Resistance to airflow and the effects on cooling efficiency of multi-scale ventilated pome fruit packaging

By

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SUMMARY

Inadequate cooling of produce after it has been packed into ventilated packaging can result in inconsistent fruit quality. Misalignment of ventilation holes during stacking as well as the use of internal packaging, such as trays, polyliner bags and thrift bags reduces airflow distribution through the packaging. Consequently, the complex needs of maintaining the cold chain of perishable produce and the considerable variations in packaging designs have made it challenging to find an optimal ventilated package and stacking arrangement. The aims of this study were, therefore, to assess the status of ventilated packaging in the South African pome fruit industry, and to characterize the effects of package design and multi-scale packaging components on the resistance to airflow and cooling performance of apples under forced-air cooling conditions.

A survey of the pome fruit industry identified over twenty packaging designs which were grouped into eleven unique designs and further categorised into either 'display' or 'telescopic' designs. Although South African fruit industry standards recommend ventilation areas of at least 5%, the ventilation areas of package designs identified from the survey varied considerably between <1 and 11%. Furthermore, the study showed that use of stacking renders many of the ventilation holes ineffective, due to blockages from adjacent cartons.

The contribution of each component of the multi-scale packages used for handling apples was determined by analysis of pressure drop during forced-air cooling. The results showed when utilising a combination of cartons, fruit trays and plastic liner bags, the total pressure drop contribution of the cartons (8%) and fruit trays (3%) was minimal, while the use of plastic liner bags contributed 89%. However, in a carton and thrift bag packaging combination, the thrift bags contributed 66% to the pressure drop while the carton contributed 34%.

The cooling results indicated a negative correlation between the total stack ventilation area and the cooling heterogeneity. In addition, the airflow velocity was correlated positively with fruit cooling rate and negatively with total moisture loss. Fruit packed inside polyliner bags had cooling rates four times slower than fruit on trays and three times slower in thrift bags. The use of liner bags blocked the ventilation holes, thereby reducing the airflow velocity. As a result of the longer cooling times in the polyliner bags, fruit remained at higher temperatures for longer periods, resulting in up to three times more moisture loss during forced-air cooling. In addition, a temperature gradient formed due to a progressive increase in air temperature through the stack, thereby resulting in a similar gradient of moisture loss.

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This research showed that airflow velocity and distribution were the most important factors contributing to the effectiveness of fruit cooling in multi-scale packaging. From a cold chain perspective, future packaging designs should therefore focus on optimising ventilation characteristics and alignment during stacking to ensure adequate airflow. Given the contribution of internal packaging to high resistance to airflow, such packaging components should be used with caution and only when necessary to meet physiological and market requirements.

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OPSOMMING

Onvoldoende verkoeling van vars produkte nadat hulle verpak is kan lei tot wisselende vruggehalte. Wanbelyning van ventilasiegate tydens stapeling sowel as die gebruik van interne verpakking soos rakkies (eng. “trays”), poli-etileensakke en drasakkies (eng. “thrift bag”) verminder die lugverspreiding deur die verpakking. Komplekse behoeftes om bederfbare produkte in die koue ketting te behou en die aansienlike verskille in verpakkingsontwerpe het dit 'n uitdaging gemaak om 'n optimale geventileerde verpakking en stapelskikking of -rangskikking te vind. Die doelwitte van hierdie studie was dus om die status van geventileerde verpakking in die Suid-Afrikaanse kernvrugbedryf te asseseer, en die gevolge van die verpakkingsontwerp en multi-skaal verpakkingskomponente op die weerstand teen lugvloei en verkoeling van appels onder geforseerde lugverkoeling te bepaal.

‘n Opname van die kernvrugbedryf het meer as twintig verpakkingsontwerpe geïdentifiseer, wat in elf unieke ontwerpe gegroepeer is en verder getipeer word in ‘vertoon’ en ‘teleskopiese’ kartonontwerpe. Alhoewel die Suid-Afrikaanse vrugindustrie-standaarde ventilasie areas van ten minste 5% aanbeveel, het die ventilasie areas van die verpakkingsontwerpe geïdentifiseer uit die opname aansienlik gewissel tussen <1 en 11%. Verder het die studie getoon dat gebruik van stapeling baie van die ventilasiegate ondoeltreffend laat weens blokkasies veroorsaak deur aangrensende kartonne.

Die bydrae van elke komponent van die multi-skaal verpakkingskombinasies gebruik vir die hantering van appels was bepaal deur analise van die afname in lugdruk tydens geforseerde lugverkoelingskondisies. Die resultate het getoon dat wanneer ‘n kombinasie van kartonne, poli-etileensakke en vrugte plus rakkies gebruik word, die bydrae van die kartonne (8%) en vrugte plus rakkies (3%) tot die totale afname in lugdruk minimaal was, terwyl die gebruik van poli-etileensakke ‘n 89% bydrae gemaak het. In ‘n karton en drasakkie kombinasie het die drasakkies 66% bygedra tot die afname in lugdruk, terwyl die karton 34% bygedra het.

Die verkoelingsresultate het 'n negatiewe korrelasie getoon tussen die totale stapelventilasie-area en die verkoelingsheterogeniteit. Daarbenewens was die lugvloeisnelheid positief gekorreleer met vrugverkoelingstempo en negatief gekorreleer met totale vogverlies. Die verkoelingstydperk van vrugte in die poli-etileensakke was vier keer langer as die rakkie met vrugte kombinasie en drie keer langer in die drasakkies. Die poli-etileensakke het die ventilasiegate versper en dus die lugvloeisnelheid verlaag. Weens die langer verkoelingstye in die poli-etileensakke was vrugte veel

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langer aan hoër temperature blootgestel, wat uiteindelik gelei het tot drie keer meer massaverlies gedurende geforseerde lugverkoeling. Daarby het ‘n temperatuurgradiënt gevorm as gevolg van ‘n progressiewe verhoging in lugtemperatuur deur die stapel wat gelei het tot ‘n gelykstaande gradiënt van vogverlies.

Hierdie navorsing het getoon dat die lugvloeisnelheid en -verspreiding die belangrikste faktore was wat die doeltreffendheid van vrugverkoeling in multi-skaal verpakking geaffekteer het. Uit 'n koelketting perspektief moet die toekomstige verpakkingsontwerpe dus fokus op die optimalisering van ventilasie eienskappe en belyning (eng. “alignment”) tydens stapeling om voldoende lugvloei te verseker. Gegewe die bydrae van die interne verpakking tot hoë weerstand teen lugvloei, moet sulke verpakkingskomponente met omsigtigheid gebruik word en slegs wanneer dit nodig is om aan markvereistes te voldoen.

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DEDICATION

To my wife Esmari Berry, for all your encouragement and support; you are truly wonderful

To my Parents for giving me the opportunity

And to the Lord for all your blessings

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NOTE

This thesis presents a compilation of manuscripts where each chapter is an individual entity and some repetition between chapters, therefore, has been unavoidable.

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GENERAL INTRODUCTION

Packaging performs a vital role in the transportation, protection and marketing of pome fruit (apples and pears) during the cold chain (Robertson, 2006). The shipping of containerized pome fruit to overseas markets can take between 4 and 6 weeks (Henk Griessel, personal communication), and is the culmination of significant investments from farms to storage and packaging facilities. In order to produce a commercially competitive product, the cold chain system must make use of an unbroken sequence of temperature-regulated steps. Fruit should therefore receive immediate and continuous cooling from harvest to postharvest handling till it reaches the end user. However, chilled fruit can significantly increase in temperature during the unrefrigerated sorting and packaging process. Failure to maintain the correct fruit temperatures can result in accelerated senescence, reduced fruit quality and ultimately a poor fruit market value (Kader, 2002; Thompson et al., 2008).

Controlling environmental temperature and relative humidity is one of the main tools used in the fruit cold chain to impede fruit respiration and to effectively increase the storage time of fruit (Brosnan & Sun, 2001; Kader, 2002). Apple and pear fruit need to be maintained at a temperature of about -0.5°C and 90-95% relative humidity (Little & Holmes, 2000), although there are specific optimal environmental storage treatments for specific types of fruit and cultivars. In the South African export fruit industry, pome fruit packages are usually stacked onto 1.2×1.0 m pallets and stored under either refrigerated regular atmosphere or controlled atmosphere conditions. Fruit are then removed from the refrigerated storage room, put through a sorting/packaging line and then palletized. From there, the palletized stack is forced-air cooled (FAC) to remove excess field heat energy and then stored under refrigerated conditions, ready for containerization and export (Hortgro, 2013; Kader, 2002).

Ventilated corrugated fibreboard cartons are the most commonly used form of pome fruit packaging in the South African industry. Fruit are packed using several layers of multi-scale packaging inside the carton. In addition, internal packaging types such as trays, thrift bags, punnets and polyethylene liner bags may be used, depending on the market destination, to facilitate the handling, improve storage potential and enhance marketability of the produce (Robertson, 2006). The combination of packaging designs and different combinations of inner packaging (multi-scale packaging) influences the effectiveness of the FAC process (Ladaniya & Singh, 2000), specifically, the produce cooling rate and energy utilization (Ngcobo et al., 2012; Thompson et al., 2010).

High resistance to airflow has a negative influence on energy and cooling efficiency during FAC (Delele et al., 2008). Packaging designs with high resistance to airflow can significantly retard the cooling process, extend the duration of FAC and increase energy consumption. In order to reduce packaging resistance to airflow, ventilation holes are added, which increase penetration of the cold air into the stacked cartons (Opara, 2011). However, ventilation use is limited, as it reduces the mechanical strength of corrugated fibreboard cartons (Han & Park, 2007; Singh et al., 2008). Therefore, balancing the needs for cooling and energy efficiency with effective and cost-efficient mechanical design remains an on-going challenge for the fruit packaging industry.

Successful FAC should ideally generate a uniformly cooled stack of cartons, and to achieve this, airflow must therefore travel through the stack in a uniform pattern (Smale et al., 2006). Since heat transfer between the cooling medium (air) and produce occurs mainly by convection (Beukema et al., 1982; Dehghannya et al., 2011; Laguerre et al., 2006; Zou et al., 2006a), the design of ventilation holes (area, number, position and shape) should aim to deliver uniform air streams throughout stacked packages containing produce (Alvarez & Flick, 1999a, 1999b, 2007; de Castro et al., 2004, 2005a; Verboven et al., 2006; Vigneault & Goyette, 2002).

Several researchers have noted the effect of packaging materials and stacking arrangement on the resistance to airflow through different types of horticultural products, including fruit (Chau et al., 1985; Vigneault & Goyette, 2002). Current recommendations by the South African fruit export industry are to utilize a total ventilation area (TVA) of 5% (Hortgro, 2013). This practice is consistent with recommendations by Thompson et al. (2002), which considered a TVA of 5-6% for fibreboard cartons as a trade-off between cooling performance and carton mechanical strength. However, other studies have shown that a TVA of 25% is needed on plastic crate packaging under FAC conditions to minimize resistance to airflow and thus improve cooling rate (Vigneault & Goyette, 2002). Energy optimization studies using produce simulators and an airflow tunnel recommended a TVA of 8-16% on packaging during FAC based on lower energy efficiency (de Castro et al., 2005b). The researchers noted, however, that produce physiology (such as respiration rate) and multi-scale packaging design should also be taken into account before selecting a final TVA.

Numerous studies have investigated the relationship between resistance to airflow, TVA, airflow characteristics and cooling rate for different container types and produce (de Castro et al., 2004, 2005b; Pathare et al., 2012; Vigneault & Goyette, 2002; Vigneault et al., 2006). Most of the

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research, however, focused primarily on airflow through individual ventilated cartons filled with fruit layers (trays), or bulk fruit (Opara & Zou, 2007; Tanner et al., 2002a, 2002b, 2002c; Zou et al., 2006a, 2006b). Limited studies have thus examined the influence of multi-scale packaging on resistance to airflow (Ngcobo et al., 2012).

The wide range of package designs and packing formats used in the South African fruit export industry may primarily be a result of the restrictions and economical practicalities that have been imposed by the different importers, especially the major supermarket chains. The potential of improving efficiency, streamlining designs and refining packing formats through the scientific method has been left largely unexploited. For example, the use of experimentally validated computational fluid dynamic (CFD) models would allow for the near instantaneous testing of packing systems, materials, ventilation configurations, as well as a host of other variables related to package design and performance (Opara & Zou, 2007; Opara, 2011). However, before new ventilated packaging systems can be developed, an improved understanding of the efficiency of current packaging systems must be attained. The aims of this study were therefore to:

- survey the different apple and pear cartons currently available in the South African market and to quantify the ventilation characteristics;
- investigate the effects of package design on the resistance to airflow characteristics of stacked cartons with internal packaging;
- examine the effects of package design on cooling characteristics and mass loss of fruit.

In Paper 1, a detailed survey on the different package designs used for handling pome fruit was conducted in the fruit growing areas in the Western Cape of South Africa. Each package design was characterised geometrically based on physical dimensions, vent number, size and shape. Total vent area of each package design was calculated. Based on this survey, three of the most frequently used types of ventilated package design for postharvest handling of pome fruit (Mark 4, Mark 6 and Mark 9) were selected for the packaging performance characterisations reported in Paper 2 and 3. In both studies, each package design contained one or more internal packaging (trays in layers containing fruit, polyliner bags and thrift bags), which is referred to as multi-scale packaging. Specifically, Paper 2 reports the results of the investigation on resistance to airflow patterns of multi-scale packages stacked onto pallets, while Paper 3 contains the findings of experimental studies on spatial variation of fruit mass loss, cooling rate and cooling heterogeneity within the

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stacks of different package designs. Forced-air cooling equipment which operates under a range of controlled airflow velocities and pressure drops was constructed and used for this study.

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LITERATURE REVIEW: Developments in ventilated packaging used for handling fresh fruit in the cold chain

Nomenclature

a	resistance coefficient, kg.s$^{(b\text{-}2)}$.m$^{-(b+2)}$
APD	total pressure drop across produce and container, Pa
b	resistance exponent
C	cooling coefficients, s^{-1}
c	3600 kJ/kWh
C_p	products specific heat above freezing point, 4.19 kJ.kg^{-1}.K^{-1}
c_p	specific heat of produce, kJ.kg^{-1}.°K^{-1}
D_{air}	airflow rate, m^3.s^{-1}
E	energy consumed to operate the facility, kWh/month
E_l	total thermal energy removed, kJ
EAR	energy added ratio
EC	energy coefficient, kJ heat removed/kJ of electricity used
EE	electrical energy imputed, kJ
E_p	produce field heat, kJ
E_r	respiration heat, kJ
E_v	ventilation energy, kJ
HI	heterogeneity Index
J	lag factor
K	Darcy permeability, m^2
M	mass of the product cooled per month, kg/month
m	mass of produce, kg
n	number of samples taken
P	pressure, Pa
$Q_{r,produce}$	respiration rate of produce, mW.kg^{-1}
RH	relative humidity of the air around the fruit, %
S	seven-eighths cooling time, s
T	product temperature at time t, °C
t	typical cooling time for cooling cycle, hour
T_a	cooling medium temperature, °C
T_c	products average representative temperature in a stack layer, °C
T_f	products final temperature after cooling, °C
T_i	initial product temperature, °C
T_{max}	maximum temperature, °C
T_{min}	minimum temperature, °C

Tp	instantaneous pulp temperature at specific position, °C
$\overline{T_p}$	mean instantaneous pulp temperature over all positions, °C
t_s	operating time, s
u	velocity vector, $m.s^{-1}$
VPD	vapour pressure deficit, Pa
V_p	vapour pressure at given temperature, Pa
β	Forchheimer drag coefficient, $m.s^{-1}$
η_m	motor efficiency
θ	dimensionless temperature
ρ	density, $kg.m^{-3}$
φ	heterogeneity factor
μ	dynamic viscosity, Pa.s

1. Introduction

Packaging performs an important and dynamic role in the postharvest handling of fruit and other horticultural produce. Packaging not only protects fruit from the physical stresses of handling and bulk transport (Lewis et al., 2007), but can also be used to modify the environmental conditions around the fruit (Geeson et al., 1994; Sandhya, 2010). In addition, packaging can improve the marketability of the produce when traded at the retailer (Robertson, 2006).

A great deal of interest and recent research has been published on improving the design of packaging for the purposes of increasing cold chain efficiency and reducing unnecessary wastage (Pathare et al., 2012). For example, it has been estimated that annual worldwide postharvest losses reach up to 40% and over 50% for fruit and vegetables (Gustavsson et al., 2011). In addition, it has been estimated (FAO, 2009) that the world population will increase from 7 billion in 2012 to 9.2 billion by 2050. These current and imminent pressures on the global food industry indicates that significant improvements in postharvest technologies, including packaging, will be necessary to reduce food loses and waste to meet the food demands of a growing population.

Once fruit has been packaged and palletised, rapid cooling to optimal temperature is required to maintain quality and extend storage life. Static cooling in the cold room is generally insufficient due to poor airflow circulation between the cold room air and the packaging. Forced-air cooling (FAC) thus makes use of fans to produce a pressure drop in front of the stack in order to exhaust cold air through the stacked packaging, resulting in an increased heat exchange rate (Brosnan & Sun, 2001; Talbot & Fletcher, 1993; Thompson et al., 2008).

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Temperature is one of the most important factors affecting fruit quality and postharvest storage life. This is due to the significant influence that temperature has on the physiological and metabolic reactions occurring in the fruit after harvest (Ravindra & Goswami, 2008). High temperatures consequently result in increased rates of respiration, which accelerates the onset of fruit senescence and deterioration of fruit quality (Caleb et al., 2012; Taiz & Zeiger, 2010).

The effects of packaging on fruit cooling are influenced by several factors, many of which interact with one another. These factors include the geometrical design of the packaging, ventilation design, packaging stacking arrangement, internal packaging, multi-scale packaging, fruit geometry, fruit respiration rate, packaging porosity, cooling system used and the thermal properties of the packaging materials (Delele et al., 2008; Opara, 2011; Pathare et al., 2012; Teruel et al., 2011; Thompson et al., 2008). These factors affect fruit quality by influencing resistance to airflow, pressure drop, airflow rates, airflow distribution, energy efficiency and heat and mass transfer rates (Alvarez & Flick, 2007; de Castro et al., 2005a; Ferrua & Singh, 2009; Güemes et al., 1989; Nahor et al., 2005; Opara & Zou, 2007).

The objective of this review is to examine the effects of packaging on heat transfer and fruit quality during precooling and storage. In addition, an overview of the functions of packaging in the cold chain is presented, including a discussion on types of packaging used in the fruit industry, the use of corrugated fibreboard, and the influence of multi-scale packaging on airflow and cooling. The review also highlights the importance of developments in ventilation design as well as methods for the evaluation of packaging performance.

2. Functions of packaging and effects of packaging on fruit quality

The term quality in the fruit industry is relatively abstract and can only be quantified when the needs and demands of the consumer are considered. Horticultural produce are often measured by certain perceptible (firmness, colour, flavour) quality attributes and imperceptible (genetically modified, safety, organic, cultural factors) attributes (Opara, 2009).

According to Shewfelt & Prussia (2009), quality can be divided into intrinsic and extrinsic factors. Intrinsic factors are measurable, such as texture, colour, shelf life period and nutritional value and these values can be measured and used by a consumer to describe the quality of fruit. Extrinsic factors include those related directly to the product, such as method of handling, pre-harvest treatments, packaging materials used and biotechnological methods applied in producing and handling the product. The combination of intrinsic and extrinsic factors is what makes the product valuable to the customer.

Horticultural produce such as fruit, vegetables and flowers are living entities that continue to respire and transpire after harvest. They undergo not only physiological changes, but must also resist pathological threats during storage. The physiological processes of harvested produce require energy and this is mainly attained from energy stores inside the produce (Thompson et al., 2008). Reducing fruit respiration is one method of inhibiting quality degradation and thus extending the duration of acceptable quality (Ravindra & Goswami, 2008). This becomes critically important during export when pome fruit must reach a distant destination by way of extended shipping.

Respiration occurs in fresh produce through a complex series of reactions that make use of oxygen in the environment and carbohydrates inside the fruit, such as sugar and starch. The net products of respiration are carbon dioxide and water. Restriction of oxygen to levels below the anaerobic compensation point results in anaerobic fermentation, which will often have deleterious effects on product quality (Taiz & Zeiger, 2010). The chemical reactions of respiration are regulated by enzymes and therefore follow Van't Hoff's rule, which states that for every 10°C increase in temperature, product respiration rate increases by a factor of two to three (Brosnan & Sun, 2001; Salisbury & Ross, 1992). To emphasise the exponential relationship between respiration and temperature, table grapes will deteriorate more in one hour at 30°C, than they would have for an entire day at 4°C or for almost a week at 0°C (Nelson, 1985). The Van't Hoff's rule also explains why fruit need to be cooled quickly to an optimal temperature and maintained during postharvest handling. The maintenance of ideal fruit temperatures throughout the postharvest handling chain is referred to as the 'cold chain' (Brecht et al., 2003). Better understanding of the ideal cold chain treatment regime for fruit under a specific supply chain will assist in better postharvest management and marketing of fruit, especially for long distant export (Franck et al., 2007).

2.1 Generalised functions of packaging

Convenience, communication, containment and protection are the four factors that successful fruit packaging should implement (Robertson, 2006). The first factor, convenience refers to the mobility and accessibility that the packaging offers the fruit industry during the cold chain. A packaging's convenience is largely dependent on the area of origin, the cold chain, its handling requirements and the produces postharvest requirements (Cortez et al., 2002). The communication factor refers to the information and marketing aspects that the packaging conveys to the fruit cold

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chain industry as well as to the consumer. Very often there are legal requirements for wholesale produce distributers to communicate certain information concerning the products origin, type and grade to be displayed on the outside of the packaging (Thompson, 2003). The correct implementation of communication, improves the produces' presentation. This can raise its market value or assist in the sale of the produce. In comparison, containment highlights the need for packaging to increase the fruit number per volume of space (density). For example, palletised stacks of pome fruit are used to better exploit the available space in shipping containers, which in turn is used to better exploit the space of a cargo ship (Ladaniya, 2008; Thompson, 2003). The final and arguably most challenging packaging factor is protection, which refers to the packaging's ability to protect fruit from its environment. An important environmental attribute is mechanical damage, which needs to be resisted by the packaging. In addition, the packaging needs to protect the produce from excessive exposure to pathogens and infection (Thompson, 2003). As many pathogens grow poorly at low temperatures, packaging should therefore facilitate good temperature control. The regulation of temperature and duration in storage or transport conditions also affects the biochemical and metabolic changes. These changes include the concentration of volatiles, acids, sugars and pigments in the fruit and can result in fluctuations in firmness and qualities such as texture or colour (Ladaniya, 2008; Thompson, 2003).

Many authors have demonstrated that ventilation openings in packaging are imperative for cooling of produce. It has also been shown that increasing the velocity of the airflow through the vents of the packaging will decrease cooling time (Dehghannya et al., 2011; Lindsay et al., 1983; Pathare et al., 2012). This makes carton ventilation (section 3.3) essential to produce quality preservation during storage and transit.

Export through shipping of pome fruit is a cost intensive process and it is vital that the fruit are packed with a high fruit to packaging volume ratio. Simultaneously, the fruit should ideally not be exposed to conditions that will cause mechanical damage, mass loss or microbial decay (Kader, 2002; Little & Holmes, 2000; Maguire et al., 2001). Packaging also needs to provide sufficient mechanical strength, in order to allow stacking and movement during transit, while still offering ventilation to maintain an ideal internal environment around the produce. Furthermore, packaging should not only increase the attractiveness of the fruit, but should also maintain the fruit in a clean and hygienic environment. For these reasons, fruit cannot be shipped or transported effectively if they are unpackaged.

