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Modelling the forced-air cooling mechanisms and performance of polylined horticultural produce

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ABSTRACT

A 3-D computational fluid dynamics (CFD) model was developed to describe and predict the temperature profiles of palletised polylined kiwifruit packages undergoing forced-air cooling. The geometrical configuration of the kiwifruit, polyliner and cardboard box were explicitly modelled. The model included the effects of natural convection on the airflow behaviour and heat transfer process occurring within the packed fruits inside the polyliner. The capability of the model to predict the fruit temperatures in each package was quantitatively validated against experimental data. A laboratory scaled experimental rig was used to monitor the forced-air cooling process of a half pallet of kiwifruit boxes under controlled operating conditions. The numerical model was able to predict cooling times within experimental error.

Cooling within the pallet was primarily influenced by air temperature and to a lesser extent airflow distribution into each package. A maximum recommended volumetric flowrate through the pallet of 0.34 L kg^{-1} s^{-1}, far lower than flowrates recommended for the cooling of non-polylined produce, was identified. Successive increases to the flowrate, particularly beyond 0.34 L kg^{-1} s^{-1}, resulted in increasingly diminished reductions (<12%) to cooling rate.

Within the polyliner there was a low transfer of energy between kiwifruit and kiwifruit surrounding air. Instead cooling was reliant on the air temperature flowing over the top of the polyliner.

1. Introduction

Postharvest cooling is essential to ensure that product quality is maintained from harvest to retail. For kiwifruit, the maximum storage potential is achieved when the fruit are cooled to near 0 °C efficiently, shortly after harvest (Ashby, 1995). Kiwifruit, kept at 0 °C and 90–95% relative humidity can have a storage period of 3–5 months (Simson and Straus, 2010). This affords market flexibility and eliminates the need for kiwifruit producers to market immediately after harvest. However, improper cooling can lead to hot or cold spots, within the package or pallet, and consequently quality loss in horticulture produce during storage (Verboven et al., 2003). The most common industrial practice to efficiently cool horticultural produce is a forced-air cooling process immediately after harvest. Forced-air cooling involves forcing refrigerated air through packages of fresh produce stacked upon pallets. Of the different air flow systems available the tunnel cooler is the most common (Brosnan and Sun, 2001).

A variety of factors can affect the cooling times of the produce inside the package. For example, strawberries (a relatively small fruit and packed in individual clamshells within trays) can cool to near 0 °C in as little as 2 h (Ferrua and Singh, 2009c). Conversely, palletized boxes of apples can take up to 12 h to cool (East et al., 2003). Introducing a barrier between the produce and cooling air (as in the case of polylined packaging or fruit wrapped in paper) can extend the cooling period even further. For example, pears stacked in boxes and wrapped in paper can take up to 24 h to cool (Thompson and Chen, 1988).

The typical flowrate range recommended in industry for the forced-air cooling of non-polylined horticultural produce is 0.5–2.0 L kg^{-1} s^{-1} (Thompson, 2004). For example, de Castro et al. (2004a) showed that, for the forced-air cooling of non-polylined horticultural produce, increasing the air flowrate from 1 to 2 L kg^{-1} s^{-1} reduced the Half Cooling Time, HCT, by 26%. For an increase in flowrate from 2 to 4 L s^{-1} kg^{-1} the reduction in HCT was only 11%.

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Nomenclature

English Symbols

C_p	Specific heat at constant pressure, $\mathrm{J\,kg^{-1}\,K^{-1}}$
E	Energy per unit mass, $\mathrm{J\,kg^{-1}}$
h	Specific enthalpy, $\mathrm{J\,kg^{-1}}$
k	Thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
m	Mass, kg
p	Pressure, Pa
P	Power, W
Q	Volumetric flowrate, $\mathrm{m^3\,s^{-1}}$
t	Time, s
T	Temperature, K
v	Velocity, $\mathrm{m\,s^{-1}}$
v	Overall velocity vector, $\mathrm{m\,s^{-1}}$
x, y, z	Cartesian coordinates, m
Y	Fractional unaccomplished temperature change, dimensionless

Greek Symbols

ε	Turbulent dissipation rate, $\mathrm{m^2\,s^{-3}}$
κ	Turbulent kinetic energy, $\mathrm{m^2\,s^{-2}}$
ρ	Density, $\mathrm{kg\,m^{-3}}$

