Mathematical Modelling of Airflow in Shipping Systems: Model Development and Testing

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Abstract

Horticultural exports are of economic significance to New Zealand. Only through providing consistently high quality products to distant markets can New Zealand hope to command a premium price. New Zealand's two major horticultural exports, apples and kiwifruit, are transported to foreign markets by sea; either in refrigerated holds on-board cargo vessels or in refrigerated containers. Long transit times mean that conditions in these systems must be carefully controlled to ensure high quality product arrives at market. Effective distribution of air is a key consideration in transport systems.

A mathematical model to describe the flow of air in marine transport systems was developed. The model was based on a resistance network framework, relying on simplification of the complex geometry within the refrigerated space to a discrete number of flow paths and points of convergence and divergence. Correlations quantifying the flow resistance of each channel were required. Some of these correlations were already available, and some were developed specifically for this purpose. A general method for predicting the flow resistance of enclosed conduits based on the Darcy-Weisbach, laminar and Colebrook equations was found to be sufficiently accurate for use. The flow resistance of horizontally vented horticultural packages was quantified and the cause of the flow resistance investigated. Entrance and exit effects were found to be significant, and a relationship between vent size and flow resistance was developed.

Air interchange between a vented carton and the general refrigerated space was shown to be a significant mode of heat transfer. The effect of vent design on the rate of air interchange was found to be complex. Quantitative relationships between vent characteristics and rates of air interchange could not be developed; however, some general observations were made. Vent size, aspect ratio and alignment were all found to affect the rate of interchange.

An existing method for determining in-package fluid velocities was refined to improve the accuracy of data and reduce the measurement time. A low-cost method for measuring airflows in transport systems was also developed utilising thermistors. These thermistor anemometers were used to monitor velocities in four shipments of fresh produce from New Zealand. Three of the four vessels monitored showed large variation in the circulation rate in the period between evaporator defrosts due to frosting. In some cases, frosting was severe enough to cause loss of delivery air temperature control. Management of defrosts was identified as an area of improvement in refrigerated hold management.

Validation of the model developed was performed using four systems: a laboratory scale test-rig, a 40' container and two of the surveyed refrigerated holds. Airflow predictions were used with a heat transfer model to predict in-package temperatures. Comparison of measured and predicted flows and in-package temperatures showed good agreement given uncertainty of geometry and input data.

The implications of altering a number of operational and design variables in both containers and refrigerated holds were investigated using the developed models. Increased circulation rates were found to increase cooling rates and reduce temperature variability in both types of systems; however, the magnitude of the benefit decreased with increasing circulation rate. Removal of the floor gratings and the use of pallet bases as an air distribution channel was found to increase temperature variability in both types of systems. The magnitude of the increase was small in a 40' container but substantial in a refrigerated hold.

The correlations and models developed in this thesis provide useful tools to analyse and optimise the design and operation of refrigerated marine transport systems.

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If you go on hammering away at a problem, it seems to get tired,
lies down and lets you catch it.

W.L. Bragg
(Nobel Prize laureate - 1915)

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Nomenclature

a = Ramsin equation coefficient (kg.s$^{(b-2)}$.m$^{-(b+2)}$)
a = Thermistor property
A = Area (m^{2})
b = Ramsin equation exponent
b = Thermistor property (K^{-1})
c = Vent resistance coefficient (kg.s$^{(b-2)}$.m$^{-(b+2)}$)
c = Thermistor calibration coefficient (J.s^{n-1}.m^{-n}.K^{-1})
C = Constant
CC = Configuration coefficient
C_g = Geometric constant
col = Jacobian matrix column index
C_p = Specific heat capacity (W.kg^{-1}.K^{-1})
d = Vent resistance exponent
D = Dimension (m)
D_h = Channel hydraulic diameter (m)
D_{short} = Rectangular channel short dimension (m)
E = Criteria employed for 'backtracking' procedure
f = Friction factor
$F(a)$ = Function of *a*
$\mathbf{F}(\boldsymbol{\psi})$ = Vector of function values (kg.s^{-1})
Fr = Energy lost through friction effects (J.m^{-3})
$FUTC$ = Fraction unaccomplished temperature change
g = Acceleration due to gravity (m.s^{-2})
g_i = External force per unit mass of fluid in the i_{th} direction (N.kg^{-1})
h = Height relative to arbitrary datum (m)
h_s = Surface heat transfer coefficient (W.m^{-2}K^{-1})
H = Number of horizontal zones
I = Current (A)
i,j,k = Cartesian co-ordinates
$\mathbf{J}$ = Jacobian matrix (kg.s^{-1}.Pa^{-1})
k = Laminar friction geometric parameter
k = Turbulent kinetic energy (m^{2}.s^{-2})
K_1 = Ergun equation constant
K_2 = Ergun equation constant
K_{add} = Additional frictional losses stated as number of velocity heads
L = Distance (m)
M'_{H_2O} = Effective permeance of the fruit surface to movement of water vapour under prevailing conditions (mol.s^{-1}.m^{-2}.Pa^{-1})
m_t = Thermistor thermal mass (J.K^{-1})
$\dot{m}$ = Mass flow rate (kg.s^{-1})
n = Index
n = Thermistor calibration exponent
Nu = Nusselt number
O = Ratio of vent area to face area
Δp_{H_2O} = Partial pressure driving force (Pa)
P = Fluid pressure (Pa)
Pm = Perimeter of conduit (m)
Pr = Prandtl number

Q = Fluid volumetric flow ($m^3.s^{-1}$)
r'_{H_2O} = Rate of water loss from product ($mol.s^{-1}$)
R = Channel aspect ratio
Re = Reynolds number
row = Jacobian matrix row index
SCP = Scale parameter
SHP = Shape parameter
t = Time (s)
T = Temperature (°C)
u = Superficial velocity ($m.s^{-1}$)
v = Fluid velocity ($m.s^{-1}$)
v' = Turbulent velocity component ($m.s^{-1}$)
V = Number of vertical zones
V = Voltage (V)
$VRC_{i,j}$ = Velocity relativity coefficient
W = Weibull distribution
x,y,z = Co-ordinates (m)
α = Calculated proportion of correction to add to solution vector
β = Flow resistance
γ = Expansion factor
$\boldsymbol{\delta\psi}$ = Vector of corrections of total pressure (Pa)
ε = Absolute roughness (m)
ε = Bed porosity
$\varepsilon_{\varphi i}$ = Viscous dissipation function ($m^2.s^{-3}$)
λ = Thermal conductivity ($W.m^{-1}.K\text{-}^{1}$)
μ = Fluid viscosity (Pa.s)
ρ = Fluid density ($kg.m^{-3}$)
υ = Kinematic viscosity ($m^2.s^{-1}$)
υ_τ = Turbulent eddy viscosity ($m^2.s^{-1}$)
ϕ = Rate of heat transfer (W)
χ = Dissipation factor ($W.K^{-1}$)
ψ = Total pressure (Pa)
$\boldsymbol{\psi}$ = Vector of total pressures (Pa)
Ω = Electrical resistance (Ω)