2.2 Effects of packaging on fruit quality

2.2.1 Mass Loss

Apples and pears experience mass loss through two processes, namely moisture loss and respiration. Respiration was discussed early in this text and is closely linked to the metabolic rate and therefore the fruit temperature. Three factors determine the rate of moisture loss. First, the surface area of the produce, for example leafy vegetables will wilt and shrivel faster than larger, more bulky produce. Second, the fruit barrier properties, which dictate the water vapour permeance of the fruit and are strongly influenced by the fruit cuticle. The third influencing factor is the driving force and is defined by the physical conditions of the environment around the fruit (Maguire et al., 2001).

Symptoms of moisture loss can result in several forms of physiological damage such as, wilting, shrivel, loss of taste as well as a reduced resistance to decay. In pome fruit, mass loss is generally considered unacceptable when more than 4% has been lost from the fruit. At this point, disorders are often prevalent and the fruit will decrease in market value (Kader, 2002; Little & Holmes, 2000).

Shrivel is the primary mass loss related disorder observed in pome fruit, is a result of moisture loss in the fruit and is frequently visible after 2.5 and 3.5% moisture loss has occurred in apples and pears, respectively (Kader, 2002; Little & Holmes, 2000). The physiological process behind shrivel starts with a decrease in cell turgor pressure due to the absent water. This is followed by cell shrinkage and a decrease in fruit volume (Kader, 2002; Nguyen et al., 2007). The reduction in water also results in weakening of cells, which can increase susceptibility to pathogens. Infection can induce stress symptoms in the produce, leading to increased ethylene production, which in turn can result in accelerated senescence, chlorophyll loss and an increase in a yellow colouration in some fruit (Little & Holmes, 2000; Taiz & Zeiger, 2010).

Rate of moisture loss can be estimated if the transpiration coefficient, the difference in temperature between the air and the product and the humidity in the air are known. The difference in temperature and humidity between the air and the product is combined into a value called the vapour pressure deficit (VPD). The high percentage of water in the fruit cells saturates the air in the openings of the fruit with moisture, resulting in a 100% relative humidity (RH) value. The VPD can therefore be calculated using equation 1 (Nelson, 1978).

$$VPD = v_p \times \frac{100 - RH}{100} \qquad 1$$

Packaging plays a significant role in the rate of moisture loss in fruit, as it can interfere with air movement. Moisture generally moves from the fruit into the boundary layer around the fruit at a rate dictated by the VPD. However, the thickness of the boundary layer is inversely related to the air velocity (Nobel, 1975). Fruit in packaging with more ventilation will therefore have an increased airflow velocity and consequently a higher rate of moisture loss, if airflow is at a low relative humidity. It was therefore recommended by Thompson et al. (2008), that under these circumstances, minimal airflow velocities be used during FAC processes. Beukema et al. (1982) and Maguire et al. (2001) showed how airflow affects the rate of moisture loss. Their results showed how a low airflow velocity partially substitutes the boundary layer around the fruit. However, after a specific velocity, the airflow fully replaces the boundary layer, thereby maximizing the rate of mass loss transfer possible.

Packaging with plastic bags liners (polyliners) reduces the airflow rate at the fruit to negligible velocities. The fruit therefore humidify the air in the polyliner, to produce a minimal VPD. Polyliners are frequently used in the pome industry to reduce fruit moisture loss during storage (Kader, 2002). However polyliners also increase the resistance to airflow in stacked cartons during FAC and consequently reduce fruit cooling rate (Lindsay et al., 1975; Ngcobo, 2013). To reduce the moisture loss, fruit need to be cooled to the recommended temperature as fast as possible after harvest (Brosnan & Sun, 2001). Pome fruit are often kept at 95% RH, although produce such as citrus, which lose moisture at slower rates, can be kept at 90% RH to reduce the risk of decay (Thompson et al., 2008).

In addition to the packaging, the temperature and RH of airflow in FAC rooms can also play a significant role in the fruit mass loss rate (Clewer & Scarisbrick, 2001). The airflow RH is dependent on the temperature and atmospheric pressure in the cold room. As the pressure generally stays constant, airflow temperature is the most manageable factor determining moisture absorption from the fruit. Figure 1 shows how airflow increases and decreases in RH, due to changes in temperature, which affects the airs capacity to absorb or condense water on the fruit. For example, if high RH airflow increases in temperature due to exposure to warm fruit, the RH will decrease and moisture may be absorbed from the fruit (de Castro et al., 2005b; Nelson, 1978).

Chourasia & Goswami (2007) created a CFD simulation to model moisture loss in potatoes. They noted that during steady state airflow, areas that were receiving a low airflow distribution due to the packing arrangement developed a lower RH value due to increases in airflow temperature, as a result of the airs' contact with warmer potatoes. In other words, 'dead airflow zones' that are excluded from sufficient distribution of airflow, under conditions of continuous non-fluctuating airflow rates, caused potatoes to lose significantly more moisture. Literature therefore also suggests that direct airflow to fruit can increase moisture loss (Maguire et al., 2001). However, a certain airflow velocity is required when utilising packaging, in order to reduce the presence of dead airflow zones (Chourasia & Goswami, 2007; de Castro et al., 2005c). The moisture loss rate is therefore determined by a combination of the temperature, velocity, turbulence and distribution of the airflow (de Castro et al., 2004a, 2005c).

2.2.2 Decay

Organisms that cause decay grow best at temperatures often found during harvest. It is therefore vital to rapidly cool the product directly after harvest to minimise decay development. Table 1 lists the most common post-harvest pathogens found in fruit (Thompson et al., 2008). In pears, blue mould (Table 1) can be listed as one of the most prolific pathogenic groups. Blue moulds usually enter the fruit through damaged flesh, but can also enter the fruit through a lenticel opening. Susceptibility increases with an increase in maturity and also in fruit that have been weakened from long storage periods (Beattie et al., 1990). Grey mould (Table 1) is commonly found in decaying pears and apples and generally develops faster in cold storage than blue moulds (Beattie et al., 1990). The fungus spores commonly infect the fruit when spores are splashed onto them from decaying or decayed plant matter. The infection enters the fruit through breaks in the skin, through the calyx or through the stalk.

Packaging can perform an important role in the prevention of microbial decay. To illustrate, van der Sman et al. (1996) investigated the effect of five different types of packaging using differing temperature treatments. The authors identified *grey mould* as highly infectious fungi in rose flowers, which commonly develop during export in cartons. The authors noted that the moisture condensation on the flowers was a result of fluctuation in temperature, which promoted the germination of spores and finally the infection of the flowers. van der Sman et al. (1996) concluded that temperature fluctuations should be carefully regulated during cold storage, to reduce condensation on the product. They also concluded that the design of the carton should allow moisture to evaporate faster and that the size and placement of the ventilation openings is crucial in removing ‘developing moisture’ inside the package.

2.2.3 Mechanical Damage

Mechanical damage significantly reduces fruit storage and shelf life. This is because the damage can provide a point of entry to microorganisms, which cause decay. In addition, damage to fruit activates stress reactions, such as the production of ethylene, which accelerates the onset of senescence. It is therefore crucial that packaging protects fruit from all forms of damage.

There are several types of mechanical damage that packaging must protect fruit from. Impact bruises can occur when pallets, bins and boxes are dropped or bounced. Compression bruises can occur when packaging is overfilled or when they are incorrectly packed and stacked. Vibrational or abrasion damage is frequently observed when fruit are in transit on roads and particularly on rough gravel roads. Vibrations result in fruit rubbing against each other or the packaging (Acican et al., 2007; Berardinelli et al., 2005; Kader, 2002; Thompson et al., 2008). Cold fruit are more susceptible to compression and impact damage than warm fruit, while cold fruit are less susceptible to vibrational or abrasion damage (Martínez-Romero et al., 2003; Thompson et al., 2008). Fruit should therefore be transported and shipped at the lowest possible temperature, while reducing any movement that may cause impact and compression damage (Thompson et al., 2008).

The geometrical design of packaging has a significant effect on the degree of protection given to the packed fruit. For example, Holt & Schoorl (1984) assessed the protection afforded by telescopic cartons, plastic crates and wooden boxes to apples when packed using varying pack-densities and dropped from 0.5 metres. The results showed that the packaging that absorbed the largest amount of kinetic energy provided the best protection, as less energy from the drop was available to damage the apples. The study concluded that the telescopic carton, when packed with apple trays, offered the best protection to the fruit.

Internal packaging can also play a significant role in mechanical damage protection. For example Jarimopas et al. (2008) observed that sweet tamarind stored in corrugated cartons had a minimal total produce loss of 33.9% and a maximum loss of 57.3%. To combat this problem, the authors proposed new packaging, which included a packaging sleeve and a specific ratio of foam balls to the product. A 16-20% mechanical damage reduction was observed when the sweet tamarinds were slotted into the packaging.

Some of the most important factors affecting fruit quality are therefore mass loss, mechanical damage and decay. These factors can be significantly influenced or even regulated by carefully controlling the temperature and humidity of the fruit during refrigeration. However, packaging significantly affects the degree of environmental control, due to its effect on airflow as well as heat and mass transfer. The design and usage of packaging is therefore critical if fruit quality preservation is going be adequately managed.

3. Developments in packaging of fresh horticultural produce

3.1 Types of packaging

There are three broad general levels of multi-scale packaging in horticultural produce. The packaging that is presented to the consumer is considered the first level, for example pre-packed apple thrift bags or punnet containers. The second level is packaging used in the transport of fruit from its source of production to the retailer. Some examples include corrugated fibreboard cartons, wooden crates and plastic crates. The third level of packaging occurs at a shipping and cargo container level. Cartons are stacked on a pallet, strapped together and transported over relatively large distances. The type of packaging used is therefore largely dependent on the location, quality of produce, and available resources of the producer (Thompson, 2003).

Many farmers are unable to make use of proper packaging due to lack of resources. This is common in the industries of developing countries and can result in a higher incidence of postharvest losses. Unpackaged produce are generally exposed to considerable amounts of mechanical injury and require more labour as the fruit has to be handled individually. Low quality produce will often be stacked and then transported on the back of a truck. For example, banana bunches are frequently transported by hand or with a trolley system using a cable way (Thompson, 2003). Many small scale farmers also make use of second-hand packaging. However, the quality of the produce can be affected by the hygienic state of the packaging. Second-hand packaging must therefore be hygienically clean, especially if they are being used for produce that will be consumed unwashed or uncooked (Thompson, 2003).

Plastic crates are a reusable and extremely sturdy second level packaging type. Although production costs are high, the plastic used in the process is relatively inexpensive. Their use is best suited to circumstances where large numbers of reusable crates are required. Plastic crates or trays are often made in a collapsible form, making it possible to return and reuse them after cleaning.

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Once collapsed, some crates will only occupy 25% of the space they originally occupied when full. Good crates have smooth surfaces, which can reduce the abrasion damage to the produce during transport (Ladaniya, 2008; Thompson, 2003).

The use of bamboo baskets is another form of second level packaging. They are common in India and their production provides a constant revenue to the local population as well as it being an eco-friendly alternative to fibreboard cartons. However, due to the geometrical design, the baskets cannot be successfully stacked or be used for long distance transport in trucks (Ladaniya, 2008). Paper, polyethylene film, sisal, hessian or woven polypropylene, are some of the materials that can be used to make bags and sacks. The volume packed into a bag is crucial, as too much produce may cause crushing within the bag. Good ventilation is a significant advantage of woven sacks, but the fruit are susceptible to impact damage during transit and other forms of mechanical injury.

Wooden boxes and crates are an additional form of second level packaging and are mostly made from readily available wood in the area of fruit production. The rough texture of the wood may cause damage to the fruit. For this reason, fruit is often afforded protection using papers and other cost effective materials. The wood crates will often break and some producers will wrap rope around the box to increase its strength. Another major obstacle is moisture absorption into the wood, which can affect the environment of the stored produce, possibly increasing the incidence of pathological diseases. It is common for the wooden boxes to be made by hand and as a result, they will often vary in size and shape, making stacking problematic. Corrugated fibreboard cartons are therefore generally preferred to wooden crates, as corrugated fibreboard cartons afford more protection to the fruit than wooden crates do, when exposed to drops and when resisting abrasion damage (Acican et al., 2007; Holt & Schoorl, 1984). For these reasons, restrictions have been imposed by some international agricultural standards, which limit the use of reusable wood containers (Vigneault et al., 2006).

Regardless of the design, packaging must ensure a hygienic environment, secure, easy handling and adequate venting for FAC (Vigneault et al., 2006). Reusable packaging can be used for many types of produce and should be designed accordingly. Ideally, packaging should be able to accommodate a variety of different produce types (Vigneault & Goyette, 2002). For instance, corrugated fibreboard cartons are currently the most common form of packaging used in fruit export (Kader, 2002).

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3.2 Corrugated fibreboard

Corrugated fibreboard makes use of two or more layers of a paperboard or fibreboard material, one or more of which uses a fluted corrugated structure (Figure 2). The fluting structure adds additional strength to the board, while minimising paper usage and reducing total mass (Twede & Selke, 2005). Corrugated fibreboard is susceptible to absorbing moisture from high RH environments and will often lose structural integrity with the absorption of excessive moisture (Dimitrov & Heydenrych, 2009). Liner bags can be ideal in these situations as they isolate the produce and the high RH environment from the fibreboard carton (Ladaniya, 2008; Thompson et al., 2008). Some fruit industries will occasionally treat the cartons with wax layers when used in high moisture situations (Thompson et al., 2008).

In the USA, over 90% of the packaging that is used in fruit transport is corrugated fibreboard or fibreboard (Little & Holmes, 2000). Fibreboard allows versatility in design, marketing, recycling and is often more economical than other materials, which makes it an ideal material for packaging. Corrugated cartons are handled predominantly at some point by hand. Hand-holes may therefore be beneficial in reducing handling damage, as well as for ventilation of air into and out of the carton. However, openings also reduce the structural integrity of the carton and can result in structural failure. Corrugated cartons have to contend with humidity, shocks, vibrations and other mechanical damage (Frank, 2013). Creep is a phenomenon that is prevalent in metallic and plastic materials, where the material will warp or distort at certain temperature ranges. Unlike metal and plastic, corrugated boxes only distort when exposed to certain moisture conditions over a period of time (Frank, 2013; Singh et al., 2008). Time and humidity therefore play an important combined role in the strength of a carton, as these factors determine the extent of creep in the carton wall (Coffin, 2005; Frank, 2013). Both factors are affected by the geometry and material properties of a carton, which in part determine how and when a carton will fail. Variable environmental conditions, which may cause condensation on the carton can accelerate the creep process, due to the degradative effects of the water on the fibre bond interactions (Frank, 2013). The shape and design of corrugated fibreboard packaging are consequently important aspects, which are dependent on the cut and folding technique used.

The international fibreboard class code uses a four digit numerical code to describe differing folding carton designs (FEFCO & ESBO, 2007). An additional code is added to the first, when a modification to the design is made. These codes are accepted and recognised in many groups and locations in the packaging industry worldwide. The international fibreboard class code lists many of the existing carton or box designs, grading for slotting, folding methods and flute directions. One example is a telescopic carton design (Telescope-type/0320 category), which forms an interlocking two piece carton and slides over one another to close (Figure 3). Another is the display carton design (Ready-glued/0773 category), which makes use of a single carton (Figure 4) with a built in display window (FEFCO & ESBO, 2007). All these factors influence the strength of the cartons and therefore the produces protection (Pathare et al., 2012).

Carton strength can be measured using several factors. Compression strength is often used as a description of a carton's mechanical strength and is measured by the momentary force used to crush or cause a carton to fail. Another important factor is stacking strength, which is defined as the maximum top load placed above it by other cartons, over an extended period of time (Frank, 2013). Stacking strength is an essential measurement, as many cartons fail in the fruit cold chain when in a stacked configuration, after being in storage for an extended duration (Skidmore, 1962).

3.3 Developments in packaging vent design

Fruit cooling after harvest and the sorting or packing process is essential for the purposes of fruit quality extension. This is frequently achieved through the use of FAC (Beukema et al., 1982; Hortgro, 2013; Talbot & Fletcher, 1993). However, the presence of packaging creates a barrier between the cold air and the fruit. Ventilation openings are therefore added to improve airflow penetration into the packaging. These openings must be carefully configured, as they also negatively influence the mechanical strength of the packaging (Émond & Vigneault, 1998).

3.3.1 Ventilation opening effect on strength

As discussed in the previous paragraph, a direct correlation is observed between the size of a ventilation opening and the mechanical strength of a carton. To compensate, stronger materials can be used or the packaging walls can be thickened (Jinkarn et al., 2006). Singh et al. (2008) also observed that there is a linear relationship between the loss of strength and total ventilated area (TVA). However, this relationship of percentage TVA does not stay linear with the loss of strength in the carton after 40%. The authors concluded that the addition of hand or ventilation openings can cause between 20 to 50% loss of strength in a single wall corrugated carton.

Singh et al. (2008) noted that vertical openings which are rectangular or parallelograms will reduce the cartons mechanical strength to a lesser extent than circular openings. However, this was in contradiction to the observations of Jinkarn et al. (2006), who concluded that circular openings were the least degradative to carton mechanical strength. Han & Park (2007) used experimental and finite element analysis to study ventilation openings and concluded that vertical oblong vent openings were the best option when considering mechanical strength. According to Frank (2013), the large standard errors in Singh et al. (2008) results, gives more credibility to Jinkarn et al. (2006) and Han & Park (2007) conclusions. Studies also showed that openings should be placed nearest to the centre of carton walls and farthest from folding scores, so as to minimise loss of mechanical strength (Han & Park, 2007; Jinkarn et al., 2006).

Although ventilation openings decrease mechanical strength, they are necessary for cooling. A cautious balance between ventilation that is large enough to cool the fruit effectively, but not large enough to impair structural integrity should be utilised. A recommended trade-off for cooling performance and strength is thus 5-6% TVA (Baird et al., 1988; Thompson et al., 2002).

3.3.2 Ventilation configurations effect on airflow and cooling

The effect of packaging's ventilation on airflow can result in differences in air distribution, airflow velocity and turbulence. These airflow patterns result in different degrees of heat transfer rates in packaging. For example, if fruit are being cooled to 0°C using sub-zero airflow, a heterogeneous cooling pattern could cause produce to freeze in some areas, while other areas remain relatively uncooled (Alvarez & Flick, 1999a; Alvarez et al., 2003; Pathare et al., 2012). Moisture loss is another challenge in heterogeneous airflow. Some portions of the packaging experience more air movement and turbulence than other areas (Alvarez & Flick, 1999b). This results in moisture loss and spatial variation of cooling in the fruit. For instance, up to 50% more moisture loss can occur between a hot and cold area (Alvarez & Trystram, 1995). Section 2.2.1 contains further discussion with regard to the relationship between mass loss and airflow.

The interactions between the size, shape, position and number of ventilation holes are the primary factors that determine the airflow distribution during the FAC process. The TVA should therefore be large enough to not restrict airflow. However, ventilation configuration is generally correlated to the mechanical strength of the carton and should be designed accordingly (Thompson et al., 2002; Vigneault & Goyette, 2002).

Number of vent holes

The number of ventilation holes in packaging can significantly influence uniformity of airflow during FAC. Numerous holes in the packaging wall allow airflow to evenly distribute into multiple airflow streams, which may result in homogeneous airflow patterns and thus homogeneous cooling. However, the ventilation area, airflow rate, position of the holes and internal packaging significantly affect the uniformity of cooling (Alvarez & Flick, 1999b; de Castro et al., 2004a, 2005a; Vigneault & Goyette, 2002). The situational configuration of the packaging and packed produce therefore also plays a determining role in the effectiveness of using multiple ventilation openings (Dehghannya et al., 2012). For example, Vigneault et al. (2006) observed that in wooden crates with horizontal ventilation slits, the ventilation number did not significantly influence ventilation effectiveness. Conversely however, de Castro et al. (2005c) demonstrated that the use of more ventilation openings increased the rate of airflow and reduced pressure drop, when making use of round holes and a ball matrix. The position of the ventilation holes therefore influences the effect that ventilation number will have on airflow and cooling.

Ventilation position

Ventilation holes would ideally cover most of a packaging walls, as cooling homogeneity is influenced by the airflow distribution in the packaging (Smale et al., 2006), which is in turn influenced by the ventilation positions (Faubion & Kader, 1997). However, this is rarely possible in packaging such as corrugated fibreboard containers, which are structurally impaired by the addition of open areas (Thompson et al., 2002). The limited ventilation configuration should therefore be carefully determined by the factors in the packaging, which also affect airflow distribution (Kader, 2002).

One of the factors that may affect cooling under non-FAC conditions is the effect of gravity force. Vigneault et al. (2005a) determined that the position of ventilation openings interacted with the gravity force effect on cooled air. Cold air that entered a top vent would sink downward as it was denser than the warmer air in the carton, while cold air that entered a bottom vent would stay low until it increased in temperature due to its contact with warm produce, at which point it rises up. They observed that the rate of airflow determined which vent, bottom or top, played a dominant role in cooling. The authors also noted that the gravity effect played a more significant role when dealing with partially open packaging packed with horticultural produce under low airflow rates.

The position of the ventilation has a significant effect on the airflow turbulence inside the packaging. Alvarez & Flick (1999a) examined the effect of spherical produce in a plastic crate with perforated centre walls and non-perforated corners. The researchers observed that turbulence was high (50%) in the non-perforated corners and between 15-40% at the perforated centre walls. Furthermore, the air velocity was 3 to 4 times lower in the corners than in the perforated centre walls. This observation was noted as a back-mixing effect in the "dead airflow zones". Alvarez & Flick (1999a) also noted that turbulence was higher in the area furthest from the airflow source around the spherical objects (simulated fruit), than in the area just in front (upstream). They concluded that non-perforated walls of packaging should be kept as close together as possible to promote uniform airflow and therefore uniform cooling.

In addition, the position of the ventilation and the resulting airflow distribution also has an effect on the rate of heat transfer in different areas of the packaging. Alvarez & Flick (1999b) found that the highest heterogeneity was in the horizontal direction along the path of the air steam. They also found that there was a difference of 40% in the heat transfer coefficient between the first and fourth rows (of seven rows), after which the heat transfer coefficient in the subsequent rows became constant. Another pattern of heat transfer heterogeneity was found in the vertical plane, perpendicular to the air steam. Alvarez & Flick (1999b) observed that the produce near the side walls were 10% lower in heat transfer coefficient than produce in other areas, which was most likely related to the high turbulence and low air velocity along the sides of the packaging. The researchers concluded that air velocities as well as turbulence are highly important factors in heat transfer rates and therefore cooling patterns.

Ventilated area

In addition to the position of the ventilation, the size of the ventilation and airflow rate also plays a significant role in airflow distribution and cooling. Dehghannya et al. (2012) showed that unless the correct ventilation positioning is used, increasing the ventilation size might not improve airflow uniformity and cooling rate. Collaboration between these factors is therefore necessary. For example, using a CFD model, Tutar et al. (2009) determined that increasing TVA along the top or bottom and side walls of packaging, improved airflow rate and thus allowed for better airflow circulation. However, the researchers noted that increasing the ventilation area (10% for top or bottom and 20% for sides) did not significantly affect airflow circulation until a certain TVA was reached. This is due to air turbulence only arising after a certain airflow velocity (3 $m.s^{-1}$), which results in improved heat transfer rates. In addition, the airflows effect on the boundary layer around the produce may also have played a role in the rate of heat transfer (Maguire et al., 2001; Tutar et al., 2009).

