANDARD MODEL SIMULATION	89
7.2.1 Introduction	89
7.2.2 Results	90
7.2.2.1 Graphical evaluation	90
7.2.2.2 Sensitivity analysis	97

	viii
7.2.3 Discussion	101
7.2.3.1 Respiration rate	101
7.2.3.2 Onion and air temperature	103
7.2.3.3 Relative humidity	103
7.2.3.4 Weight loss	105
7.2.3.5 Sensitivity analysis	107
7.3 MODIFIED MODEL SIMULATION	108
7.3.1 Introduction	108
7.3.2 Results	109
7.3.2.1 Graphical evaluation	109
7.3.2.2 Statistical analysis	109
7.3.3 Discussion	114
7.4 OVERALL DISCUSSION	114
CHAPTER 8	
CONCLUSIONS AND RECOMMENDATIONS	117
8.1 CONCLUSIONS	117
8.2 RECOMMENDATIONS	118
REFERENCES	121
APPENDIX A	131
MEASURED FLOWFIELD PROPERTIES	131
A1 Transport Container Ventilation Rate	131
A2 Transport Container Air Pressures	132
A3 Modified Model Ventilation Rate	132
APPENDIX B	133
MODEL PROGRAMMING AND DATA FILES	133
B1 Model Simulation	133
B2 Model Input File	142
B3 Model Initialization File	143

LIST OF TABLES

Table

2.1	Weight Loss from Onion Bulbs during Storage	33
4.1	Probe and Sensor Measurement Positions in Transport Container	47
5.1	Onion Bulb and Flowfield Thermophysical Data	71
7.1	Standard Simulation Model Statistical Results	100
7.2	Simulation Model Sensitivity Analysis	101
7.3	Modified Simulation Model Statistical Results	113
A.1	Air Velocity Measurements from Transport Container Exhaust Ports	131
A.2	Static Air Pressure Measurements from Transport Container	132
A.3	Modified Simulation Model Flow Rate in Zone Columns	132

LIST OF FIGURES

Figure

4.1 View of Transport Container False Door Design	38
4.2 Views of Transport Container Plenum and Duct Design	39
4.3 Photograph of Transport Container and Ventilation System	40
4.4 View of Transport Container False Door Design	41
4.5 Labelling of Onion Bed Zones	43
4.6 Photograph of Transport Container Partially Filled with Onions	45
4.7 View of Transport Container Ventilation Exhaust Ports	48
5.1 Onion Bulb Volume as a Function of Mass	55
5.2 Onion Bulb Surface Area as a Function of Mass	55
5.3 Heat of Respiration and Carbon Depletion as a Function of Temperature	60
5.4 View of Flow Through Pressure Drop System Design	64
5.5 Onion Water Loss as a Function of Vapour Pressure Deficit	65
6.1 Measured Onion Centre and Surface Temperature	76
7.1 Transport Container Inlet and Outlet Air Ventilation Temperature	88
7.2 Measured and Simulated Onion Temperature in Zones 3,3,k	91
7.3 Measured and Simulated Air Temperature in Zones 3,3,k	92
7.4 Measured and Simulated Onion Temperature in Zones 2,2,k	93
7.5 Measured and Simulated Air Temperature in Zones 2,2,k	94
7.6 Measured and Simulated Relative Humidity in Zones	95
7.7 Measured and Simulated Relative Humidity in Zones	96
7.8 Measured and Simulated Onion Weight Loss	98
7.9 Measured and Modified Simulation of Onion Temperature in Zones 3,3,k	110
7.10 Measured and Modified Simulation of Air Temperature in Zones 3,3,k	111
7.11 Measured and Modified Simulation of Relative Humidity in Zones 1,3,k	112

LIST OF SYMBOLS

Symbol in Text	Symbol in Model	Description	Units
A	As	surface area of onion bulb	m ²
A _z	-	total surface area of onions in zone	m ²
AHL	-	absolute humidity lowering effect	-
Bi	-	Biot number	-
C _p	Cpa	specific heat capacity of air	J.g ⁻¹ .°C ⁻¹
C _{p(on)}	Cp	specific heat capacity of onion	J.g ⁻¹ .°C ⁻¹
CO ₂ ^f	-	carbon dioxide final concentration	%
CO ₂ ⁱ	-	carbon dioxide initial concentration	%
d	-	diameter of average onion	m
dm _c /dt	DelMd	mass transfer of carbon	g.s ⁻¹
dm _{H₂O} /dt	DelMw	mass transfer of water vapour	g.s ⁻¹
dT _{on} /dt	DelT	temperature change of onion	°C.s ⁻¹
D _{AB}	-	binary mass diffusion coefficient	m ² .s ⁻¹
g	-	gravitational acceleration	m.s ⁻²
Gr	-	Grashof number	-
h _c	htc[]	convective heat transfer coefficient	W.m ⁻² .°C ⁻¹
j _h	-	Colburn j factor for heat transfer	-
j _m	-	Colburn j factor for mass transfer	-
k	-	thermal conductivity of onion	W.m ⁻¹ .°C ⁻¹
k _a	-	convective air mass transfer coefficient	g.m ⁻² .s ⁻¹ .Pa ⁻¹
k _{a(r)}	-	convective air mass transfer coefficient	m.s ⁻¹
k _s	-	skin mass transfer coefficient	g.m ⁻² .s ⁻¹ .Pa ⁻¹
k _t	-	mass transfer coefficient	g.m ⁻² .s ⁻¹ .Pa ⁻¹
k _{t(r)}	mtc[]	mass transfer coefficient	m.s ⁻¹
L	-	characteristic dimension	m
m	-	mass of onion bulb	kg
ṁ _{a(z)}	-	mass flow of air in zone	g
ṁ _{H₂O}	fevap	mass flow rate of water vapour	g.s ⁻¹
m _s	-	mass of onion sample	kg
m _z	-	mass of onions in zone	kg

