Significant factors affecting the forced-air cooling process of polylined horticultural produce

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

in

Food Technology

at Massey University, Palmerston North, New Zealand

Justin O'Sullivan

2016

Abstract

New Zealand is the world's third biggest producer of kiwifruit, with 94 % of the kiwifruit produced exported (NZ $ 1.0 bn in 2014). Forced-air cooling of the produce (from the harvest temperature of about 20 ℃ to near storage temperature of 0 ℃) immediately after harvest improves storage potential and maintains produce quality before transportation to market. The design of the kiwifruit packaging system influences the rate of cooling and temperature achieved, mainly by affecting the airflow within and throughout the package.

The typical kiwifruit package contains 10.5 kg of fruit and consists of a cardboard box and polyliner bag to prevent the loss of moisture and fruit shrivelling. Individual boxes are assembled onto pallets (10 boxes to a pallet layer, 10 layers high) Open areas or vents (in the box) facilitate cooling by allowing cool air to enter and circulate throughout the package. In forced-air cooling pallets are assembled into double rows with an aisle between the rows. Cool air is sucked through the pallets by a fan in the aisle, cooling the fruit and warming the air. The air is then either blown or ducted to the refrigeration system to be re-cooled. The polyliner keeps the local humidity high near the fruit, preventing weight loss due to evaporative cooling, but, as a barrier to direct fruit to air contact, slows the cooling rate. This project investigated the impact of operating conditions and package design on the cooling performance in such systems.

A numerical model was developed (a CFD model implemented using the Fluent CFD software) that describes and predicts the temperature profiles of palletised kiwifruit packages undergoing forced-air cooling. The capability of the model to predict the fruit

temperatures in each package was quantitatively validated against experimental data. The numerical model was able to predict temperature profiles within experimental error bars over 14 h of cooling.

The numerical model was used to determine the operating point (in terms of pressure drop and flowrate across the pallet) to ensure rapid cooling of the produce without incurring excessive operational costs due to the power requirements. Results from both experimental work and the numerical model informed that there was an effective limit to the volumetric flowrate of 0.243 L kg^{-1} s^{-1}: flowrates in excess of the limit had no or little effective benefit. This threshold flowrate is below the typical range recommended in industry for the forced-air cooling of non-polylined horticultural produce, which is 0.5 – 2.0 L kg^{-1} s^{-1}.

The numerical model demonstrated that the overall cooling performance (cooling rate, uniformity, power consumption and pallet throughput per week) can be improved by controlling the airflow distribution between the fastest and slowest cooling kiwifruit packages. An alternative design that channels cool air through the pallet towards the slowest cooling packages, located at the back of the pallet, by using two package designs in the same pallet, was presented.

At 0.243 L kg^{-1} s^{-1} it was found that the pressure drop and power required to achieve equivalent cooling rates with the new design was reduced (by 24 % each) compared to the conventional design. Additionally, at the half-cooling time the cooling uniformity was improved by 19 %. The key features of the new design can be expected to be applicable for the cooling of horticultural produce involving an inner packaging liner.

Acknowledgements

I would like to thank a number of people who assisted me over the course of this project.

At Massey University Dr. Andrew East (principle supervisor) Dr. Maria J. Ferrua (co-supervisor) and Dr. Richard Love (co-supervisor) provided invaluable advice and guidance, which I am truly grateful for. I am also thankful for the technical assistance provided by Peter Jeffery, Sue Nicholson and Gary Radford, who made all the experiments carried out in the laboratory possible.

As part of this project I spent six months at KU Leuven, Belgium, where I would like to thank Dr. Pieter Verboven (co-supervisor) and Dr Bart M. Nicolaï (co-supervisor) who taught me about numerical modelling.

I would also to thank Dr Patricia Kieran and Professor Brian Glennon of UCD, Ireland who gave me a research internship when I was an undergraduate and inspired me to pursue a doctorate.

I would like to thank Zespri International Ltd for their financial support.

I would like to take the opportunity to appreciate my parents, brothers and sister for their support and encouragement.

Table of Contents

List of Figures

List of Tables

Nomenclature

English Symbols

A – area, m^2

B – ratio of outer to inner diameter, dimensionless

C_D – discharge coefficient

C_p – specific heat at constant pressure, J kg^{-1} K^{-1}

d – inner diameter, m

D – outer diameter, m

D_H – hydraulic diameter (m)

E – energy per unit mass, J kg^{-1}

g – gravity, m s^{-2}

G – generation of turbulent kinetic energy, kg m^{-1} s^{-3}

Gr – Grashof number, dimensionless

h – specific enthalpy, J kg^{-1}

I – unit tensor

J – diffusion flux, kg m^{-2} s^{-1}

k – thermal conductivity, W m^{-1} K^{-1}

l – length scale, m

L – characteristic length, m

m – mass, kg

n – number of replicates

p – pressure, Pa

P – power, W

Pr – Prandtl number, dimensionless

q – heat flow rate, W

Q – volumetric flowrate, m^3 s^{-1}

Re – Reynolds number, dimensionless

RH – Relative Humidity, %

t – time, s

T – temperature, K

u, v, w –velocity magnitude, m s^{-1}

$\vec{v}$ – overall velocity vector, m s^{-1}

x, y, z – Cartesian coordinates, m

X – mass fraction, dimensionless

Y – Fractional Unaccomplished Temperature Change, dimensionless

Greek Symbols

β – thermal expansion coefficient, K^{-1}

ε – turbulent dissipation rate, m^2 s^{-3}

κ – turbulent kinetic energy, m^2 s^{-2}

λ – latent heat, kJ kg^{-1}

ρ – density, kg m^{-3}

τ – stress sensor, N m^{-2}

μ – viscosity, kg m^{-1} s^{-1}

υ – kinematic viscosity, m^2 s^{-1}

σ – Stefan Boltzmann constant, 5.67 x10^{-8} J m^{-2} s^{-1} K^{-4}

σ_ε – turbulent Prandtl number for ε, dimensionless

σ_κ – turbulent Prandtl number for κ, dimensionless

ω – turbulent specific dissipation rate, s^{-1}

Miscellaneous Symbols

ϵ - emissivity, dimensionless

Mathematical operators

d – total derivative

Δ – difference (i.e. change in variable)

δ_{ij} – Kronecker delta function

∂ – partial derivative

∇ – partial derivative with respect to all directions in Cartesian space

Subscripts

a – species "a"

b – buoyancy

f – fruit

i, j, k – vector directions in Cartesian coordinates

t – turbulent

eff – effective

w – water

Constants

C_{μ}, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ – constants for κ-ε turbulent model

Abbreviations

CAT– Computerized Axial Tomography

FUTC – Fractional Unaccomplished Temperature Change, -

h.t.c – heat transfer coefficient, W m^{-2} K^{-1}

HCT – Half Cooling Time, h

LSD – Least Squares Difference

MBP – Modular Bulk Pack

rpm – revolutions per minute (min^{-1})

rps – revolutions per second (s^{-1})

SECT – Seven Eights Cooling Time, h

TCR – Temperature Control Room

VSD – Variable Speed Drive