Tutar et al. (2009) also investigated the effects of airflow patterns and heat transfer inside stacked ventilated packaging. It was determined that the airflow rates contributed significantly more to the rate of cooling than the size of the open areas. Higher air velocities caused stronger small-scale eddies, which produced airflow turbulence inside the packaging, resulting in increased rates of heat transfer. Similar observations were made by de Castro et al. (2005a), who showed that at low airflow rates ($\leq 2 L.s^{-1}kg^{-1}$), the major determinant to cooling rate was the TVA, while at higher flow rates ($3\text{-}4 L.s^{-1}kg^{-1}$), the position of the contents in the packaging was the main determinant to cooling rate.

The TVA of ventilation holes directly influences the rate of airflow under a consistent pressure drop (Chau et al., 1985; Vigneault & Goyette, 2002). Under low airflow rates, airflow exiting a packaging may have a significantly higher temperature than the airflow entering (de Castro et al., 2005a). This is due to the air having more time to exchange heat with the produce at the front, before it reaches the back of the packaging. The results indicate airflow should be maintained above a specific velocity to facilitate efficient heat transfer rates. This would enable the produce packed downwind of the airflow, to be exposed to sufficiently cold temperatures (Baird et al., 1988; de Castro et al., 2005c; Xu & Burfoot, 1999). A similar situation is present in stacked packaging, which has a significantly larger bed depth (Delele et al., 2008).

Misalignment of ventilation in stacked packaging may result in reduced airflow rates and consequently heterogeneous cooling rates throughout the stack (Smale, 2004). Ventilation holes thus need to be positioned in such a way that the stacking configuration aligns the ventilation holes of the packaging (de Castro et al., 2005a; Ngcobo, 2013; Shewfelt & Prussia, 2009; Thompson et al., 2008). Thompson et al. (2002) suggested a ventilation opening configuration as indicated in Figure 5, which would allow for improved ventilation alignment, while not compromising carton mechanical strength. The distribution of the produce and internal packaging inside a container can also significantly affect ventilation position (Ngcobo et al., 2012).

The discussions above indicate that a combination of the position and number of ventilation holes determines the airflow distribution and velocity (Dehghannya et al., 2012). The respiration rate of the produce also determines at what rate heat needs to be removed from the produce. Thus, the cooling of high respiration fruit may require a larger airflow velocity or larger vent size. This will reduce not only the additional heat from respiration, but also improve the energy efficiency in the cooling process (Vigneault et al., 2006).

Many studies have made recommendations with regard to the TVA needed on a packaging. Baird et al. (1988) showed that increasing the size of the vents in corrugated fibreboard boxes from 2 to 6%, resulted in an increased airflow rate in the stacked packaging. de Castro et al. (2005a) investigated the effect of only increasing the TVA and observed that the airflow uniformity, cooling rate and pressure drop improved with an increase in vent size.

The TVA of a packaging is important in FAC and therefore necessary for efficient cooling to occur (Vigneault & Goyette, 2002). Vigneault & Goyette (2002) demonstrated that packaging requires a TVA of at least 25% to achieve maximum efficiency, which is ideal in stronger plastic cartons. These results are similar to earlier results by Haas et al. (1976), who observed that when there is roughly 27% TVA in a carton without internal packaging, the largest contributor to pressure drop will be the produce. Packaging should thus ideally have about 25% ventilation to limit energy wastage. More recent research by de Castro et al. (2004a), reported that if a packaging’s structural strength is taken into consideration, the recommended TVA is 14% when considering energy efficiency, cooling rate and uniformity of cooling. In addition, de Castro et al. (2004b) observed that the best cooling energy efficiency was achieved when the TVA was between 8 and 16%. However, these recommendations did not factor in the influence of internal packaging on airflow.

The effect of produce on airflow distribution was demonstrated by Chau et al. (1985). They showed that an aligned arrangement of packed produce as opposed to a random arrangement results in a better defined airflow path. However, the use of internal packaging inside cartons could consequently influence or even obstruct ventilation openings, resulting in unpredictable airflow distribution through packaging (Delele et al., 2008; Ngcobo et al., 2012).

Ventilation shape

The number, area and position of ventilation openings play an important role in the efficiency of cooling. However, the effect of ventilation shape on airflow distribution and cooling has largely been left unexplored in literature (Pathare et al., 2012). The lack of literature can be attributed to the fact that most research which examined ventilation shape did not make use of multi-scale packaging (Arifin & Chau, 1988; Baird et al., 1988; Kader, 2002). Although, recent research utilising multi-scale packaging has indicated that ventilation shape may be an important factor in airflow distribution during FAC (Delele et al., 2012; Ngcobo, 2013; Ngcobo et al., 2012).

3.4 Multi-scale packaging

Multi-scale packaging describes the use of many successive layers or components of packaging to contain produce. For example, a pome fruit packaging system can be made up of a cargo container, a palletized stack of cartons, a ventilated carton, and one or more of the following components – a polyliner bag, a bubble wrap sheet, thrift bags or trays.

The multi-scale packaging approach therefore dispenses the potentially convoluted model of a cargo container packed with many types of packaging, into several smaller models, each of which can be individually analysed. In addition, the multi-scale approach can make use of previous non-multi-scale research. For example studies that examined the resistance to airflow as a function of the bulk contents, such as the fruit alone, the fluid properties with regard to the airflow characteristics and the container or cartons ventilated area (de Castro et al., 2004a, 2005a; Vigneault & Goyette, 2002; Vigneault et al., 2006).

The addition of internal packaging can influence the total pressure drop over the package. The number, size, stacking arrangement, internal packaging and surface texture of the fruit can significantly affect airflow characteristics (Delele et al., 2008). The degree of the airflow resistance in a system is dependent on the type of packaging used. In situations where only the fruit and carton are present, the carton was shown to be the main variable determining pressure drop and therefore the limiting factor in the cooling rate (Haas & Felsenstein, 1987). When Ngcobo et al. (2012a) examined multi-scale table grape packaging, they determined that the liner bag contributed to more than 50% of the pressure drop, while the carton component contributed only between 9.89-37.68%. In addition, the bunch carry bags (similar to thrift bags in pome fruit), contributed between 1.40-9.41% of the total pressure drop.

Although liner films have a negative effect on pressure drop, their prime function is to modify the environment around the fruit. Section 2.2.1 further discusses the effect of polyliners on fruit moisture loss. Plastic liners modify the atmospheric environment around the fruit by influencing the gas exchange across the liner film. This results in changes in the respiration and metabolism, which ideally improves quality maintenance (Kader, 2002; Martínez & Artés, 1999; Montero-Calderón et al., 2008).

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4. Pre-cooling techniques of packaged fresh horticultural produce

There are around five methods of precooling that are commonly used in the food industry (Kader, 2002). The choice of precooling technique is dependent on the cost effectiveness and efficiency of the specific circumstance (Dincer & Genceli, 1994). Vacuum cooling uses a pressure drop around produce to induce evaporation of moisture, which rapidly cools the produce. One of the simplest and slowest methods available is room cooling (static cooling), which makes use of the cold air in a refrigerated room. Room cooling is therefore generally only used when more advanced techniques are not accessible. A more sophisticated form of room cooling, forced-air cooling, makes use of the cold room air which is exhausted through produce by a fan to convectively transfer heat. Alternatively, hydrocooling chills the fruit by submerging the produce in chilled water. A combination of hydrocooling and FAC is hydro-air-cooling, which makes use of chilled air and mist/spray of water that is forced through produce by way of airflow (ASHRAE, 1994). Of the discussed cooling methods listed above, room cooling and FAC are ideal for produce that are sensitive to moisture loss or water exposure. However, FAC is significantly faster and is therefore the main method used in the pome and citrus industries in Southern Africa (Beukema et al., 1982; de Vries et al., 2003).

4.1 Room Cooling

Most cold rooms are rectangular with one or more cooling units at one side of the room. The position of a carton inside a cold room may significantly affect the amount of cooling air that will pass around it (Delele et al., 2012). This is largely due to the cooling fans at the side of the room, which continuously cycle air through the space. Delele et al. (2009) and Hoang et al. (2000) studied a cold room system where the cooling unit is placed against the ceiling, pointing towards the opposite end of the room. The fan blows cooled air along the top of the ceiling (Coanda effect), the air then moves down the wall and travels across the floor and back into the cooling unit as indicated in Figure 6. The air is travelling at its highest velocity as it comes out of the cooling unit’s fans and slows down after it reaches the opposite wall (Delele et al., 2009). This literature offers a general model of how the airflow is traveling in similarly designed cold rooms.

4.2 Forced-air cooling

FAC is accomplished by exhausting cold refrigerated air through stacked packaging. Fans in combination with organised stacking are used to apply a pressure drop on one of the stacks sides

(Figure 7). FAC can cool produce substantially faster than room cooling as demonstrated by Talbot & Fletcher (1993), who examined the difference in grapefruit cooling efficiency between room cooling and a portable FAC device. Under the FAC conditions, there was a reduction of 6.7°C in one hour and 14.6°C by 2.5 hours, whilst under room cooling conditions, a reduction of 2.0°C in the first hour and 3.5°C by 2.5 hours.

The capacity of a refrigeration unit is important, as it has a limited ability to transfer heat from the environment. A precooling device should thus be capable of removing all the heat from the system, such as the produce, surrounding structure, the storage containers and heat generating machinery, for instance motors, light bulbs, fans and points (Thompson et al., 2008; Vigneault et al., 2006). A distinguishing feature between refrigeration cargo container units and FAC cooling rooms is the amount of heat load that must be dealt with. Most shipping containers have small refrigeration designs, which typically do not have the required heat transfer capabilities. However, many FAC rooms and static cold rooms are able to cool warm fruit to the satisfactory storage temperature of the product (Thompson et al., 2008). Fruit should therefore be precooled in a FAC room before being placed into a refrigeration cargo container for transport.

In addition to the heat transfer capacity, the FAC device must produce the correct airflow distribution in order to effectively penetrate packaged fruit. Barbin et al. (2012) tested a portable FAC device under positive and negative (exhaustion) airflow directions. It was observed that negative pressure facilitated heat transfer more evenly through packaging in the exhaustion system, than the positive pressure system did. Airflow must therefore be able to overcome the resistance of packaging to effectively cool produce (Lindsay et al., 1975).

5. Techniques for analysing airflow and cooling performance of horticultural packaging

5.1 Experimental analysis

5.1.1 Resistance to airflow

Resistance to airflow in FAC of stacked packaging is expressed as the resistance presented by the packaging material and produce to the airflow (Delele et al., 2008). Multi-scale packaging contents significantly influences the pattern of airflow, even at a constant air velocity (Tapsoba et al., 2007). Tapsoba et al. (2007) noted that sideways diffusion of airflow increases with an increase in the porosity of a load. Loaded containers therefore often present a backflow phenomenon on the sides of an air jet when entering through slotted vent openings.

The resistance of airflow through packed produce can be expressed in the form of the Darcy-Forchheimer (Forchheimer, 1901) and Ramsin equations (Chau et al., 1985). These equations have been utilised for different produce types, according to the relative setup and conditions of the research (Delele et al., 2008; Smale, 2004; van der Sman, 2002; Vigneault & Goyette, 2002; Vigneault et al., 2004a). The Ramsin (equation 2) and the Forchheimer (equation 3) equations are arguably the most descriptive and efficient to describe pressure drop versus airflow rate, when dealing with turbulent flow through stacked packaging (Delele et al., 2008; Ngcobo et al., 2012; Vigneault & Goyette, 2002).

Ramsin $$\nabla P = -au^b \qquad 2$$

Darcy-Forchheimer $$\nabla P = -\frac{\mu}{K}u - \beta\rho|u|u \qquad 3$$

In addition to packaging, the Darcy-Forchheimer equation can characterise airflow through porous mediums (Teruel & Rizwan-uddin, 2009). Teruel & Rizwan-uddin (2009) noted that the Forchheimer (β) coefficient is strongly dependent on the mediums porosity and is comparatively independent of the Reynolds number as well as turbulent regimes. Another equation used to describe the relationship between airflow and pressure drop, is the Ergun correlation (Ergun, 1952). However, it does not take into consideration the confined vented walls of packaging and is therefore better able to characterise airflow through bulk, unpackaged produce (Delele et al., 2008; Kashaninejad & Tabil, 2009; Kashaninejad et al., 2010). Teruel & Rizwan-uddin (2009) also noted that the Ergun correlation was only appropriate for a limited range of porosities and that a power equation (equation 2), would perform better when characterising pressure drop over a wide range of porosities.

The K, β, *a* and *b* coefficients from the Ramsin (equation 2) and Darcy-Forchheimer (equation 3) equations, can be used to characterise variables in a stacked packaged product. The *a* and *b* parameters are experimentally determined and are dependent on the stacking pattern, diameter of produce and the porosity of the medium (Delele et al., 2008; Vigneault et al., 2004b). The Darcy permeability (K) parameter and the Forchheimer drag coefficient (β) parameters are both dependent on products diameter, stacking pattern, porosity, the fluid properties, shape, surface roughness, confinement and the vent opening ratio (Ngcobo et al., 2012; van der Sman, 2002; Verboven et al., 2004).

5.1.2 Airflow patterns

There are many tools and techniques available to experimentally measure the rate of airflow travelling through an area such as produce. The method of choice will determine the amount of influence the experimental devices will have on the results and the degree of accuracy that can be achieved (Smale, 2004). The selection of device is typically determined by budget and the practicality of use in an experiment. Experimental techniques for the quantification and measurement of airflow can be allocated into non-intrusive, direct intrusive and indirect intrusive methods.

Non-intrusive methods

Laser doppler anemometry (LDA), makes use of two intersecting laser beams which create an interference fringe pattern. When a particle passes through the beam, the resulting scattered light is used to calculate velocity (Smale, 2004). Although highly accurate, some of its limitations include that it can only measure optically transparent fluids, only a single point is sampled and the equipment can be expensive as well as bulky. Moureh et al. (2002) used LDA to continuously monitor flow rate inside a scale model of a refrigerated truck. The front wall was made of glass to allow penetration of the LDA laser into the scale model.

A similar method to LDA is particle image velocimetry (PIV). The techniques utilises non-buoyant particles, which are placed in a fluid flow. A digital camera then captures multiple pulses of laser light. The distance between the particles is used to calculate velocity (Kumara et al., 2010; Smale, 2004).

Direct intrusive methods

Hotwire anemometry uses the relationship between the rate of heat loss and the velocity of a convective fluid over a known surface. Two types of hotwire anemometry are available. ‘Constant temperature’ keeps the resistance of a wire/film constant and the required voltage to maintain set temperature is measured. In contrast, ‘Constant current’ keeps the same current constant and measures changes in resistance. One of the advantages of hotwire/film anemometers are that they are readily available commercially and are therefore commonly used in horticultural related markets (Al Khalfioui et al., 2003; Smale, 2004).

Sonic anemometry makes use of the principle that sound waves are influenced by the velocity of the medium it is travelling through. The setup therefore requires two transducers, which are used to determine the speed of an ultrasound pulse and consequently fluid velocity (Smale, 2004).

Vane anemometry makes use of a propeller. The rate of the propellers spin indicates the fluid velocity. Some of the limitation of vane anemometry is that unlike hotwire anemometry, vane anemometry is directional, it cannot operate at high fluid flow rates and it is bulky when compared to other anemometers (Foster et al., 2002; Smale, 2004).

Indirect intrusive methods

Indirect intrusive methods are beneficial in situations where direct instrumentation measurement is not possible. Some examples of indirect intrusive methods or techniques are tracer gases, thermal tracers, thermocouples and infrared sensors. The advantage of using an indirect intrusive approach is that they do not directly influence the experimental system. For example, the presence of a velocimetry probe can affect the airflow as well as the air streams, which are constantly shifting and changing. Keeping a probe perpendicular to variable air streams is also not always possible due to random changes in turbulent airflow (Alvarez & Flick, 1999a).

5.1.3 Cooling performance of packaging

Fruit cooling rate

Packaging with less resistance to airflow results in a more cost effective cooling process, which can be achieved by using stacks with a smaller bed depth or larger porosities (Delele et al., 2008). Airflow velocity ($m.s^{-1}$) has been linearly correlated to produce cooling rates, while airflow rate ($L.s^{-1}$) was exponentially correlated to cooling rates (de Castro et al., 2004a; Vigneault & de Castro, 2005). By doubling the air velocity, the cooling rate can be increased by up to 40% (in plums and cantaloupe), but the cost in energy is increased nearly 4 times (Thompson et al., 2008). The rate of cooling is also influenced by the temperature difference between the product and the medium in contact with the fruit (Brosnan & Sun, 2001). In addition, the fruit diameter significantly influences the cooling time during FAC. Larger fruit thus take longer to cool than smaller fruit.

Cooling rates usually follow an exponential form (Becker & Fricke, 2004). As a description of cooling rate, the time required to cool produce to half the temperature difference between the product and the surrounding medium is referred to as the half-cooling time. This time is equal to the period it would take to cool from the half-cooling time to the three-quarter cooling time and three-quarter cooling time to the seven-eighths cooling time (ASHRAE, 1994; Brosnan & Sun, 2001). The dimensionless temperature (θ) can be expressed as a function of the cooling time using equation 4 (Dincer, 1995). By substituting θ with 0.5 and 0.125 (equation 5), the half-cooling time (H) and seven-eighths cooling time (S) can be calculated, respectively. S can therefore be calculated using equation 6 (Dincer, 1995).

$$\theta = \frac{T - Ta}{Ti - Ta} \tag{4}$$

$$\theta = \mathrm{Jexp}(-\mathrm{Ct}) \tag{5}$$

$$S = \frac{[\ln(8J)]}{C} \tag{6}$$

Cooling heterogeneity

The cooling rate of a packaged produce can be significantly prolonged due to lack of cooling uniformity inside the package (Alvarez & Flick, 1999a; Alvarez et al., 2003). The effect of ventilation on airflow distribution is closely related to cooling heterogeneity and is further discussed in section 3.3.2. A technique for the determination of total package cooling heterogeneity is shown in equation 7 and 8 (Barbin et al., 2012), while Dehghannya et al. (2008, 2011) demonstrated a method of calculating heterogeneity at a sample location in packaged produce (equation 9).

$$\Delta T_c = \bar{T}_c - T_{min} \;\; or \;\; \Delta T_c = \bar{T}_c - T_{max} \tag{7}$$

$$\varphi = \frac{\sqrt{\frac{\sum(\Delta T_c)^2}{n}}}{\bar{T}_c} \tag{8}$$

$$HI = \frac{\sqrt{(Tp - \overline{Tp})^2}}{\overline{Tp}} \times 100 \tag{9}$$

Cooling heterogeneity can be described as variation in temperatures between multiple areas in an object such as stacked palletised fruit. Cooling heterogeneity thus prolongs the cooling process, as the heat transfer rates are not evenly distributed across all the fruit. This results in excess energy utilisation and therefore poor cooling efficiency.

Cooling efficiency

A significant reduction in FAC cost is possible, by addressing one or more of the factors affecting cooling efficiency (Thompson et al., 2010). For example, fans are used in the FAC device to exhaust air through tightly packed cartons. The energy used by a fan is related to the airflow rate, which is related to the fan's physical characteristics, operating speed and pressure drop (de Castro et al., 2004a). Other factors affecting cooling efficiency are the product size, shape, thermal properties, packing configuration, TVA of the packaging, depth of product load (in the airflow direction) and the difference between the initial and final product temperatures during cooling (de Castro et al., 2004a; Vigneault et al., 2006). In addition, the fluid properties being applied to the fruit such as the RH, temperature and flow rates of the cooling air also have an effect (Baird et al., 1988; de Castro et al., 2005a).

The design of a FAC system requires certain trade-offs, it is frequently the case that increasing cooling rate results in less efficient energy utilisation (Baird et al., 1988). For example, decreasing the temperature of the airflow will result in a faster cooling rate, but will significantly increase energy usage (Baird et al., 1988). In addition, a higher air velocity will usually generate a higher cooling rate. However, a higher air velocity will also require a disproportionately large amount of power usage by the fans (de Castro et al., 2004a; Parsons et al., 1972).

The airflow rate or packaging design should ideally be adjusted to accommodate the fruit respiration rate. de Castro et al. (2005a) recommended that low airflow rates (0.5 $Ls^{-1}kg^{-1}$) and high airflow rates (2 $Ls^{-1}kg^{-1}$) be used for low and high respiring fruit during FAC, respectively. However, the resistance of the packaging and fruit to airflow will have a significant effect on the pressure drop during high airflow rates and therefore the energy usage. Packaging should thus be designed with the correct TVA in accordance with the fruit type.

Numerous studies have evaluated the efficiency of a cooling system using several techniques (de Castro et al., 2004a, 2005a; Ferrua & Singh, 2011a; Thompson et al., 2010; Wang & Muller, 2000; Zhang & Sun, 2006). Two perspectives are generally possible. The energy coefficient (EC) calculates the ratio of cooling work successfully performed per amount of electricity purchased by the facility, as shown in Equation 10 (Thompson et al., 2010). In contrast, the energy added ratio

(EAR) as shown in equation 11, takes into account the field heat energy (equation 12), respiration energy (equation 13) and ventilation energy (equation 14) used during precooling (de Castro et al., 2005a). Therefore, the EAR is distinct from the EC, as it excludes the mechanical characteristics of the cooling system.

$$EC = MC_p \frac{(T_i - T_f)}{(Ec)} = \frac{E_1}{\sum EE} \tag{10}$$

$$EAR = \frac{E_r + E_v}{E_p} \tag{11}$$

$$E_p = mc_p(T_f - T_i) \tag{12}$$

$$E_r = 10^{-6} m \sum Q_{r,produce} \Delta t \tag{13}$$

$$E_v = \frac{D_{air} APD}{\eta_m} \mathrm{t_s} \tag{14}$$

In an assessment of precooling facilities in California (USA) using the EC calculation, Thompson et al. (2010) observed that there have been almost no improvements in EC values from previous assessments 20 years before and concluded that fan operation made use of the most energy during precooling processes. Consequently, in order to reduce energy usage, the researchers suggested increasing the carton porosity by using a larger TVA and less internal packaging.

Produce simulator

The experimental testing of the relationship between produce and packaging and its influence on airflow, cooling and quality are crucial to improving and developing new packaging systems or designs. The use of fresh (real) produce is ideal for examining the effect of packaging on the preservation of quality during storage and transport. However, generating replicable experiments using real produce can be challenging. This is due to the different sizes, shapes, surface textures, heat or mass transfer properties, variable respiration rates and general unpredictability between each individual fruit. In addition, living produce mature over time, resulting in an additional variable between the same fruit over the duration of one or more experiments (Vigneault & de Castro, 2005). The need for statistical replication makes the use of large quantities of fruit necessary. However, large fruit volumes can make research costly, wasteful and due to senescence, not always possible with the same fruit (Ngcobo, 2013). Many researchers thus make use of synthetic produce replicates

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for the purposes of testing airflow, heat and mass transfer properties. This can reduce experimental error and can make the tests more replicable.

The use of simulation fruit in airflow experiments has been discussed extensively in literature (Alvarez & Flick, 1999a, 1999b; de Castro et al., 2004a, 2004b; Maul et al., 1997; Vigneault et al., 2005b). Produce simulators need to be low cost, experimentally predictable and must not generate unknown responses during the experiment (heat transfer and air circulation). Some examples of previously used produce simulators in literature are shown in Table 2. Most of these studies found the results repeatable with minimal variability. However, de Castro et al. (2004a) found that the plastic balls were not always sufficiently precise. The best results were obtained from the aluminium and nylon balls (Alvarez & Flick, 1999b; Vigneault et al., 1995, 2005b). The correct choice of material is therefore essential to achieve replicable results.