Subscripts

a	Air
avg	Average
i	Initial
t	Turbulent
eff	Effective

Abbreviations

CFD	Computational fluid dynamics
FUTC	Fractional unaccomplished temperature change
HCT	Half cooling time, h
MBP	Modular bulk pack
RH	Relative humidity, %
SECT	Seven eights cooling time, h
TCR	Temperature control room
VSD	Variable speed drive

The packaging structure usually consists of a corrugated cardboard package that contains vents or hand holes to facilitate its handling and provide a means of contact between the refrigerated air and the produce. In addition, depending on the product, individual products (such as kiwifruit, grapes and berryfruit) are also contained within an internal package. In some situations this is used to separate consumer units of produce, in either bags or clamshells (e.g. strawberries are field packed into individual clamshells; Ferrua and Singh, 2009a). In other cases, including for kiwifruit and grapes (East et al., 2013) a polyliner bag is used to assist in moisture retention of the fruit during the storage period. Following harvest, kiwifruit are at risk of developing shrivel if more than 4% of the total weight at harvest is lost due to water evaporation (Burdon and Lallu, 2011). This affects both visual appearance and the sell weight at the end of the supply chain. Kiwifruit are encased within a polyliner to prevent excessive loss of product moisture and maintain product quality.

The growth of computer power in recent years has led to an increased use of numerical models to predict complicated airflow patterns and cooling profiles of horticultural packages during forced-air cooling (Defraeye et al., 2013, 2014; Dehghannya et al., 2008, 2011, 2012; Delele et al., 2008; Delele et al. 2013a,b,c; Ferrua and Singh, 2009a,b,c; Ferrua and Singh, 2011). The use of numerical modelling facilitates an exact control of different operating conditions, while providing detailed information on the local airflow behaviour and temperature profile within the system. This allows a more fundamental analysis of the design principles and mechanisms underpinning the overall performance of the cooling process.

The aim of this paper was to develop a numerical model to simulate the forced-air cooling of polylined kiwifruit in cardboard packages in a typical industrial pallet layer arrangement used during forced-air tunnel cooling. The model was then used to identify the airflow distribution and temperatures within the pallet and the maximum recommend flowrate, as well as the cooling performance and mechanisms occurring within both the pallet and the polyliner.

2. Materials and methods

2.1. Experimental studies

2.1.1. Industrial forced-air cooling

Hayward kiwifruit (*Actinidia deliciosa*), harvested in Te Puke, New Zealand, are typically packaged in a modular bulk pack (MBP). The MBP consists of a cardboard box with a folding lid at the top, with a 7 cm gap across the middle (Fig. 1a). The length, width and depth of the box are 40 cm, 30 cm and 19.5 cm, respectively. Two rectangular vents (hand vents) are located at the top of the front and back face. Hemi-spherical end vents are located at each end face. Inside the box the kiwifruit are contained within a single non-perforated polyliner bag, constructed of high density polyethylene and folded at the top. Each kiwifruit MBP holds approximately 10 kg of kiwifruit, with the exact number of fruit determined by the size grade of the fruit. For this numerical model 100 count 36 kiwifruit, weighing between 93 and 103 g, were contained in each MBP.

A standard ISO industrial pallet (1.2 × 1.0 m) holds 100 MBPs, evenly distributed into 10 layers (Fig. 1b). In commercial forced-air cooling operations in New Zealand air is usually pulled through the 1.0 m pallet face (Wilton-Jones, 2012).

2.1.2. Experimental system for validation

A laboratory-scale operation was designed and developed to simulate forced-air cooling of produce stacked a half-pallet high (5 layers, "A"–"E"; Fig. 1), while allowing precise control over the temperature and flowrate of the refrigerated air.

For validation purposes a test duct with a solid wooden base, prevented air from being pulled under the pallet (Fig. 2). Blocks of insulation where used to fill all the space around the sides of the pallet. This imposed a zero flux condition though the side walls of the pallet. An insulation block was also used to fill the remaining space between the top of the pallet and the fan system. The top and side walls of the test duct were constructed from transparent plastic polycarbonate sheets. A metal duct, containing a wire-mesh at the entrance and exit, was placed in front of the test duct to promote a uniform distribution of the airflow.

A fan pulled refrigerated air through the pallet in a temperature control room (TCR). A variable speed drive (VSD) was used to fix the flowrate across the pallet. The air flowrate was measured by the pressure drop occurring across an orifice plate located downstream of the palletized structure. For experiments the metal duct containing the wire-mesh, the insulated test duct, the orifice and fan system were all attached together (Fig. 2).