M_C	-	molecular mass of carbon	g.mol^{-1}
P_a	pa[]	vapour pressure of air	Pa
P'_a	pasat	saturated vapour pressure of air	Pa
P_{ATM}	-	atmospheric pressure	Pa
P_{PDS}	-	air pressure in pressure drop system	Pa
P_s	-	vapour pressure of onion surface	Pa
Pr	-	Prandtl number	-
ΔP_{z11}	-	air pressure difference across zone column	Pa
r_h	-	heat of respiration	W.kg^{-1}
π_C	-	relative respiratory carbon mass depletion	$\text{g.kg}^{-1}.\text{s}^{-1}$
π_{CO_2}	-	relative respiratory carbon dioxide production	$\text{mol.kg}^{-1}.\text{s}^{-1}$
Re	-	Reynolds number	-
RH	RH[]	relative humidity of air	%
Sc	-	Schmidt number	-
St	-	Stanton number	-
St_m	-	Stanton number for mass transfer	-
t	-	time	s
T_a	Ta[]	temperature of air	$^{\circ}\text{C}$
ΔT_a	-	temperature change of zone air	$^{\circ}\text{C}$
$T_{a(i)}$	Tai	temperature of air entering zone	$^{\circ}\text{C}$
$T_{a(o)}$	Tao	temperature of air exiting zone	$^{\circ}\text{C}$
ΔT_m	lmtd	onion/flowfield log mean temperature difference	$^{\circ}\text{C}$
T_{on}	Ton[]	temperature of onion	$^{\circ}\text{C}$
T_s	-	temperature of onion surface	$^{\circ}\text{C}$
u	-	air velocity	m.s^{-1}
u_{∞}	-	upstream air velocity	m.s^{-1}
v	v[]	volumetric air flow rate through zone	$\text{m}^3.\text{s}^{-1}$
V	-	volume of onion bulb	m^3
V_j	-	volume of jar	m^3
V_s	-	volume of onion sample	m^3
W	wtfrac	onion water content fraction	-
α	-	thermal diffusivity of air	$\text{m}^2.\text{s}^{-1}$
β	-	volumetric thermal expansion coefficient	K^{-1}
ε	-	packed bed volumetric void fraction	-

λ	Lambda	latent heat of vaporization of water	$J.g^{-1}$
ρ	rho[]	density of air	$g.m^{-3}$
ρ_{on}	-	density of onion	$kg.m^{-3}$
ν	-	kinematic viscosity of air	$m^2.s^{-1}$
Φ_{conv}	Qc	convective heat transfer from onion to zone air	W
Φ_{evap}	Qevap	latent heat transfer from onion to zone air	W
Φ_{resp}	Qresp	heat generation from respiration	W
χ	Xa[]	absolute humidity of air	$g.m^{-3}$
$\Delta\chi$	-	absolute humidity change of zone air	$g.m^{-3}$
χ_i	Xai	absolute humidity of air entering zone	$g.m^{-3}$
$\Delta\chi_m$	lmXd	onion/flowfield log mean absolute humidity diff.	$g.m^{-3}$
χ_o	Xao	absolute humidity of air exiting zone	$g.m^{-3}$
χ_{on}	Xonsat	absolute humidity of onion surface	$g.m^{-3}$

Additional symbols used in model not used in text

Asav	surface area of average onion bulb	m^2
fresp	mass transfer rate of carbon	$g.s^{-1}$
massav	mass of average onion bulb	kg
masst	total mass of onions in container	kg
Mdon[]	mass of onion dry fraction	g
Mon[]	mass of onions in zone	g
Mwon[]	mass of onion wet fraction	g
number	number of onion in container	-
pin	vapour pressure of air entering container	Pa
psatin	saturated vapour pressure of air entering container	Pa
rho _{in}	density of air entering container	$g.m^{-3}$
RH _{in}	relative humidity of air entering container	%
simtime	simulation step length	s
step	simulation step length	s
T _{in}	temperature of air entering container	°C
vent	total container ventilation rate	$m^3.s^{-1}$
X _{in}	absolute humidity of air entering container	$g.m^{-3}$

where:

[] = array of zone positions