5.2 Computational fluid dynamics (CFD) modelling

Several numerical and analytical modelling techniques have been used to study the airflow patterns and heat and mass transfer of fruit packaging during cooling (Tanner et al., 2002a, 2002b, 2002c; Zou et al., 2006a, 2006b). However, CFD modelling is the most widely used approach in simulating the cooling performance of horticultural packaging (Ambaw et al., 2013a). Computational fluid dynamics (CFD) models have shown great promise in predicting airflow characteristics as well as heat and mass transfer rates inside cold chain systems, such as packaging and cooling facilities. With the use of CFD modelling, time and resources can be saved by limiting the number and cost of experimentation such as the testing of packaging designs and configurations. However, the use of a specific CFD model should always be experimentally validated to limit the possibility of unforeseen errors in the simulations and therefore inaccurate predictions (Versteeg & Malalasekera, 2007).

CFD modelling has been used to simulate the effectiveness of horticultural packaging as well as cold storage facilities. For instance, Chourasia & Goswami (2007) simulated heat and moisture loss rates in a potato cold store, using a simplified two-dimensional model. In another example, Ferrua & Singh (2009) were able to successfully predict the airflow movement between clamshell containers holding strawberries. The same model was later used to recommend new ventilation designs in order to improve airflow in the strawberry clamshell containers (Ferrua & Singh, 2011a, 2011b).

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Ideally, computer modelling should try to incorporate all known physical and biochemical factors of a model simulation. However, despite the continually improving capabilities of computers on the market, an all-encompassing approach would still require an unrealistically large amount of computing power. Many current strategies therefore aim at only including the most important and fundamental factors of a model (Versteeg & Malalasekera, 2007).

Many studies have attempted to create a generalised CFD model of horticultural packaging. Different models have, for instance, focused on airflow distribution, mass loss or heat transfer rates inside the package (Ambaw et al., 2013a; Mirade & Picgirard, 2006; Opara & Zou, 2007; Zou et al., 2006b), while others have considered conditions outside packaging (Delele et al., 2008, 2012; Norton & Sun, 2006; Versteeg & Malalasekera, 2007). The use of validated CFD modelling can therefore provide extended detailed information at any position of a simulation domain beyond the results of experimentation alone (Delele et al., 2008; Ambaw et al., 2013b; Versteeg & Malalasekera, 2007). For instance, Tanner et al. (2002b) worked on creating a generalised model, which can be used flexibly in a multitude of different situations. The authors reported good correlation to their experimental results. They concluded that the heat transfer modelling was satisfactory, but some limitations were still present with regard to experimental correlation. Additional studies by Tanner et al. (2002c) using the same model, showed that the mass transfer elements of the modelling software were sufficiently accurate, although some small experimental correlation were still not always precise. It was concluded that the model could be used as an alternative to experimental studies for horticultural researchers, but further refining work would be useful.

A generalised model for the mathematical characterisation of heat and mass transfer properties in food operations has been attempted by many food engineers (Delele et al., 2012; Norton & Sun, 2006; Opara & Zou, 2007). However, food packaging is generally hierarchically structured (multi-scale packaging). These structures range from the molecular reactions in fresh produce to the internal arrangements inside packaging and even the stacking arrangement of the packaging inside a cold store. The inherent limitation of computer technology and the time needed to combine all factors of interest into one model or equation has made a large-scale approach challenging. Models designed to predict macroscopic factors will therefore ignore the microscopic factors (and visa versa), due to the excessive complexity of the task. Multi-scale modelling is therefore an emerging approach to individually characterise each of the sub-models of the interconnected hierarchical positions. In other word, highly complex models are broken down into smaller more manageable models and then solved individually (Delele et al., 2008; Ho et al., 2013; Ngcobo, 2013).

6. Conclusions

Horticultural produce are living, respiring bodies that are significantly more sensitive to environmental conditions after harvest. Temperature control is the primary method used in the cold chain to preserve fruit quality during storage and transport. Specifically, fruit at low temperatures are more resistant to abrasion mechanical damage, less prone to decay by microorganisms, have a lowered moisture loss rate and have a reduced respiration rate, which extends the time period to senescence. Precooling systems, such as forced-air cooling are therefore employed to rapidly remove field heat from packaged produce.

Packaging improves fruit marketability by offering protection from physical damage, modifying the environment and improving fruit transport density per volume. However, packaging also limits the fruit cooling rate, which is important for the maintenance of fruit quality. To improve cooling rates, many packaging types have adopted the use of ventilation openings in the walls of the carton, which are designed to work in conjunction with forced-air cooling. These openings are designed to channel airflow from areas outside the packaging or stacked packaging, to areas where heat transfer can successfully take place between the fruit and cold air. The geometrical design (shape, size, position and number) of the ventilation holes significantly affects the airflow rates and distribution, which in turn influences the cooling rates and homogeneity of cooling. In addition, the presence of ventilation holes also negatively influences the mechanical strength of the packaging. Numerous studies have focused on optimisation of ventilation design, which has resulted in an improved understanding of airflow and cooling through packaged produce. However, no universal recommendation has been possible as each package and fruit type is unique and should be considered as such.

Multi-scale modelling is a recent methodology, which allows the examination of interconnected hierarchically structures systems such as the multiple layers of packaging (e.g. fruit, internal packaging, carton, stack, cargo container). Findings using multi-scale packaging have shown that internal packaging, such as plastic liner bags, can have significant effects on resistance to airflow and therefore cooling rates.

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Packaging systems can be evaluated using either experimental or numerical tests. Experimental tests require either real produce or produce simulators. Quality examinations will still require real produce, however, the produce simulators were shown to be ideal for airflow and cooling experiments. In addition, experimental systems require anemometry and velocimetry devices to measure the airflow properties. CFD simulations are another method available for packaging evaluation and allow an infinite level of detail in any portion of the examined system, although they should always be experimentally validated.

The performance of forced-air cooled stacked packaged produce (multi-scale packaging) has been examined using several approaches. The resistance to airflow of stacked packaged produce was significantly related to the packaging ventilation design and airflow rate. The Darcy-Forchheimer polynomial equation and the Ramsin power equation were reported to be the most accurate in characterising packaged produce. Other important performance attributes, were the cooling rate, homogeneity of cooling and cooling efficiency, which were significantly affected by the airflow distribution.

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Table 1: List of common microbial diseases, which cause decay of fruit during storage.

Species	Common name
Botrytis cinerea	grey mould
Penicillium expansum	blue mould
Penicillium verrucosum	blue mould
Penicillium italicum	blue mould
Penicillium digitatum	green mould
Alternaria alternata	brown rot
Cladosporium herbarum	brown rot
Monilinia fructicola	brown rot

Table 2: List of experiments performed using produce simulators.

Nylon cylinders were used to measure ice distribution inside a liquid ice system.	(Vigneault et al., 1995)
Rubber balls filled with water/agar-agar solution were used to measure the water flow through a hydrocooling system.	(Maul et al., 1997)
Aluminium balls were used to measure airflow distribution through a forced-air precooling system.	(Alvarez & Flick, 1999b)
Plastic balls filled with water/agar-agar solution were used to simulate horticultural produce in a forced-air precooling system.	(de Castro et al., 2004a)
'Snooker balls' (polymer balls) were used as a substitute for horticultural produce in an airflow simulator.	(Vigneault & de Castro, 2005)

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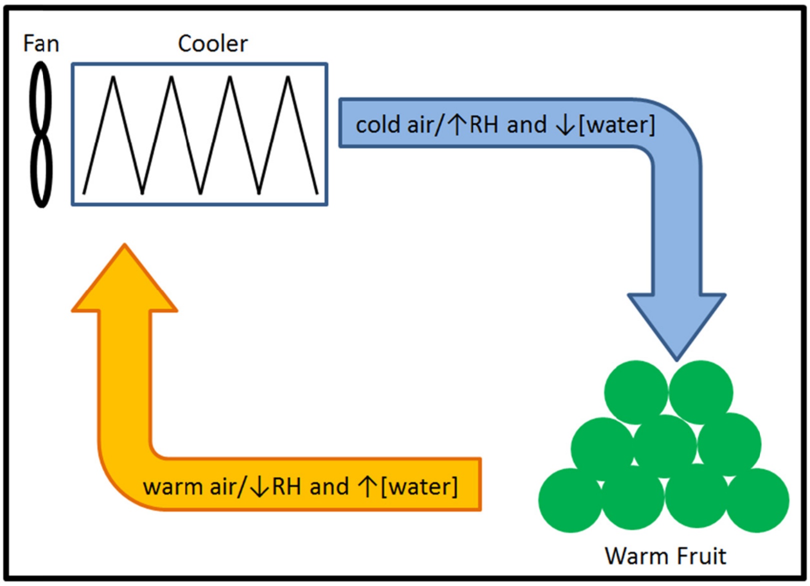

Figure 1: The migration of water from warm fruit to cooler (cooling coil) during cooling in a cold room.

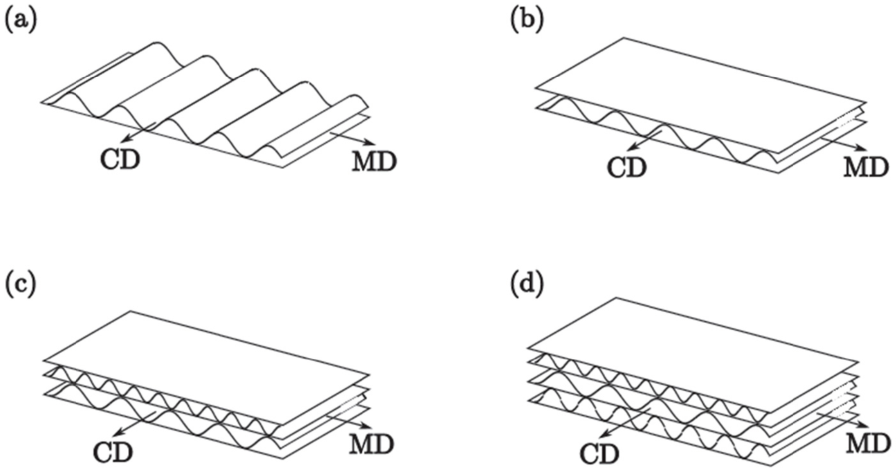

Figure 2: Diagram of a (a) single face, (b) single wall, (c) double wall and (d) triple wall corrugated fibreboard (Flatscher et al, 2011). MD: machine direction, CD: cross direction.

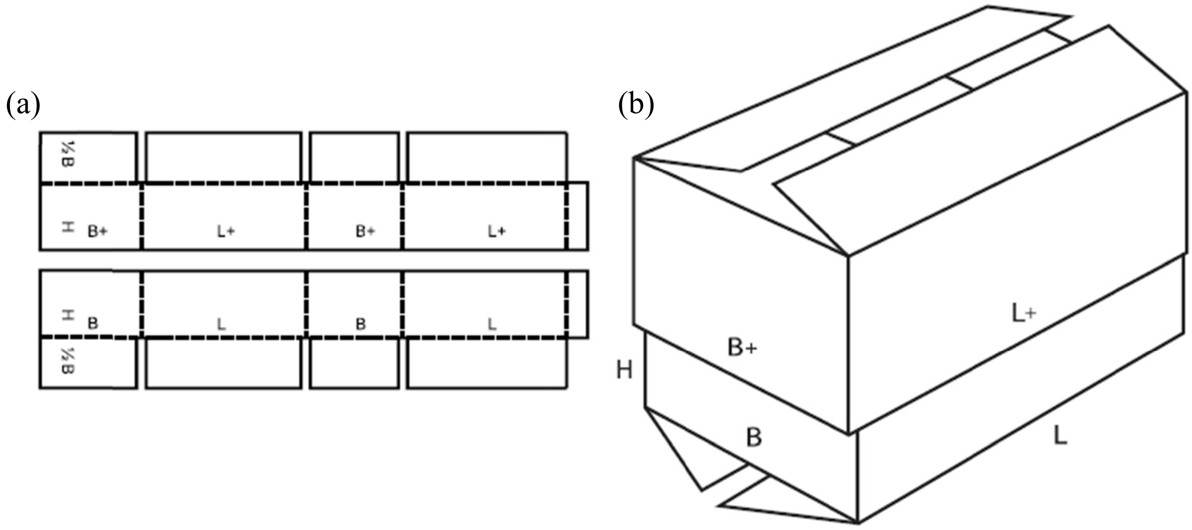

Figure 3: Diagram of (a) unassembled and (b) partially assembled telescopic carton, the style code according to the International fibreboard case code system is 0320 (FEFCO & ESBO, 2007).

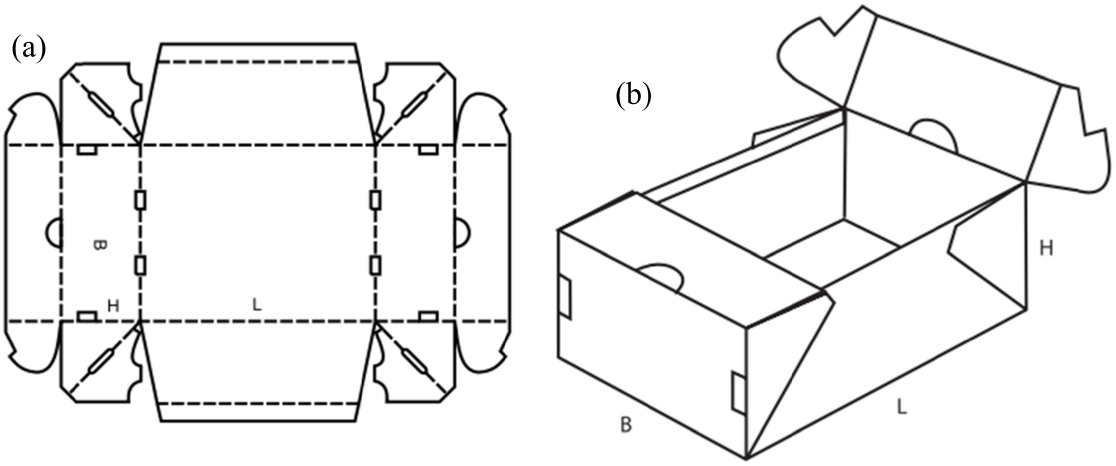

Figure 4: Diagram of (a) unassembled and (b) partially assembled display carton, the style code according to the International fibreboard case code system is 0773 (FEFCO & ESBO, 2007).

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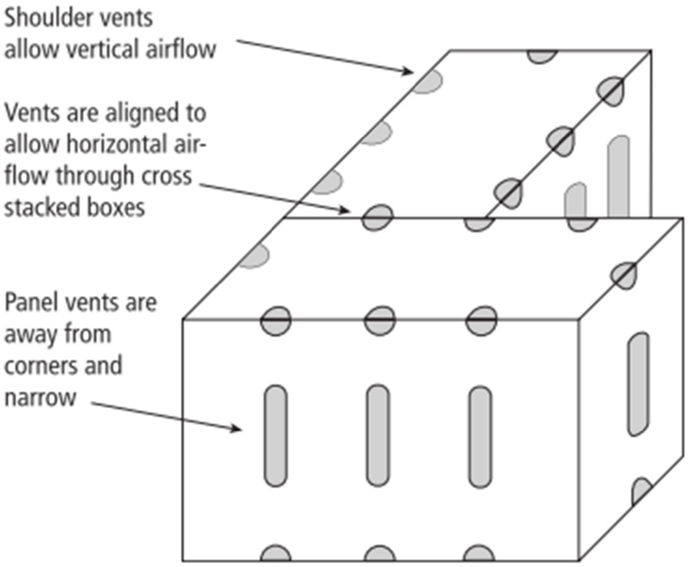

Figure 5: Carton and vent design recommendation by Thompson et al. (2002) to allow improved ventilation alignment during carton stacking.

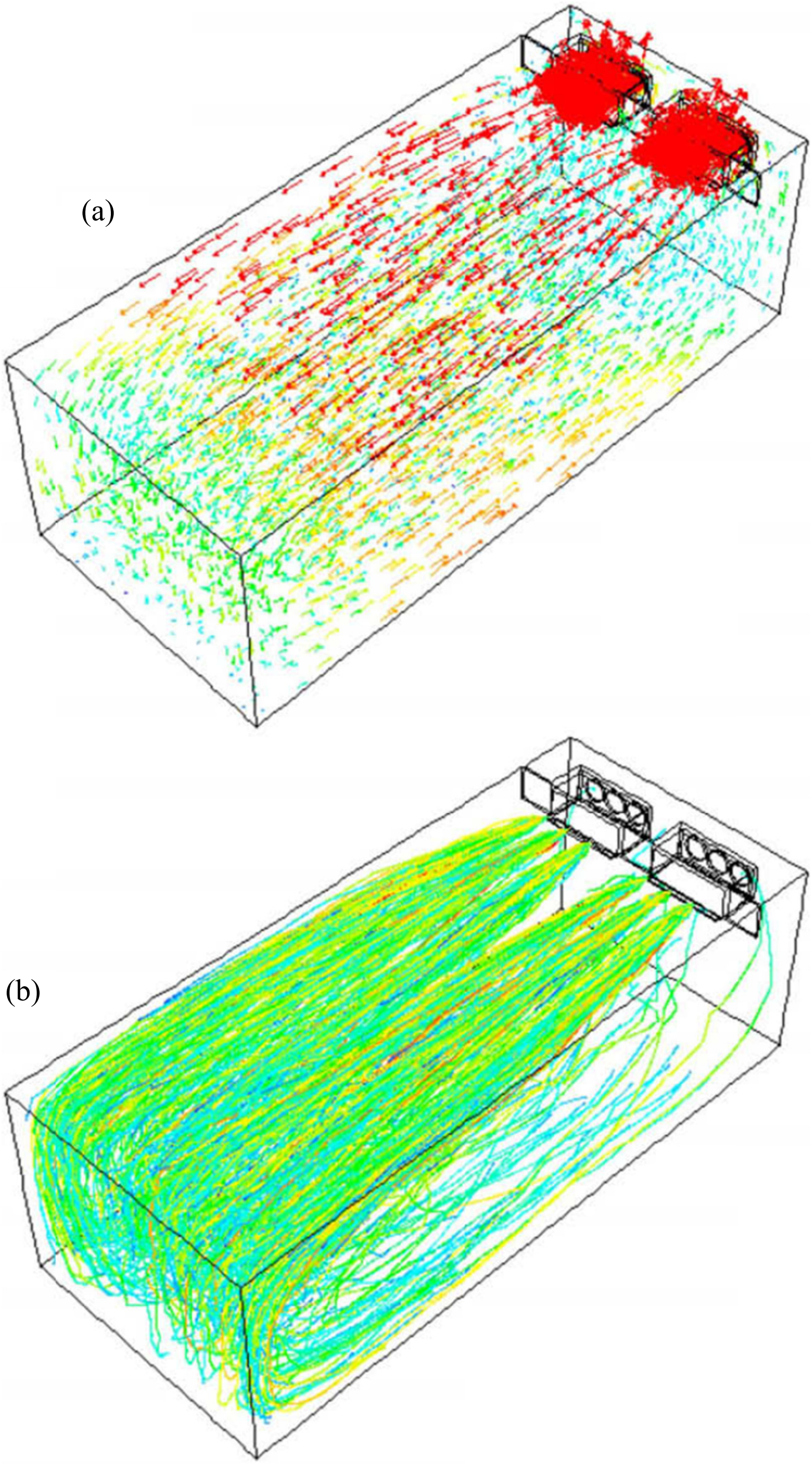

Figure 6: CFD simulation of air velocity vectors (a) and tracks of sprayed droplets (b) for an empty chicory root cold storage room, with a deflector length of 0.2 m: velocity vector: 2 $m.s^{-1}$ = red, 0 $m.s^{-1}$ = blue; droplet diameter: 18.5 µm = red, 2.5 µm = blue (Delele et al., 2009).

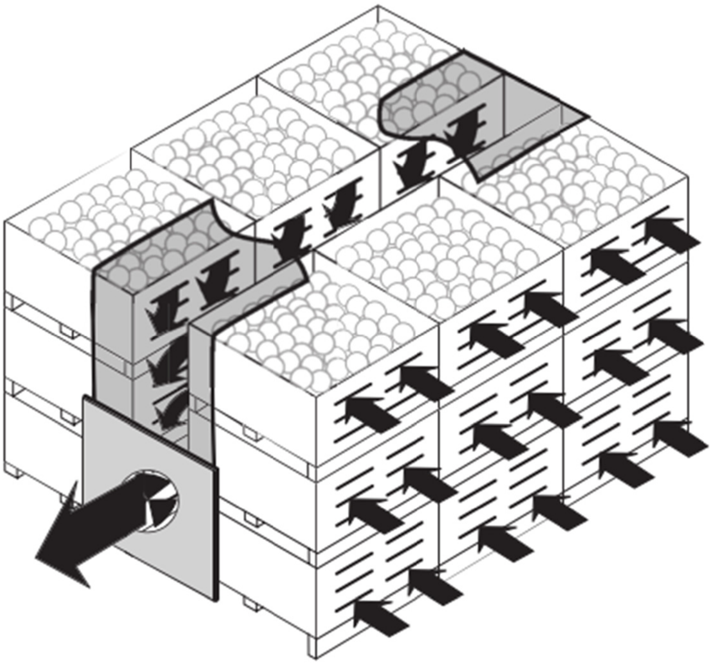

Figure 7: Diagrammatic view of a FAC tunnel. Either bins or stacked palletised cartons can be placed to form a tunnel from which air is exhausted. The negative pressure then causes cold air from the room to pass through ventilation holes to directly exchange heat with the fruit (Thompson et al., 2002).

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PAPER 1: Geometric design characterisation of ventilated multi-scale packaging in the South African pome fruit industry

Keywords: packaging, vents, airflow, ventilation area, inner packaging, cooling rate, compression damage, fruit, packages

Abstract

Ventilated packages are the primary types of packaging used in the shipment of fresh fruit, including apples and pears. The use of inappropriately ventilated packaging can result in cooling heterogeneity, increased incidence of physiological disorders during cold chain handling of fresh fruit and in extreme cases, mechanical damage of packaging and fruit. A survey on the types of ventilated packaging used in export handling of pome fruit in South Africa showed that eleven different corrugated fibreboard package designs are predominantly used. The export distribution during the 2008-2012 period was 48% for apple packages and 57% for pear packages shipped in Mark 4 and Mark 6 packages, respectively. In addition, each package design type is used in several dimensional formats in order to accommodate different fruit sizes and market requirements. Overall, the different package designs can be classified into 'display' and 'telescopic' packages and four stacking configurations are commonly employed to palletise the packages. The vent hole ration of ventilation per package varied between <1 and 11%. In addition, sub-optimal vent positioning on most packaging results in non-alignment of ventilation in stacked pallets, which in turn can influence airflow patterns during forced-air cooling.

1. Introduction

Fruit are living entities that deteriorate in quality as they respire, leading ultimately to senescence (Brosnan & Sun, 2001; Salisbury & Ross, 1992). Temperature is the most important factor in moderating fruit deterioration, as it controls the rate of biological reactions occurring inside fruit (Nelson, 1978; Ravindra & Goswami, 2008). Precooling is therefore used to reduce the temperature of fruit immediately after harvest, thereby extending storage life. Forced-air cooling (FAC) is acknowledged as the most common precooling technique used in the fruit industry to remove field heat (de Castro et al., 2004; Zou et al., 2006), and is often performed after packing fruit inside ventilated packaging (Ladaniya & Singh, 2000; Talbot & Baird, 1990). Heat transfer between fruit and the cooling medium (cold air) is largely facilitated by ventilation holes in the walls of the

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stacked packages, which allows airflow penetration through a pallet stack. During FAC, ventilation holes in the packaging should facilitate a homogenous cooling pattern throughout a package stack by directing uniform airflow through the packaging. The cooling efficiency inside packaging, containing fruit, is significantly affected by the ventilation configuration (size, shape, position and number) on the package walls (de Castro et al., 2004; Kader, 2002; Vigneault & Goyette, 2002). Corrugated fibreboard carton strength is also significantly affected by the configuration of the ventilation holes (Singh et al., 2008). For example, oblong shaped ventilations holes reduce mechanical strength the least when compared to other shapes (Han & Park, 2007; Jinkarn et al., 2006).

In order for ventilated packages to function optimally, packages should have sufficient mechanical strength to protect the fruit (Robertson, 2006; Vigneault et al., 2006), while supplying adequate ventilation to maintain the cold chain. According to Kader (2002), a total ventilation area (TVA) of 5-6% for fibreboard packages is a good compromise between strength and ventilation area. However, de Castro et al. (2005a) showed that TVA between 8 and 16% results in the best air cooling efficiency. In earlier studies, it was shown that TVA <25% significantly restricted airflow in ventilated containers (Vigneault & Goyette, 2002). However, open areas of this size could compromise the structural integrity of paperboard based packaging.

In order to meet the wide range of export and domestic market demands, different designs of packaging are used, resulting in a large variety of geometrical configurations and sizes (Opara & Zou, 2007; Pathare et al., 2012). Despite the availability of numerous designs, it has been reported that many packaging types used in the fruit industry are not effective in promoting fast and uniform cooling (Ferrua & Singh, 2007). Several authors have recommended that new packaging systems should be thoroughly evaluated to optimise ventilation design and ultimately improve cooling efficiency (Pathare et al., 2012; Thompson et al., 2010; Vigneault et al., 2006, 2009). Rising electricity costs (Sebitosi, 2008) and the need to reduce the cold chain carbon footprint, has made it necessary to improve packaging systems thermal and mechanical efficiencies (Thompson et al., 2010). However, little is known about the geometric and ventilation characteristics of existing packages used in the industry. The objective of this study was therefore to quantify the geometric design characteristics of ventilated packaging used in the South African pome fruit (apples and pears) industry. In the horticultural industry, the terms ‘package’ and ‘carton’ are often used interchangeably; however, for consistency in this chapter and throughout the thesis, the word 'package' is used while 'carton' is used where it is necessary to represent the information reported by previous researchers or to distinguish between different package components.

2. Material and methods

2.1 Survey methodology

The survey was carried out by collecting samples of all available apple and pear packages from major pack houses in two of the largest pome fruit growing areas (Grabouw and Ceres) in South Africa, as well as from the fresh produce section of major supermarkets. The survey was performed between January and July 2012 and the Western Cape Province was chosen at the study area, because it accounts for over 92% of apples and pear production in South Africa (PPECB, 2013a).

Each package was examined based on three broad geometric characteristics: (a) package dimensions (length, width and height); (b) ventilation (size, position, number and shape of vents/holes); and (c) presence of internal packaging (plastic liner bags (polyliner), trays, punnets or thrift bags).

2.2 Data Analysis

Statistics, with regard to the export number of different packages in the industry between 2008 and 2012, were collected from the Perishable Products Export Control Board (PPECB, 2013b). Each package design was linked to a local 'pack code' which in turn is linked to a 'Global Trade Item Number' of fruit exports. The descriptive capabilities of the 'pack code' was found to be limited while classifying the packages, given that the same code may be used for different variations of similar package designs, produced by different packaging production companies. In addition, the 'pack code' may also be dissimilar for the same package design if one of them contained differing internal packaging. To improve clarity, packages were named in this chapter and throughout the thesis by using common package terminology from the South African fruit industry.

3. Results and Discussion

3.1 Packaging export statistics

The main types of packaging used to export apples and pears from South Africa to various markets are shown in Table 1 and Table 2 and were indicative of a market-driven package design

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and deployment strategy. From a design perspective, each package type may be used for both apples and pears. However, due to practical limitations such as retail shelf layout and restrictions on package weight and regional market preferences, certain package types were favoured more for certain fruit types. For instance, the Central Europe (C/Europe) and United Kingdom regions were responsible for 95% of the Mark 7 (Mk7) and Mark 9 (Mk9) package exports, while there was a relatively even distribution for the rest of the package designs. This high preference can be explained due to many of the supermarkets in these areas making use of retail shelves specifically designed to accommodate the Mk7 and Mk9 dimensions (600 x 400 mm).

Package volume appeared to play a significant role in the export preference of the two primary display packages (Mk7 and Mk9). The Mk7 (Figure 1a) package design represented <1 and 22% of total apple and pear exports, respectively. Furthermore, the Mk7 package is used primarily with a single tray of fruit, in contrast to the Mk9 (Figure 1b) package which has capacity for two trays and therefore represented 22 and 11% of total apple and pear package exports, respectively. In addition, the increase height (39-91 mm) of the Mk9 package allowed convenient packing of thrift bags and punnets, which may have made the package design more popular for handling and marketing of pome fruit.

The two most widely used telescopic packaging types are the Mark 4 (Mk4) and Mark 6 (Mk6) packages, which are both designed to facilitate high density packing of pome fruit. These two packages were used for 48% (Mk4) and 4% (Mk6) of total apple exports and <1% (Mk4) and 57% (Mk6) of total pear exports. This significant difference in package preference use can be attributed to the higher density of pears (approx. 1.05 kg/L) compared to apples (approx. 0.86 kg/L). Although the Mk4 (Figure 1c) offers a larger packing volume, the average mass of packed fruit would be 18 kg for apples and 22 kg for pears. The mass of a 22 kg package is generally considered excessive for human lifting, resulting in a preference for the 12 kg Mk6 (Figure 1d) pear packages.

3.2 Packaging formats and types

The survey identified four stack configurations as shown in Figure 2. These configurations are based on the standard 1.2×1.0 m export pallet (Figure 2a, b, d) and the 1.2×0.9 m (Figure 2c) pallet which was used predominantly in the local market. These pallet designs allow the stacking of packages with various dimensions to increase pack density inside freight containers (Cargo Systems International, 1989).

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There are several companies in the Western Cape Province (South Africa) producing numerous package designs, which is often a market-driven process. Overseas and local markets will place an order for fruit packed inside a specific package design, to meet the requirements for their handling systems and marketing logistics, including transportation using freight containers (Thompson et al., 2008).

Two distinct package designs were identified in the survey, namely the display (Figure 3a) and the telescopic designs (Figure 3b). Telescopic packages are commonly used for packaging of fruit in layers or bulk, allowing fruit to be repackaged or placed in a heap at the point of retail. Display packages on the other hand, serve a communication function by allowing the whole package to be placed directly on the shelf at the point of retail. Fibreboard packages, irrespective of its size and ventilation can be described according to 'The International fibreboard class code' (IFCC) document, which uses a simple code to describe the packages construction design (FEFCO & ESBO, 2007). According to the IFCC, the construction of display packages follows the 'Ready-glued cases' category (code 0773-M design) and 'Folder-type' (code 0432-M design). The telescopic packages follow the 'Telescope-type boxes' category (code 0200-M/A). Within the two categories, a total of twenty package designs were identified during the survey, and on closer examination, they were further classified into eleven distinct types of packages as shown in Table 3.

The Mini-mk9 (Figure 1e) and Econo-D (Figure 1f) packages are both display package designs, which are used primarily on the local market, although a small number of exports do occur. The Mini-mk9 package is frequently used at local convenience stores near motor-vehicle refuelling stations. Trays are regularly used in the Mini-mk9 to enable consumer purchase of individual fruit as a 'snack food'.

The Econo-D (Figure 1f) and Econo-T (Figure 1g) have been designed to accommodate the different transport requirements of the local South African market. This entails the use of thinner corrugated fibreboard and different package dimensions to accommodate different pallet sizes and smaller transport distances. According to industry experience, these characteristics usually reduce the resistance of the palletized stack to compression damage. However, given the significantly shorter transport duration and the competitive nature of the local market for low cost fruit, the reduced strength of the package is justified as a minor decrease in quality may be acceptable if there is a significant reduction in cost. The Econo-T is the telescopic version of the Econo-D package. The Econo-T design is also used predominantly with thrift-bags of fruit in the local market.

The Mini-T (Figure 1h) packages are telescopic designs used in conjunction with two trays and sometimes with a polyliner bag. The Mini-T is half the height (and capacity) of the Mk6 package and is used for both apple and pear export. This design offers a larger degree of physical protection to the fruit by making use of a larger package-to-fruit ratio than the Mk6 and Mk4 packages. The Mark 11 and Bushel (Figure 1i) package designs are used for high density packaging of pome fruit, with two and six trays, respectively, while the Mk4 and Mk6 designs hold four trays of fruit.

The jumble (Figure 1j) package is high density bulk packaging used primarily for apples where fruit are packed loose inside the package. The lack of internal packaging thus reduces the overall packaging cost. The package is almost exclusively used for the transport of lower grade apples in the local informal market, as well as for export to other African countries.

3.3 Internal packages

Several types of internal packaging are used in the pome fruit industry, resulting in multi-scale ventilated packaging. Internal packaging can play both an aesthetic and functional role in the postharvest handling of fruit. The tray was the most commonly observed internal packaging and is either produced from polystyrene or pulp paper and mostly used to hold fruit inside telescopic packages (Holt & Schoorl, 1984).

Polyliner bags are also used inside apple and pear packages, by packing them inside the package surrounding the trays and fruit. Polyliner bags are usually used in telescopic and display packages in combination with fruit trays. The primary functions of polyliner bags are to modify the moisture, oxygen, carbon dioxide or volatile gas concentrations surrounding fruit (Geeson et al., 1994; Linke & Geyer, 2013; Shorter et al., 1992). Three predominant polyliner bag film thicknesses were found (20, 37.5 and 60 µm), which also present a physical barrier between the fruit and pathogens in the surrounding air.

Thrift bags and punnets are also used in pome fruit packaging. These packages allow several fruit to be placed inside a bag or punnet and are then placed into a carton to facilitate handling and retail marketing (Vigneault et al., 2009).

In addition to the above types of inner packaging, shrivel sheets, riffled paper, sponge sheets, jiffy pads and bubble pack sheets are often used as mechanical insulators between fruit and the package top wall, to prevent physical damage to fruit from fruit-package contact. Bubble pack sheets were the most commonly observed type used in pome packaging.

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The effects of multi-scale packaging on fruit quality and cooling rate have been studied (Chau et al., 1985; Delele et al., 2008; Smale, 2004; van der Sman, 2002; Vigneault & Goyette, 2002). For instance, Ngcobo et al. (2012) showed that the presence of internal packaging (such as polyliner bags) in multi-scale packages of table grapes restricted airflow through the package during FAC. The results showed that polyliner bags contributed between 40 to 83% of the total pressure drop of packages. In addition, the use of bunch carry bags (which are similar to thrift bags) accounted for 2 and 13% of the total pressure drop.

3.4 Ventilation characteristics

The ventilation characteristics of the eleven major package types identified are displayed in Table 3. Mk4, Mk6, Mk11 and Bushel packages have oblong vent holes in accordance with the mechanical strength recommendation by Han & Park (2007). The ventilation configuration of Mini-T, however, closely resembled the recommendation of Thompson et al. (2002), that 5 to 6% package wall ventilation should be used as a compromise between mechanical strength and airflow penetration. The Econo-T, Econo-D and Jumble packages also have mainly oblong vents; however, many carton sidewalls were found to have circular shaped holes, usually with a diameter of 26 mm. Finally, the Mk7 and Mk9 packages, which are relatively low in height, have circular holes (26 mm) and/or large cavities along the top edge of the package side walls. Several slot holes were also present, although during stacking, these would be obstructed by the corresponding tabs of the package below.

Many of the packages are stacked in configurations which allow both the package length and breadth to align perpendicular to the direction of airflow (Figure 2), highlighting the importance that both sides of the package are ventilated. Table 3 shows that the package ventilation varied considerably between 0 and 11% (TVA). Among telescopic package designs, only Mini-T has TVA >10%, while only Micro-D (Figure 1k) and Mark 7 of the display package designs have TVA >10%. The Mini-mk9, Mk7 and Mk9 packages have zero ventilation along the breadth (shortest side of the package).

Due to the different stacking configurations, these packages will not have complete ventilation alignment in stacking types a, b and d (Figure 2) in both stack orientations (1.2 m and 1.0 m). The lack of ventilation alignment will result in large pressure drops (Vigneault et al., 2004) and poor airflow rates during forced-air cooling and will therefore contribute to ineffective precooling of fruit (Kader, 2002). Computational fluid dynamic modelling of airflow, heat and mass transfer inside ventilated multi-scale packaging of spherical objects showed the stacking patterns have considerable influence on airflow distribution and fruit cooling rates (Delele et al., 2008).

None of the commonly used pome fruit packages were within the range of ventilation area (8-16%) recommended by de Castro et al. (2005b), while only the Mk7, Micro-D and Mini-T had mean ventilation area within the range (5-6%) recommended by Kader (2002). It should be noted, however, that these recommended TVA reported in the literature were based on experimental analysis of ideal package systems without internal packaging. It is therefore difficult to compare the different designs used to handle different types of fruit in different supply chains. More research is required in this area, including the application of recent advances in computational fluid dynamics and finite element modelling to improve package design and performance (Pathare et al., 2012).

4. Conclusions

Appropriate ventilated packaging is an essential tool in the process of postharvest management of fresh horticultural produce such as fruit. In addition, good temperature control in the cold chain is vital to maintain fruit quality and increase the duration of fruit storage in postharvest systems. The survey of ventilated package geometrical designs in South Africa showed that eleven corrugated fibreboard package designs are predominantly used in commercial handling and marketing of pome fruit. Furthermore, these package designs can be packed with several types of internal packaging, including trays, polyethylene liner bags, thrift bags and punnets.

The different types of packaging used to handle apples and pears can be divided into ‘display’ and ‘telescopic’ designs. Display packages, can through the use of internal packaging such as thrift bags and punnets, offer retail ready pre-packaged fruit, and therefore add additional marketing value to the package. Telescopic packages, on the other hand, offer high density fruit packing during shipping; however, they usually require repacking at the retailer. For the telescopic package designs, the Mk4 made up 48% of the apple package exports and the Mk6 made up 57% of the pear package exports in the 2008-2012 period. For display packages, the Mk7 was mostly used for pear exports (22%), while 22% of the apple exports were packed in Mk9. Total ventilation area of packages varied considerably between <1-11%, and there was no evidence of a standardised approach to optimise vent design. Although recommendations on TVA have been reported in literature based on specific package designs and types of fruit, these cannot always be applied to all

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packaging systems, due to several constraints, such as by importer specifications or excessive production costs.

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Table 1: Apple packages exported between 2008 and 2012, categorised by package type and region (PPECB, 2013).

	Africa	America	Atlantic Ocean Isle	Australia	C/Europe	F/East & Asia	Indian Ocean Island	M/East & Mediterranean	Unknown	Russia	United Kingdom	Total %
Bushel	41 662	23 046	0	0	15 793	556 139	42 217	623	1 767		2 993	0.61%
Econo-D	357 224	450	0	0	341 579	22 186	15 752	215 224	16 151	5 643	66 007	0.93%
Econo-T	107 555	3 702	0	216	1 219 051	58 707	18 546	127 153	9 434	28 146	268 021	1.65%
Micro-D	1 129	0	0	0	0	0	140	115	0	0	75	0.00%
Jumble	200 322	0	0	0	4 896	0	0	0	0	0	820	0.19%
Mini-mk9	3 363	0	0	0	3 641	0	0	185	0	0	52 739	0.05%
Mini-T	8 019	0	0	0	40 617	8 638	0	52 664	0	46	2 252	0.10%
Mark 4	15 429 298	283 275	3 077	1 972	19 063 127	11 055 384	610 483	4 226 980	496 208	315 350	2 163 004	48.20%
Mark 6	645 613	11 824	414	20	2 025 115	149 666	22 747	1 198 346	81 847	402 308	184 527	4.24%
Mark 7	7 605	430	0	0	285 406	10 271	0	12 428	20	920	284 747	0.54%
Mark 9	109 317	72 781	0	2	6 567 388	193 666	996	74 904	206 778	24 159	16 800 338	21.61%
Other	2 533 227	67 924	62	0	4 239 058	1 508 911	35 286	1 025 067	35 351	85 689	14 528 043	21.61%
Plastic	0	0	0	0	20 306	9 378	0	0	10 365	0	241 765	0.25%
Total %	17.47%	0.42%	0.00%	0.00%	30.39%	12.19%	0.67%	6.23%	0.77%	0.77%	31.08%	

Table 2: Pear packages exported between 2008 and 2012, categorised by package type and region (PPECB, 2013).

	Africa	America	Atlantic Ocean Isle	Australia	C/Europe	F/East & Asia	Indian Ocean Island	M/East & Mediterranean	Unknown	Russia	United Kingdom	Total %
Bushel	56	0	0	0	11 486	4 050	0	0	0	0	480	0.02%
Econo-D	30 479	0	0	0	80 753	3 284	8	217	770		13 065	0.17%
Econo-T	15 293	0	0	0	402 153	6 217	2 019	1 806	12 204	1 504	34 118	0.62%
Micro-D	14 947	0	0	0	6 530	0	20	34	0	0	36	0.03%
Jumble	2 363	0	0	0	0	0	0	63	0	0	0	0.00%
Mini-mk9	1	0	0	0	43 857	0	70	13 636	0	0	10 070	0.09%
Mini-T	62	280	0	0	314 732	1 095	700	0	16 585	80	4 290	0.44%
Mark 4	39 823	1 616	74	0	372 419	35 083	1 980	4 651	75 010	3 291	14 142	0.71%
Mark 6	1 322 479	1 077 697	823	17 973	28 639 825	4 035 054	261 231	2 655 450	1 410 063	2 023 905	2 018 872	56.63%
Mark 7	22 401	103 144	11 515	0	14 989 115	186 026	11 342	197 717	434 446	34 475	1 020 520	22.16%
Mark 9	144 201	39 715	0	75	5 144 087	25 340	84	16 861	434 096	8 657	2 595 403	10.96%
Other	385 864	21 683	30	226	4 087 668	933 648	14 091	528 540	41 677	220 133	0	8.12%
Plastic	15	0	0	0	4 745	0	0	0	975	0	28 392	0.04%
Total %	2.58%	1.62%	0.02%	0.02%	70.49%	6.81%	0.38%	4.45%	3.16%	2.99%	7.48%	

Table 3: Generalized package design specifications.

		Display					Telescopic					
	Package	Micro-D	Mini-mk9	Mark 9	Mark 7	Econo-D	Econo-T	Bushel	Mark 6	Mark 4	Jumble	Mini-T
Pack code (part of GTIN*)		A02C, B02C, C02C	M05D, M06D	A12T, A12D, B12D,C12D	A06D, B06T, B06D, C06T, C06D	E12D, T12D	E12T, T12T	M22T	M12T	M18T, P15T	J11T, J10T	M07T
International fibreboard class code		0432-M	0773-M	0773-M	0773-M	0773-M	0200-M/A	0200-M/A	0200-M/A	0200-M/A	0200-M/A	0200-M/A
Dimensions (mm)	Length	400	400	600	600	460	460	500	400	500	350	400
	Breadth	300	300	400	400	300	300	330	300	330	300	300
	Height	79	150	139	91	229	238	339	220-275	287	228	142
Length-wise surface area (mm^2)	Total area	31600	60000	83100	54600	105340	109480	169500	97200	143625	79625	56800
	Vent area	3214	2094	3721	5599	1145	3680	5073	5163	5448	3520	5880
	% Vent area	10.17%	3.49%	4.48%	10.25%	1.09%	3.36%	2.99%	5.31%	3.79%	4.42%	10.35%
Breadth-wise surface area (mm^2)	Total area	23700	45000	55400	36400	68700	71400	111870	72900	94793	68250	42600
	Vent Area	220	0	49	0	2193	1473	3598	2050	3758	2086	2880
	% Vent area	0.93%	0.00%	0.09%	0.00%	3.19%	2.06%	3.22%	2.81%	3.96%	3.06%	6.76%
Internal packaging (number of trays)		1	2 or 2 +Poly-liner or thrift-bags or punnets	2 or 2+Poly-liner or thrift-bags or punnets	1 or 1+Poly-liner or thrift-bags or punnets	thrift-bags	thrift-bags	6 or 6+Poly-liner	4 or 4+Poly-lineror or thrift-bags	4 or 4+Poly-liner	Loose	2 or 2+Poly-liner
Packages per pallet layer		10	10	5	5	8	8	7	10	7	10	10

*Global Trade Item Number

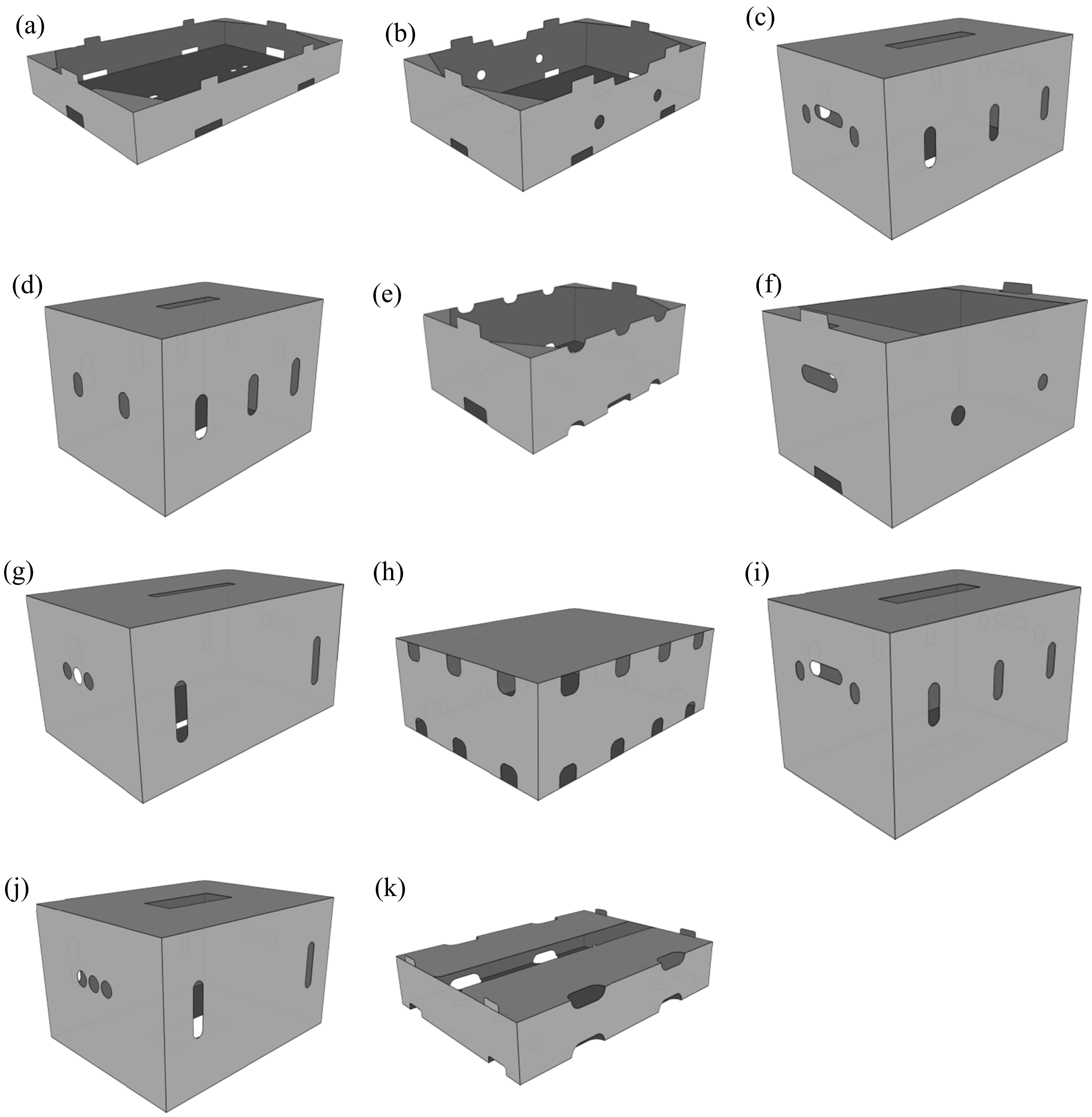

Figure 1: 3-D outlines of (a) Mark 7, (b) Mark 9, (c) Mark 4, (d) Mark 6, (e) Mini-mk9, (f) Econo-D, (g) Econo-T, (h) Mini-T, (i) Bushel, (j) Jumble and (k) Micro-D packages (not to scale).

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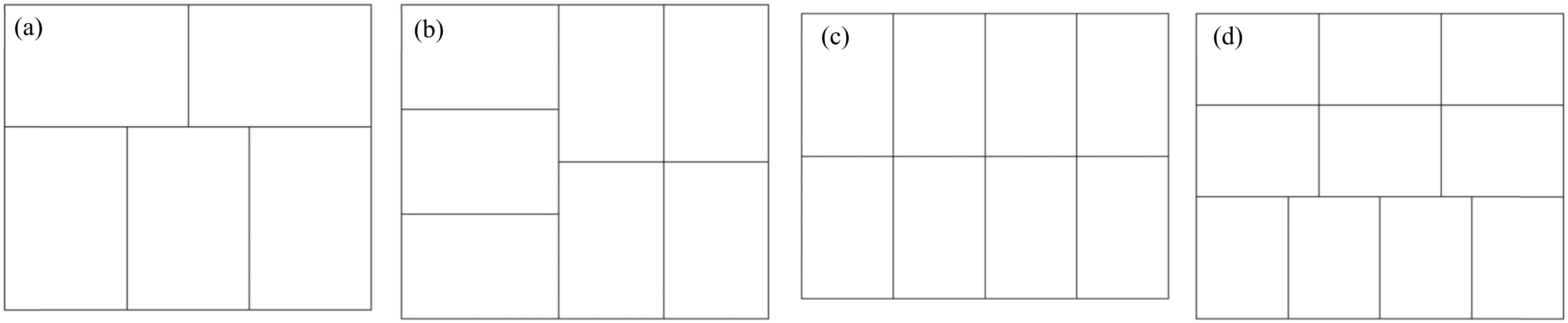

Figure 2: Pallet stacking arrangements showing (a) 5, (b) 7, (c) 8 and (d) 10 packages per layer.

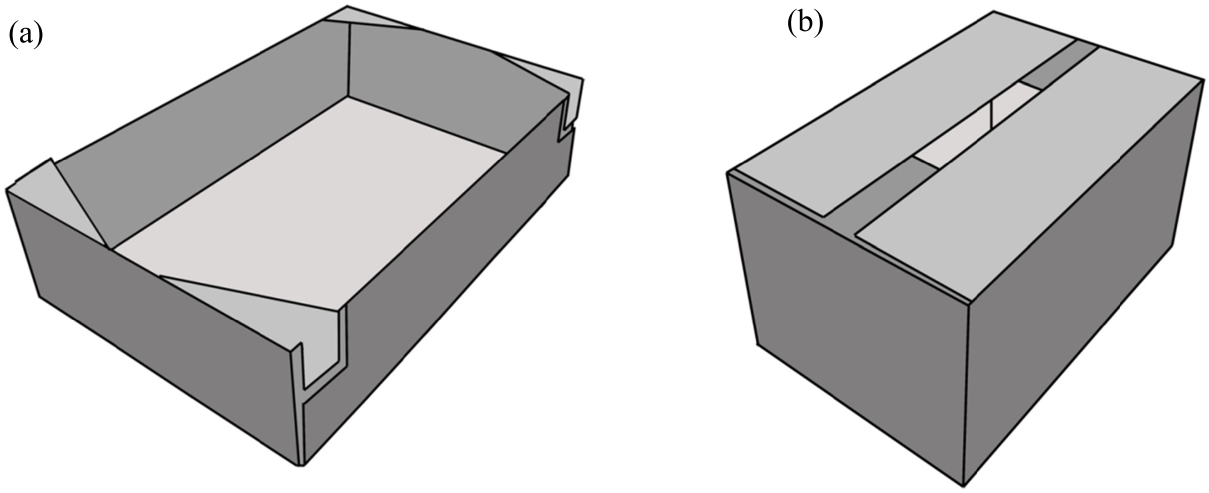

Figure 3: 3-D folding outline of (a) display/(0773-M) and (b) telescopic/(0200-M/A) package designs.

PAPER 2: Resistance to airflow inside ventilated packaging designs used for handling apples

Keywords: packaging, pressure drop, air distribution, cold chain, apple fruit, resistance to airflow

Abstract

The use of various designs in package containers, as well as the use of multi-scale packaging is part of the postharvest handling procedure of fruit, such as apples. Three different packages, in combination with three multi-packaging methods, were characterized for their resistance to airflow when in a stacked configuration during forced-air cooling conditions. Specifically, the research examined the effect of the packaging, stacking and ventilation configuration on the total pressure drop contribution. A correlation was found between the stacks effective ventilation area and the total pressure drop. This showed that large total open areas through a stack led to significantly reduced pressure drops, which emphasized the importance to align ventilation of packaging. The pressure drop contributed by the cartons was 8%, while the fruit simulators contributed 3%. The addition of polyliner bags produced up to seven times more pressure drop than the produce simulators and cartons combined. It was also found that airflow was making use of exo-carton conduits. The use of these conduits are expected to have increased as the resistance to airflow of the packaging increased, thereby bypassing the fruit simulators and reducing the efficiency of cooling. The results also highlighted the importance of the ventilation position on the package walls. Ventilation holes configuration should consequently facilitate more alignment during stacking, in order to improve airflow interaction with the produce, as this will increase the rate of heat transfer.

Nomenclature

a	resistance coefficient, kg.s$^{(b-2)}$.m$^{-(b+2)}$
b	resistance exponent
K	Darcy permeability, m^2
n	vent resistance exponent
O	vent hole ratio, %
P	pressure, Pa
u	velocity vector, m.s^{-1}
β	Forchheimer drag coefficient, m.s^{-1}
μ	dynamic viscosity, Pa.s
ρ	density, kg.m^{-3}

1. Introduction

Forced-air cooling (FAC) of fruit inside ventilated packaging is used in the cold chain to maintain the appropriate fruit temperature after sorting and grading in the packhouse. During FAC, refrigerated airflow is exhausted through stacked packaging, facilitating convective heat transfer between warm fruit and cold air (Ferrua & Singh, 2011; Thompson et al., 2002). The uniformity of cooling inside the package is important to avoid 'hot spots' which promote quality degradation or 'freezing spots' which may lead to chilling-related physiological disorders in fruit. Homogeneity of cooling or lack of it (heterogeneity) is determined by the airflow patterns and is significantly influenced by the geometrical design of the packaging as well as the vent characteristics such as shape, size, number and position on the package (de Castro et al., 2004, 2005; Dehghannya et al., 2012). As FAC processes are typically only completed once all areas in a stack have reached endpoint temperature (Thompson et al., 2008), heterogeneous cooling can result in extended periods of FAC, which can reduce energy efficiency (Ferrua & Singh, 2009).

Resistance of packaging to airflow significantly increases energy utilisation during FAC (Delele et al., 2008; Ngcobo et al., 2012a; Thompson et al., 2010). Resistance to airflow (RTA) has been investigated by examining the effects of bulk product properties (Chau et al., 1985; Haas et al., 1976), fluid properties (Sun & Hu, 2003), and the ventilation characteristics of the container (Vigneault & Goyette, 2002; Vigneault et al., 2004a). These studies have shown that porosity and ventilation characteristics of the packaging are key factors that influence the resistance to airflow. It was shown that total ventilated areas (TVA) smaller than 25% significantly increase the pressure loss of a system (Vigneault & Goyette, 2002). Based on further extended studies, TVA recommendations for optimised energy efficiency utilisation were refined to range from 8 to 16% (de Castro et al., 2005).

Numerical models have been used to characterise the relationships between airflow velocity and pressure drop. Consequently, several studies have documented resistance to airflow through bulk fruit and vegetables as well as vented cartons/packages (Chau et al., 1985; Delele et al., 2008; Haas et al., 1976; Neale & Messer, 1976, 1978; Ngcobo et al., 2012a; Verboven et al., 2004; Vigneault & Goyette, 2002; Vigneault et al., 2004b). However, the relationship between airflow velocity and pressure drop through stacked packaged horticultural produce has been best characterised using the Darcy-Forchheimer and Ramsin equations (as depicted in equation 1 and 2).

In addition, the coefficients of the Darcy-Forchheimer and Ramsin equations are generally influenced by certain factors, specifically the Darcy permeability of a porous matrix (β) parameter and the Forchheimer drag constant (1/K) parameter (van der Sman, 2002; Verboven et al., 2004). These coefficients are determined experimentally from the Darcy-Forchheimer equation and are primarily influenced by produce size, porosity, stacking pattern, fluid property, product's shape, roughness, confinement ratio and box vent hole ratio (Delele et al., 2008; van der Sman, 2002). In contrast, the *a* and *b* coefficients from the Ramsin equation are also experimentally determined, but are mainly influenced by stacking pattern, fruit diameter and box porosity (Chau et al., 1985; Delele et al., 2008).

Ramsin (Chau et al., 1985)
$$\nabla P = -au^b \tag{1}$$

Darcy-Forchheimer (Forchheimer, 1901)
$$\nabla P = -\frac{\mu}{K}u - \beta\rho|u|u \tag{2}$$

Although a great deal of literature has been published on resistance to airflow through packaged produce such as citrus and tomatoes (Chau et al., 1985; Moureh et al., 2009; van der Sman, 2002; Vigneault & de Castro, 2005), it is only recently that researchers have examined the effects of multiple layers of internal packaging (multi-scale packaging) on resistance to airflow (Ho et al., 2013; Ngcobo et al., 2012a). For example, apple fruit can be packaged in stacked corrugated fibreboard cartons, polyliner bags, polystyrene/pulp trays, thrift bags or punnet containers (Kader, 2002). Knowledge of the resistance to airflow through apple fruit packaging is lacking and this information is needed to assist in the optimal design of packaging for cost-effective cold chain performance. The aim of this study was therefore to examine the contributions of the different components of multi-scale apple packaging designs to resistance to airflow. The effect of different stacking configurations was also investigated.

2. Materials and methods

2.1 Packaging materials

Three types of commercially used apple multi-scale packaging were examined. Mark 4 (Mk4, 500×333×270 mm), Mark 6 (Mk6, 400×300×270 mm) and Mark 9 (Mk9, 600×400×152 mm) packages were selected (Figure 1). The packages were stacked onto a 1.2×1.0 m pallet, using the configurations in Figure 2. The Mk4 and Mk6 packages were stacked three packages high, whereas Mk9 was stacked five packages high. The apple multi-scale packaging is comprised of a carton (corrugated fibreboard) and combinations of a plastic liner film (37.5 µm polyethylene bag with no perforations), polystyrene trays and thrift bags (37.5 µm polyethylene bag with 0.17% total perforated area).

Polyethylene balls containing air at standard atmospheric pressure (Ø=80mm; wall thickness=560±80 µm) were used as produce simulators, to mimic the presence of apples in the airflow experiment following the approach reported by previous researchers (Alvarez & Flick, 1999; de Castro et al., 2004; Vigneault & de Castro, 2005). Four trays were packed into the Mk4 (90 fruit per package) and Mk6 (60 fruit per package) packaging, while the Mk9 packed two trays (64 fruit per package) or 14 thrift bags (70 fruit per package).

For each package design, the stack of packages was assessed across both the 1.2 m (length) and 1.0 m (width) sides (a) when empty, (b) with trays and fruit (fruit trays) and (c) with a plastic liner and fruit trays. For Mk9 design, thrift bags were included. The effective ventilation area was measured as the stacks vent/hole ratio to the total package surface area excluding vents which were considered to be ineffective due to misalignment (Table 1).

2.2 Experimental setup

The stack and FAC equipment were placed near the centre of a room with temperatures ranging between 20-28°C. The FAC equipment was used to generate a spectrum of controlled airflow rates across the palletized half stack (Figure 3). A centrifugal suction fan was used to force air through the stack (KDD 10/10 750W 4P-1 3SY, AMS supplies, Sandton, South Africa).

The total pressure drop and air velocity were continually monitored using a manometer setup, positioned in the 'pressure drop tunnel' (Figure 3). The manometer was achieved using a differential pressure meter (Air Flow Meter Type A2G-25/air2guideF, Wika, Lawrenceville GA 30043, USA) and a data controller (WCS-13A, Shinko Technos CO LTD, Osaka, Japan) that captured the total pressure drop across the stack. A hotwire anemometry air velocity meter (Alnor velometer AVM440, TSI incorporated, Shoreview MN 55126, USA) was used to measure the superficial airflow rate of the output air, which escaped the top of the FAC equipment at the 'Extender tunnel' (Figure 3).

2.3 Test procedure

The tests were conducted within a range of airflow rates (0.0-0.5 $m.s^{-1}$). Packages were tightly stacked on an airtight pallet base (Figure 1). The stack was placed against the FAC equipment as shown in Figure 3 and sealed with airtight plastic liners along the sides, top and bottom. so that air was only able to enter the stack from the opposite side of the FAC equipment. Resistance to airflow of the stack was measured by applying a range of controlled airflow rates across the stack and monitoring the corresponding pressure drop. The first experiment (with Mk4 length package design) was repeated three times and the results showed that there were no significant variations among the replicates (Figure 4), irrespective of airflow rate and pressure drop. Therefore, experiments on other package designs were not replicated.

2.4 Statistical Analysis

Statistical tests used SAS 9.2 software (SAS, North Carolina, USA). Bonferroni comparisons were completed on the replicated data ($\alpha = 0.05$).

3. Results and discussion

3.1 Airflow through empty apple packages

Misalignment of ventilation holes was observed in each of the three stacked packages across the length or width orientation (Figure 5). Reduction in the effective ventilation was

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therefore frequently observed (Table 1), ranging from no reduction in ventilation area of Mk4 lengthwise to over 95% for Mk9 lengthwise. The equations of Ramsin (equation 1) and Darcy Forchheimer (equation 2) were used to express the resulting superficial airflow velocity versus pressure drop values (Ferrua & Singh, 2009; Ngcobo et al., 2012a; van der Sman, 2002; Vigneault et al., 2004c). The resulting *a, b,* β and 1/K coefficient values for these two equations are shown in Table 2 and Table 3. The *a* coefficient had the strongest linear correlation to total pressure drop and was therefore used for comparisons when examining different multi-scale packages.

Stacks orientated to provide ventilation alignment (Figure 5) were observed to have lower pressure drops. The reduced pressure drop can be attributed to the larger effective ventilated area (Table 1), which reduced the resistance to airflow through the stack (Vigneault & Goyette, 2002). The stack with the lowest *a* coefficient (1.11E+03) from the Ramsin equation and therefore the lowest resistance to airflow occurred in the Mk4 stack tested in the length-wise direction without fruit (empty) inside the package (Figure 6). Higher *a* values (larger airflow resistances) were obtained in the Mk6 width (6%), Mk6 length (67%), Mk4 width (92%), Mk9 width (117%) and Mk9 length (356%) stacks than in the Mk4 length (Table 2).

With the use a velometer, airflow was observed entering between the stacked package edges and corners during the forced-air experiments, offering evidence that airflow was by-passing ventilation holes. The effects of vent/hole ratio, expressed in percent (O), on parameter β have been documented by several authors (Delele et al., 2008; Ngcobo et al., 2012a; Smale, 2004; van der Sman, 2002). This relationship can be characterized with a power equation ($\beta = CO^n$), where C is a constant and *n* can be used to represent the vents influence on RTA. In this study, the *n* value was found to be -0.66 ($R^2=0.70$), while other researchers have reported *n* values of -0.89, -1.5, and -2.43. The high *n* value obtained in the present study indicates that ventilation area contributed less to pressure drop than in previous research. This can be attributed to several factors including the presence of airflow through the gaps between the packages (exo-carton routes), the presence of ventilation holes, differences in package design and type of produce inside the package.

The unobstructed total ventilation in the stacks ranged between 2.07 and 4.42%, which is the maximum ventilation possible if no ventilation holes are misaligned (Table 1; Figure 5). However, the effective ventilation ranged between 0.09 to 4.42% (Table 1; Figure 5). The effective ventilation for each package design tested was well below the range (8-25%) recommended in the literature to improve energy efficiency (de Castro et al., 2005; Vigneault & Goyette, 2002). The small ventilation ratios in this study thus significantly increased RTA, which explains why exo-carton airflow routes occurred during the cooling of fruit in stacks. Consequently, airflow pathways may not only be affected by the ventilation and contents (de Castro et al., 2004, 2005; Dehghannya et al., 2012; Vigneault & Goyette, 2002; Vigneault et al., 2006), but also by factors affecting the size of exo-carton routes, such as the stacking configurations and carton deformation.

3.2 Airflow resistance of trays and fruit

The results of pressure drop during airflow through stacked packages packed with trays and fruit (fruit-trays) are shown in Figure 7. An increase in *a* values was observed between the empty stacks and the corresponding Mk4 length (134%), Mk4 width (215%), Mk6 length (79%), Mk6 width (170%), Mk9 length (97%) and Mk9 width (300%) stacks, which were packed with fruit trays (Table 2). The results show that the presence of the fruit on trays affected the RTA differently in each stack of different package designs. This may be attributed to the ventilation size, position and stacking patterns, which together are directing different amounts of air flowing past the fruit trays. These results suggest that the quantity of airflow in contact with the package contents influences the increase in RTA (Delele et al., 2008).

Stacks orientated with ventilation alignment towards the airflow (Figure 5) had lower pressure drop values than stacks with misaligned ventilation. This result corroborates earlier research findings, which showed that larger effective ventilation reduces resistance to airflow (Parsons et al., 1972). The Mk4 stack (length) again produced the lowest *a* value and therefore had the lowest resistance to airflow (Figure 7). The *a* values were higher in the Mk6 width (22%), Mk6 length (27%), Mk4 width (158%), Mk9 width (270%) and Mk9 length (283%) than in the Mk4 length. The effect of stacking pattern on RTA was similar in the empty packages (Figure 6) and those packed with fruit trays (Figure 7). This may be attributed to the fact that the presence of internal packaging (trays) did not significantly influence the routes and patterns of airflow distribution in the stacks. Consequently, airflow was still able to utilize the ventilation holes and flow through the packages in a similar manner, as it did in the empty stacks (Ngcobo et al., 2012a).

3.3 Airflow resistance of multi-scale packages

When the polyliner and fruit trays (poly-bag) were added to the empty cartons, the *a* values increased for the Mk4 length (3622%), Mk4 width (2970%), Mk6 length (2923%), Mk6 width (3688%), Mk9 length (305%) and Mk9 width (645%) stacks (Table 2). The addition of thrift bags (thrift-bags) to empty cartons also resulted in increased *a* values for the Mk9 length (69%) and Mk9 width (519%) stacks. The increase was higher in the stack orientations which had higher effective ventilation (Table 1), indicating that airflow preferentially followed aligned ventilation holes in the empty stacks. The polyliner bags therefore increased resistance to airflow at the ventilation holes, which corroborates the findings of previous studies on multi-scale packaging of table grapes (Ngcobo et al., 2012a).

The results of pressure drop through the stacks packed with fruit on trays inside a polyliner bag and fruit inside thrift bags are shown in Figure 8. The resulting coefficients using the Ramsin and Darcy Forchheimer equations are shown in Table 2 and Table 3. When a polyliner was added, the lowest resistance to airflow (lowest *a* value) occurred when the stack of Mk9 packages was tested in the width direction (Table 2). The *a* values were thus higher in Mk9 length (15%), Mk4 length (131%), Mk6 width (149%), Mk6 length (213%) and Mk4 width (265%) than in the Mk9 width. Furthermore, packing fruit with thrift bags resulted in 39% lower *a* value than polyliner bags (Figure 8).

The total pressure drop in a stack of multi-scale packaging was calculated as the sum of the factors ($\Delta P_{total} = \Delta P_{box} + \Delta P_{fruit} + \Delta P_{bag}$) affecting pressure drop (van der Sman, 2002). The results showed that polyliner bags contributed 95.2±0.9% of the total pressure drop in the Mk4 and Mk6 stacks, and 75.0±2.0% in the Mk9 stacks (Figure 9). This difference in pressure drop contribution can be attributed to the position of the ventilation openings in each package design, given that the contribution to total pressure drop appeared to be independent of ventilation area (Table 1). Mk4 and Mk6 designs have vent openings near the centre of the package, while the Mk9 vents are placed at the top and bottom of the package (Figure 5). Airflow entering at the centre of a package must consequently flow around the polyliner bag. This presents several changes in direction and velocity of the airflow, which increases friction and therefore higher RTA (McCabe et al., 1993). The Mk9 shallower design allows for a more direct airflow route and therefore less resistance. Similar results were observed by Ngcobo et al. (2012a), who reported that polyliners contributed over 80% to the total pressure drop through multi-scale table grape packaging. The authors also found that grape carry bags, which are similar to apple thrift bags contributed much less (30%). The table grape packages have similar geometrical designs to the Mk9 as well as vent positions at the lower and upper parts of the package walls. When using the thrift bag in Mk9 packages which had an effective ventilation of 2.43% (width) and 0.09% (length), the pressure drop contribution was 84 and 41%, respectively (Table 1; Figure 9). In contrast to the polyliner stacks, the thrift bags provide multiple airflow routes through the carton. The RTA was therefore dependent more on the effective ventilation area than the ventilation position (Table 1).

The polyethylene bags create a barrier around the fruit, which limits the exchange of air between inside and outside the bag (Ngcobo et al., 2012b; Thompson et al., 2008). Liner bags are generally used to reduce fruit moisture loss, thereby preserving quality during transport and storage (Maguire et al., 2001; Watkins & Thompson, 1992). However, the present study has shown that the use of polyliners resulted in a large increase in RTA, while the thrift bags produced a considerably smaller RTA value. Thrift bags may consequently offer a convenient alternative to polyliner bags, especially when fruit are sensitive to water loss and rapid pre-cooling is required.

The second largest contributor to pressure drop was the carton (8.2±8.0%), while the fruit trays component contributed the least (3.3±4.4%) to the total pressure drop (Figure 9). These findings are consistent with observations in literature, which reported that the carton component without internal packaging is the largest contributor to pressure drop, even when ventilation is higher than those of the present study (Haas et al., 1976).

Mk4 package design was used to investigate the changes in pressure drop as a function of the approach velocity of air and the results showed that the degree of variation was minimal for each type of inner packaging format used (Figure 4). Analysis of the inner packaging of Mk4 showed that they had significant effects ($p < 0.05$) on the β (Darcy Forchheimer) and a coefficients, which are related to resistance to airflow. The Darcy-Forchheimer and Ramsin equations were successfully used to characterise airflow through packaged produce. The Ramsin equation was preferable to the Darcy-Forchheimer equation, as it had a stronger R^2 value (0.995 versus 0.965). In addition, the Ramsin equation provided better predictions of pressure drop within the range of airflow velocities tested, while the best fit Darcy-Forchheimer equation frequently predicted negative values for pressure drop at low airflow

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velocities ($<0.1 \mathrm{m.s^{-1}}$). This phenomenon can be attributed to the higher pressure drops in this study, compared with those reported in the literature for other package designs and other types of fruit such as oranges (Chau et al., 1985; Vigneault & Goyette, 2002).

4. Conclusions

The effect of stacking, multi-scale packaging and ventilation design was examined in apple fruit packaging. The study showed that the examined apple fruit packaging designs had individual ventilation ratios significantly smaller than recommendations made in literature. In addition, the stacking patterns resulted in even smaller ventilation ratios (effective ventilation), due to misalignment of ventilation holes. The effective ventilation area thus influenced the total pressure drop of all the packaging components.

The second largest pressure drop contributor was the carton (8%) while fruit trays had the lowest contribution (3%). The position of ventilation holes on the carton appeared to be more important in determining the package contribution to total pressure drop when using polyliner and thrift bag components. The contribution of polyliner bags to total pressure drop (89%) was almost seven times higher than the combination of the carton and fruit tray packaging components, while the contribution of fruit filled thrift bags to total pressure drop was 66% larger than the cartons contribution (24%). It is therefore recommended that more research be performed on the use of thrift bags in cooling and moisture loss control during forced-air cooling conditions.

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Table 1: Ventilation of empty carton stacks. Effective ventilation shows total stack ventilation area after blockages by other cartons. Unobstructed ventilation shows the average theoretical ventilation if no obstructing cartons were blocking ventilation holes.

Package stack	Individual carton dimensions (mm)	Orientation	Total area (cm^2)	Effective Ventilation		Unobstructed ventilation	
				Ventilated area (cm^2)	Open area (%)	Ventilated area (cm^2)	Open area (%)
Mk4	500×333×270	length	9720	430	4.42%	430	4.42%
		width	8100	124	1.53%	318	3.93%
Mk6	400×300×270	length	9720	72	0.74%	214	2.20%
		width	8100	289	3.57%	289	3.57%
Mk9	600×400×152	length	9120	8	0.09%	189	2.07%
		width	7600	185	2.43%	185	2.43%

Table 2: The *a* and *b* coefficients derived from the Ramsin equation for the resistance to airflow experiments per pallet stack of packages.

Carton	Orientation	Packaging	*a*	*b*	R^2
Mk4	length	Empty	1.11E+03 (±1.43E+02)	1.41E+00 (±1.49E-02)	0.9970
		Fruit trays	2.60E+03 (±1.30E+02)	1.67E+00 (±2.60E-02)	0.9981
		Polyliner	4.13E+04 (±1.20E+03)	1.77E+00 (±3.25E-03)	0.9971
	width	Empty	2.13E+03	1.48E+00	0.9978
		Fruit trays	6.70E+03	1.77E+00	0.9960
		Polyliner	6.53E+04	1.83E+00	0.9993
Mk6	length	Empty	1.85E+03	1.45E+00	0.9997
		Fruit trays	3.31E+03	1.60E+00	0.9846
		Polyliner	5.60E+04	1.80E+00	0.9975
	width	Empty	1.18E+03	1.42E+00	0.9958
		Fruit trays	3.18E+03	1.72E+00	0.9969
		Polyliner	4.46E+04	1.79E+00	0.9974
Mk9	length	Empty	5.06E+03	1.57E+00	0.9995
		Fruit trays	9.96E+03	1.89E+00	0.9897
		Polyliner	2.05E+04	1.71E+00	0.9945
		Thrift-bag	8.58E+03	1.89E+00	0.9921
	width	Empty	2.41E+03	1.50E+00	0.9982
		Fruit trays	9.61E+03	2.03E+00	0.9951
		Polyliner	1.79E+04	1.71E+00	0.9988
		Thrift-bag	1.49E+04	1.99E+00	0.9826

Table 3: The β and 1/K coefficients derived from the Darcy-Forchheimer equation for the resistance to airflow experiments per pallet stack of packages.

Carton	Orientation	Packaging	β	1/K	R^2
Mk4	length	Empty	1.73E+03 (±8.15E+00)	8.30E-01 (±8.18E-01)	0.9992
		Fruit trays	2.52E+03 (±2.15E+02)	4.60E-02 (±4.08E-02)	0.9995
		Polyliner	6.42E+04 (±2.02E+03)	3.11E+00 (±4.82E-01)	0.9501
	width	Empty	3.84E+03	1.93E-01	0.9818
		Fruit trays	5.70E+03	3.01E+02	0.9978
		Polyliner	9.42E+04	4.04E+02	0.9260
Mk6	length	Empty	2.60E+03	1.28E+02	0.9978
		Fruit trays	4.10E+03	1.19E+02	0.9986
		Polyliner	8.37E+04	1.82E+00	0.8621
	width	Empty	2.27E+03	6.99E-01	0.9752
		Fruit trays	3.04E+03	1.25E+02	0.9996
		Polyliner	6.89E+04	1.71E+00	0.8122
Mk9	length	Empty	7.77E+03	1.15E+02	0.9996
		Fruit trays	8.34E+03	2.07E+02	0.9989
		Polyliner	3.54E+04	2.60E+00	0.8624
		Thrift-bag	7.32E+03	1.48E+02	0.9982
	width	Empty	3.93E+03	4.28E-01	0.9958
		Fruit trays	7.30E+03	5.76E+01	0.9994
		Polyliner	2.76E+04	9.26E-01	0.9614
		Thrift-bag	1.16E+04	1.34E+02	0.9970

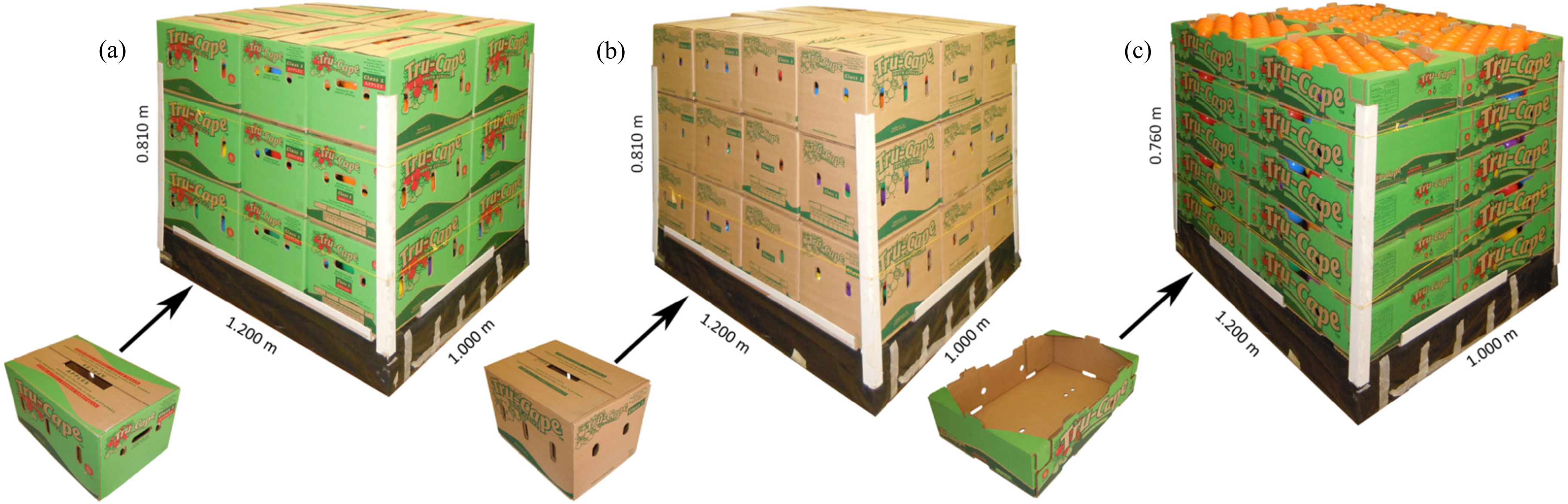

Figure 1: Photos of the (a) Mark 4, (b) Mark 6 and (c) Mark 9 palletised stacks and individual packages.

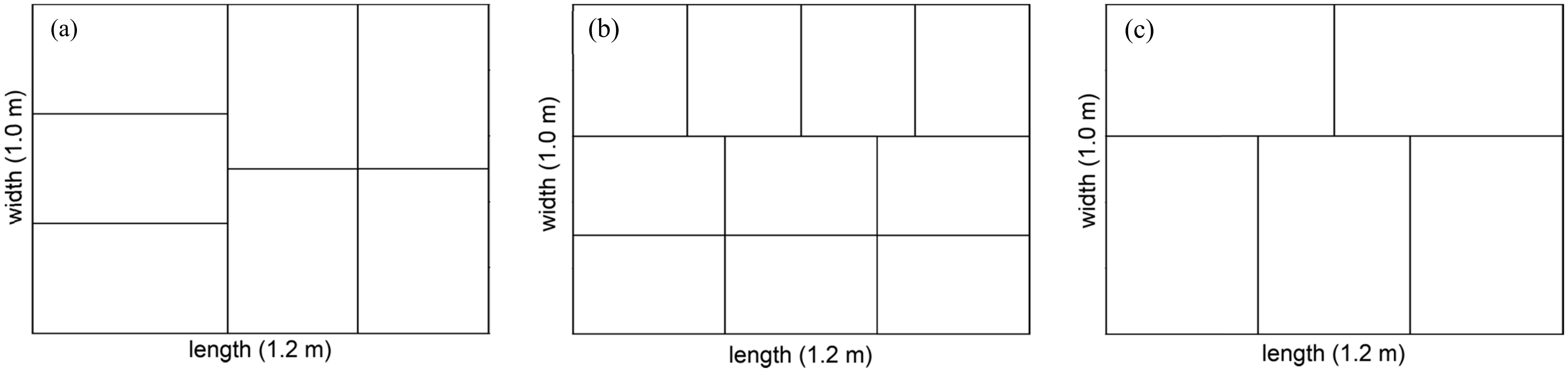

Figure 2: Layout of the individual cartons in a single horizontal layer for the (a) Mark 4, (b) Mark 6 and (c) Mark 9 pallet stacks.

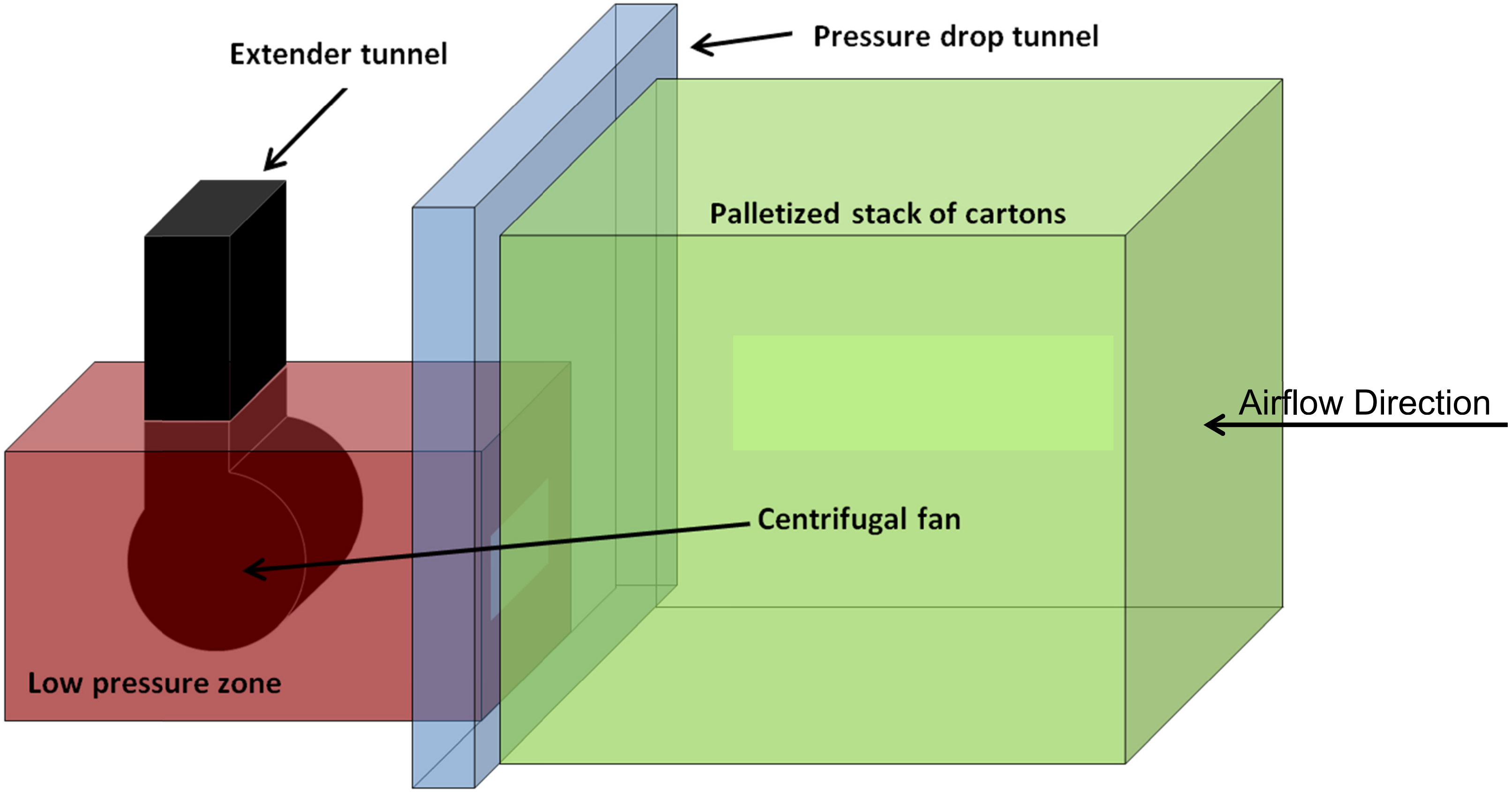

Figure 3: Schematic diagram of the FAC equipment. Airflow progressed through the stack into the pressure drop tunnel. All sides of the stack except the side in which airflow entered were sealed using plastic liners.

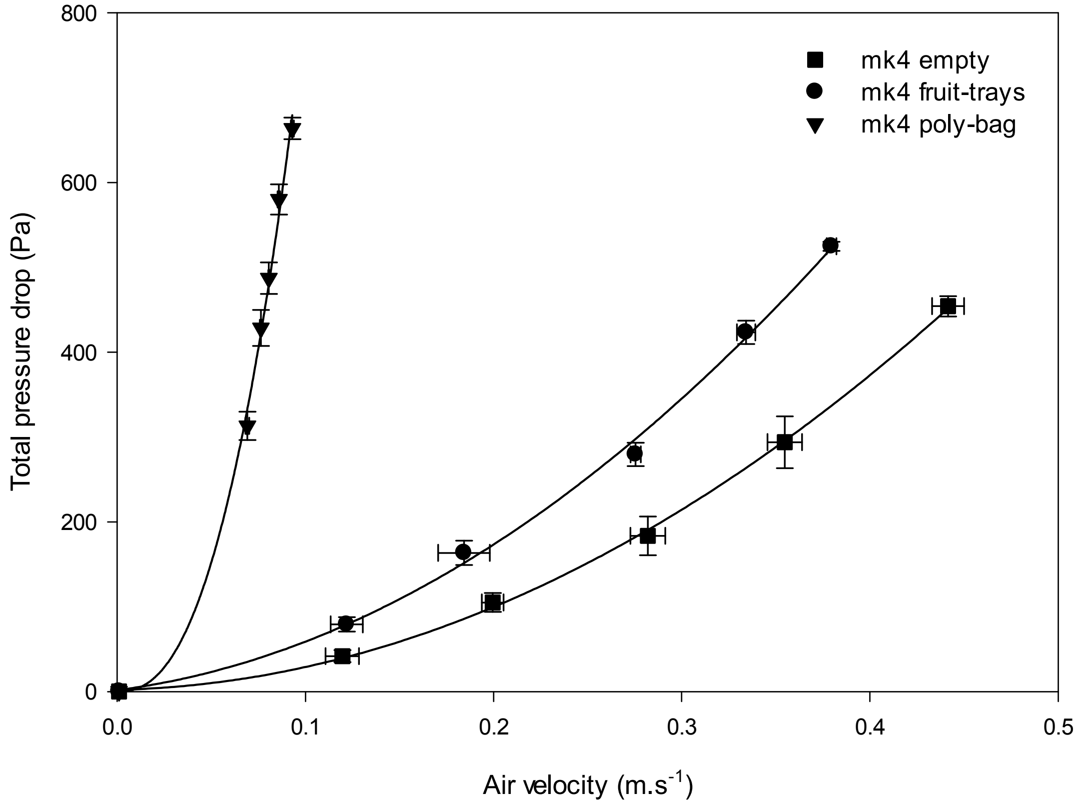

Figure 4: Pressure drop as a function of approach air velocity across the length of all Mk4 packages treatments, error bars show standard error of the mean.

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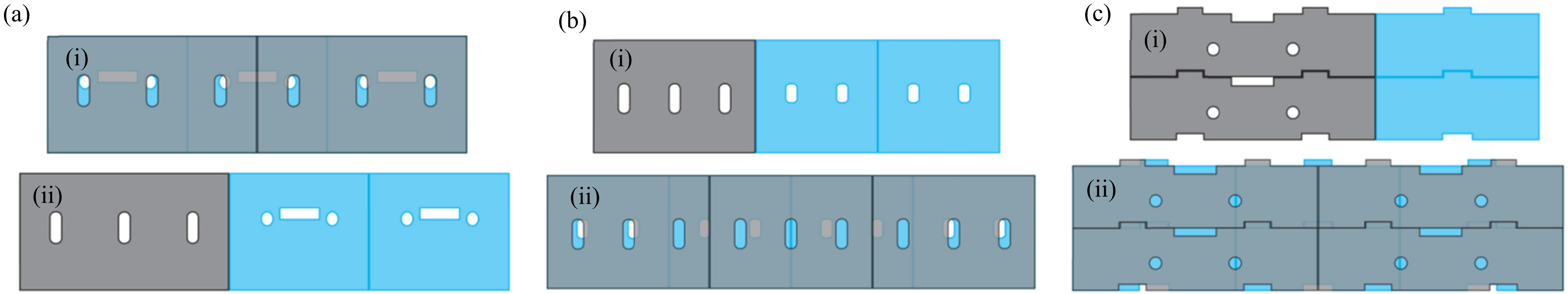

Figure 5: Ventilation alignment when (a) Mark 4, (b) Mark 6 and (c) Mark 9 packages are in a stack at (i) width (1.0 m) and (ii) length (1.2 m) orientations. Grey shows the longest side of the packages, blue shows the narrowest side of the packages and the white spaces indicate alignment of ventilation through the stack. Areas in white thus indicate effective ventilation in the stack.

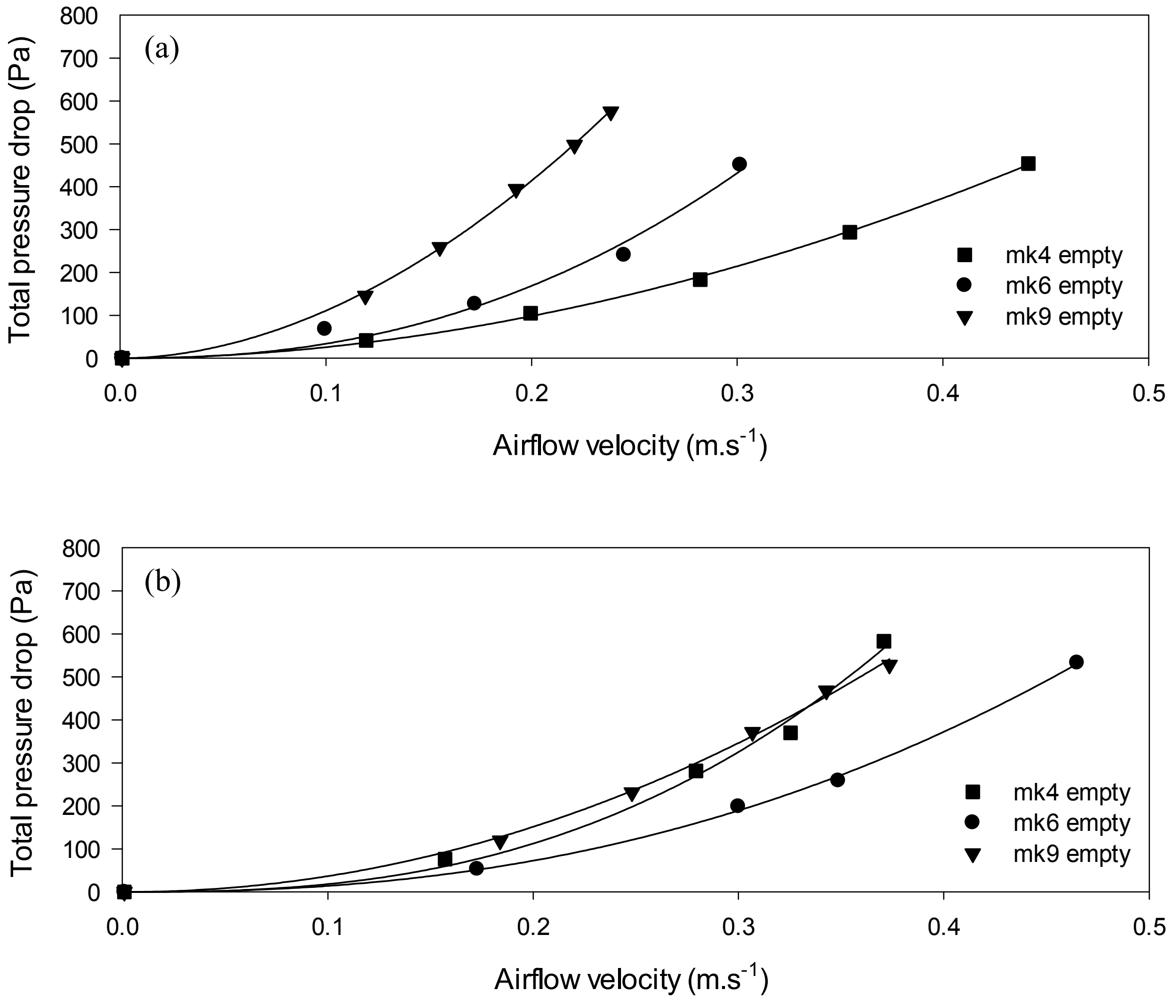

Figure 6: Pressure drop as a function of approach air velocity (a) across the length and (b) the width for empty packages.

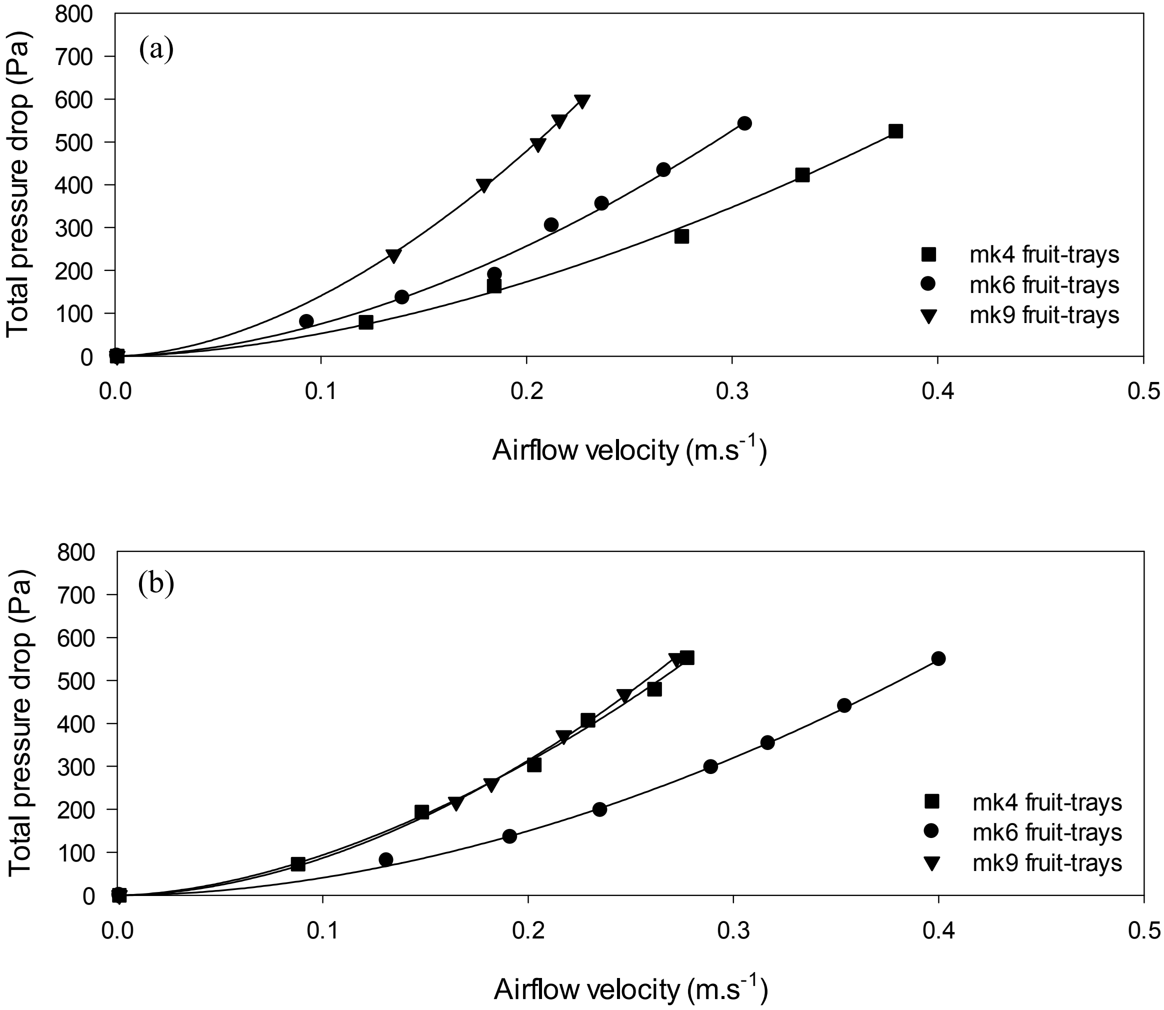

Figure 7: Pressure drop as a function of approach air velocity (a) across the length and (b) the width for the cartons packed with trays and fruit.

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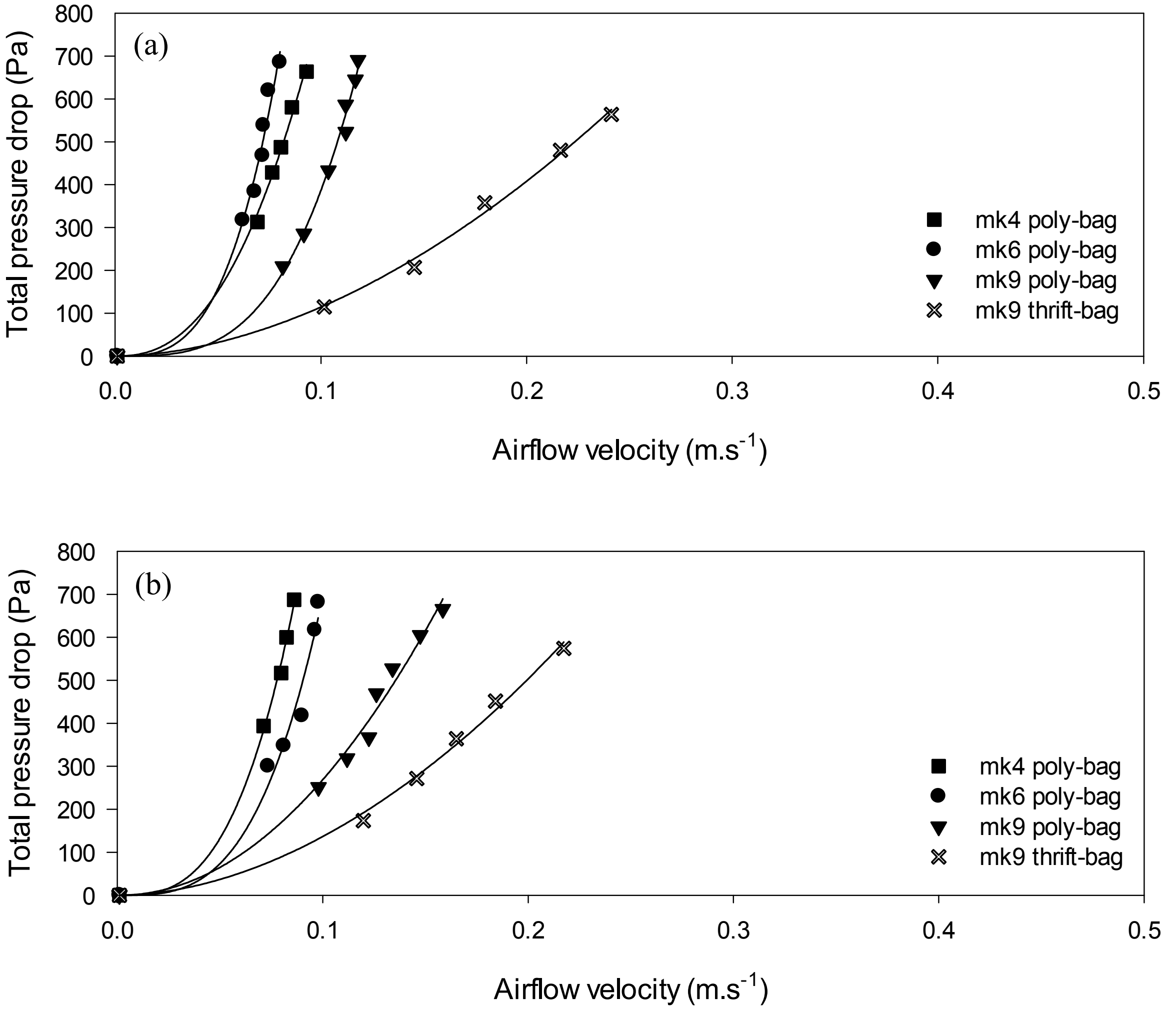

Figure 8: Pressure drop as a function of approach air velocity (a) across the length and (b) the width for the cartons packed with liner bags, fruit trays or fruit in thrift bags.

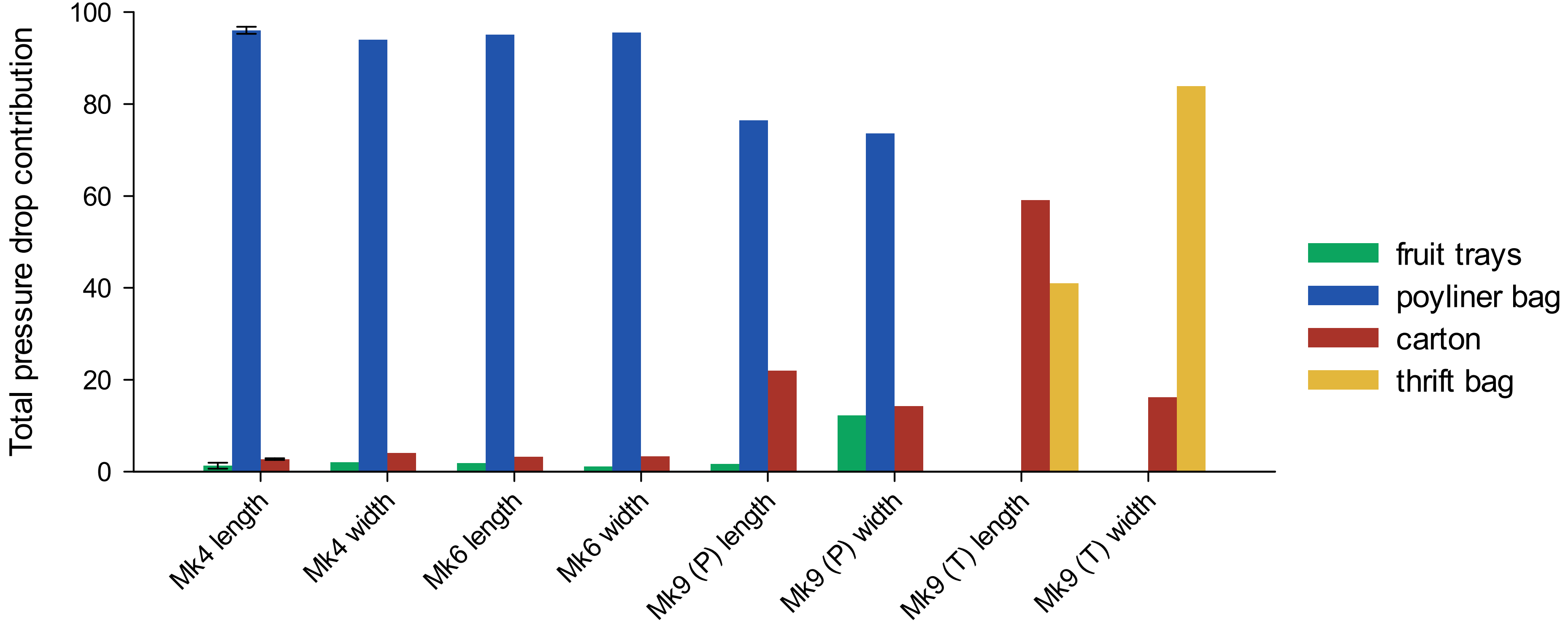

Figure 9: Percentage contribution to total pressure drop by each multi-scale packaging component. The parenthesis P indicates a Mk9 stack when using trays. The parenthesis T indicates the use of thrift bags. Error bars for the Mk4 length results indicate the standard deviation of the mean.

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PAPER 3: Spatial variation in fruit cooling rate and moisture loss of apples inside ventilated packaging during forced-air cooling

Keywords: forced-air, apples, cooling rate, cooling heterogeneity, moisture loss, multi-scale packaging

Abstract

Forced-air cooling is commonly used in the horticultural industry to remove the field heat of harvested fruit. This study investigated the effect of stacking, package design and internal packaging on the cooling rate, cooling heterogeneity and moisture loss of fruit under forced-air cooling conditions. Positive correlations were observed between airflow velocity, cooling rate and mass loss, while the uniformity in cooling was correlated to the effective ventilated area of the stack. A deficiency in ventilation was observed in the packaging types due to the lack of ventilation alignment in the stacked packages as well as limited ventilation of individual packages in stack. A spatial gradient in cooling rate was observed in all the stacks, which was caused by the air stream progressively increasing in temperature, as it flowed through the stacked packaging. This gradient in temperature corresponded with a gradient in fruit moisture loss. Fruit placed inside packages with polyliner bags cooled over four times slower than the non-polyliner bag treatments, due to the increased resistance to airflow.

Nomenclature

HI	heterogeneity index
Tp	instantaneous pulp temperature at specific position, °C
$\overline{T_p}$	mean instantaneous pulp temperature over all positions, °C

1. Introduction

The variability of postharvest fruit quality inside a cold store and containers such as packaging has been widely associated with spatial temperature variations (Ngcobo, 2008; Smale et al., 2006; Zou et al., 2006). The relationship between temperature and fruit quality is best described in terms of the Van't Hoff's rule, which states that for every 10°C rise in fruit temperature there is a 2-3 fold increase in the state of metabolic reactions inside the fruit (Brosnan & Sun, 2001; Salisbury & Ross, 1992). Therefore, in order to maintain postharvest quality, fruit should be cooled rapidly after harvest and maintained at low temperatures to reduce the rate of metabolic reactions, which ultimately lead to senescence and spoilage (Ravindra & Goswami, 2008; Thompson et al., 2008). Forced-air cooling (FAC) is a

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precooling technique commonly used to remove the field heat from freshly harvested produce (de Castro et al., 2004; Thompson et al., 2008) and is achieved by exhausting refrigerated airflow through packaged fruit, in order to convectively remove heat from the fruit (ASHRAE, 1994; Thompson et al., 2008). The resulting cooling rate and cooling patterns are therefore determined by the airflow distribution through the packaging (Smale et al., 2006; Zou et al., 2006).

Ventilation openings are used in packaging in order to improve cold air penetration and distribution inside stacked fruit packages during FAC (Delele et al., 2012; Pathare et al., 2012). The shape, position, number and size (vent/hole ratio) of ventilation holes on the package surface are some of the factors reported to significantly affect the airflow distribution in the stacked packaging (de Castro et al., 2005a; Dehghannya et al., 2012; Vigneault & Goyette, 2002). Furthermore the effect of multi-scale packaging, which is made up of bulk fruit stacking (Chau et al., 1985; Tutar et al., 2009; Verboven et al., 2004), the internal packaging (Ngcobo et al., 2012a, 2012b), the package stacking arrangement (Chau et al., 1985; Delele et al., 2008) and resulting alignment of ventilation holes of stacked packaging also influence the homogeneity of airflow. The combination of all these factors determines the homogeneity of fruit cooling patterns and rates (Smale et al., 2006).

Inadequate cooling does not only result in accelerated rates of fruit respiration, but it also subjects the fruit to decay and other handling related quality defects such as fruit moisture loss (Brosnan & Sun, 2001; Jarimopas et al., 2008; Martínez-Romero et al., 2003). The effects of packaging on airflow velocity, turbulence and cooling rates can also have a significant effect on the fruit moisture loss rate (Maguire et al., 2001). Air movement across the fruit can alter the environmental conditions of the boundary layer and consequently change the vapour pressure deficit (VPD) between the fruit and the boundary layer. A larger VPD results in an increased rate of moisture loss (Beukema et al., 1982; Maguire et al., 2001; Thompson et al., 2008). Consequently, the control of airflow, temperature and relative humidity (RH) during FAC is important, as these factors have direct influences on VPD (Chourasia & Goswami, 2007; Dijkink et al., 2004; Nelson, 1978).

Excessive moisture loss in apple fruit may result in a physiological disorder called shrivel and a higher susceptibility to infection and decay (Kader, 2002). Shrivel is the primary indication of moisture loss in apple fruit and is usually visible after about 2.5% moisture loss

(Kader, 2002; Little & Holmes, 2000). In order to reduce moisture loss in fruit, plastic liner bags are frequently added as part of a multi-scale packaging system. Plastic liner bags allow the fruit to humidify the air in the bag, which reduces the VPD and therefore decreases further moisture loss of the packaged fruit (Kader, 2002; Lindsay et al., 1975; Ngcobo et al., 2013a). However, although liner bags can be used to preserve fruit quality, they also obstruct airflow and therefore increase cooling times (Ngcobo et al., 2012a, 2012c).

There is a dearth of information on the effects of multi-scale ventilated packaging used in the apple industry on resistance to airflow and cooling (Ngcobo, 2013; Ngcobo et al., 2012a, 2013b). This information is needed to optimise future package designs to maintain fruit quality and minimise energy utilisation in the cold chain. The aim of this study was to examine the effects of packaging on fruit cooling rates, cooling patterns and mass loss of apple fruit. Fruit simulators were used to mimic the presence of apples in stacked multi-scale ventilated packaging during forced-air cooling.

2. Materials and methods

2.1 Fruit and packaging supply

Three types of commercially used multi-scale packaging used in apple handling were examined. Mark 4 (Mk4, 500×333×270 mm), Mark 6 (Mk6, 400×300×270 mm) and Mark 9 (Mk9, 600×400×152 mm) packages were selected as per Figure 1. The packages were stacked onto a 1.2×1.0 m wooden pallet base, using the configurations in Figure 2. The Mk4 and Mk6 packages were stacked three packages high, whereas the Mk9 were stacked five packages high. The apple multi-scale packaging was comprised of the carton (corrugated fibreboard), plastic liner films (37.5 µm polyethylene bag with no perforations), polystyrene trays and thrift bags (37.5 µm polyethylene bags with 0.17% total perforated area).

Produce simulators were used to mimic the heat transfer properties of apples in the stacked packaging following the approach reported by previous researchers (Alvarez & Flick, 1999; de Castro et al., 2004; Vigneault & de Castro, 2005). Each polyethylene ball (Ø=80 mm; wall thickness=560±80 µm) was filled with a saline solution (NaCl 0.234 M). The ‘Granny Smith’ apples (282±7 g) were used for temperature measurement and evaluation of mass loss. Four trays were packed into the Mk4 (90 fruit per package) and Mk6 (60 fruit per package) packaging, while either two trays (64 fruit per package) or 14 thrift bags (70 fruit per package) were packed into the Mk9.

Each package design was stacked and assessed (a) across the 1.2 m side when empty; (b) with trays and fruit; and (c) with a plastic liner, trays and fruit (with thrift bags for Mk9). When empty, the Mk4, Mk6 and Mk9 stacks (Figure 1) had effective ventilated area across the 1.2 m pallet side of 4.42, 0.74 and 0.09%, respectively. Effective ventilation area of the stack was measured by excluding ventilation misalignment and expressed as vent/hole ratio.

2.2 Experimental setup

The pallet stack and FAC equipment (Figure 3) were placed near the centre of the cold room, with the front (the side that airflow entered) of the stack facing the cooling unit. The FAC equipment was used to generate 300±20 Pa pressure drop over the palletized half stack (Figure 3). A centrifugal suction fan (KDD 10/10 750W 4P-1 3SY, AMS supplies, Sandton) was used to force air through the stack.

Fruit pulp temperature was monitored using T-type thermocouples and a 34970A Data Acquisition / Data Logger Switch Unit (Agilent Technologies, Santa Clara CA 95051, USA) was used for data logging at 30 minute intervals. Temperature and humidity in the cold room were monitored using a Tinytag sensor (Tinytag TV- 4500, Hastings Data Loggers, Australia).

Total pressure drop and air velocity were monitored using a manometer setup, positioned in the ‘pressure drop tunnel’ (Figure 3). The manometer was achieved using a differential pressure meter (Air Flow Meter Type A2G-25/air2guideF, Wika, Lawrenceville GA 30043, USA) and a data controller (WCS-13A, Shinko Technos CO LTD, Osaka, Japan) which recorded the total pressure drop across the stack. An air velocity meter based on hotwire anemometry (Alnor velometer AVM440, TSI incorporated, Shoreview MN 55126, USA) was used to measure the superficial airflow rate of the output air, which escaped the top of the FAC equipment at the ‘Extender tunnel’ (Figure 3).

2.2.1 Fruit cooling rate

The momentary cooling rate was calculated by determining the linear gradient of the initial temperature, half-cooling temperature and the seven-eighths cooling temperature. The half and seven-eighths cooling temperatures were calculated using standard equations

(Dincer, 1995). The average R^2 value of the linear equation was 0.98, indicating a good fit and validating the method.

The heterogeneity index (HI) was calculated using equation 1, with a 0 value indicating perfect cooling homogeneity and a higher value indicating high heterogeneity (Dehghannya et al., 2008, 2011). The HI value was calculated when each stack had a mean temperature of 14°C and compared positional package sample temperatures (Tp) with the mean stack temperature.

$$\mathrm{HI} = \frac{\sqrt{(\mathrm{Tp} - \overline{\mathrm{Tp}})^2}}{\overline{\mathrm{Tp}}} \times 100 \qquad 1$$

2.2.2 Moisture loss measurement

Moisture loss was determined using one apple per carton in each carton of the stack. Target fruit was positioned at the centre of the package and weighed before and immediately after precooling using a scientific weighing scale (NewClassic MF/ML3002E /01, Mettler Toledo, Switzerland). In addition, mean moisture loss rate was also calculated (moisture loss per week) over the FAC period.

2.3 Test procedure

Produce simulators and apples were heated to a pulp temperature between 26 and 30°C. Packages were packed with produce simulators and two apples (at the centre of the package). A thermocouple was inserted into the pulp of the first apple and the second apple was used for moisture loss evaluation. In addition, one single package from each stack (Figure 2) was packed with one apple in each of the eight corners and one at the centre. After packing the packages were stacked and sealed with airtight plastic liners along the sides, top and bottom. The pallet was placed in the cold room, which was set to -0.5°C and was maintained at 90% RH. Airflow entered the stacks across the length of the pallet as shown in Figure 2 and travelled from the front to the back and towards the FAC equipment (Figure 3).

2.4 Statistical analysis

Spatial variation within the stack was assessed across the width, length and height axes, with regard to the cooling and moisture loss data. ANOVA was performed using several individual samples per layer (Figure 2). For example, comparisons were made between the packages in the front, middle and back layers. Two replicate stacks were performed for each of the stack treatments (for both temperature and moisture loss assessment). Statistical tests were run on SAS 9.2 software (SAS, North Carolina, USA). A Wilcoxon test was used for the non-parametrically distributed moisture loss data, while Bonferroni comparisons were calculated on the normally distributed data at an alpha value of 0.05 for all tests.

3. Results and discussion

3.1 Analysis of fruit cooling rate

3.1.1 Effects of package/carton design

Comparisons between the stacks packed only with fruit trays (fruit-trays) showed that the stack of Mk4 packages cooled 27% faster ($p<0.05$) than the Mk6 packages (Table 1), while the stack of Mk9 packages had an intermediate cooling rate. The mean cooling rate was positively correlated ($R^2=0.82$) to the airflow velocity in the stacks as shown in Figure 4 (de Castro et al., 2004; Vigneault & de Castro, 2005). Given that each package design stack in the experiment was maintained at the same pressure drop (300 Pa), differences in measured airflow velocities also indicate differences in resistance to airflow; hence, low airflow velocity would indicate high resistance to airflow. Many of the factors that determine resistance to airflow were consistent throughout the stacks, such as fluid property, product roughness and product diameter factors. However, package porosity, stacking pattern, shape, confinement ratio and ventilation area differed for each stack treatment and may therefore be attributed to the distinct resistances to airflow (Chau et al., 1985; Delele et al., 2008; van der Sman, 2002; Verboven et al., 2004, 2006).

The uniformity of cooling in a stack has been reported to be significantly affected by the packaging ventilation configuration, specifically the vent/hole ratio, position and number of vents (de Castro et al., 2004). The effective ventilation, which was determined by measuring the total ventilation of the stack after excluding misaligned vents, was correlated ($R^2=0.99$; Figure 5) to the uniformity of cooling (Arifin & Chau, 1988; Baird et al., 1988; Pathare et al., 2012; Vigneault & Goyette, 2002). The relationship between the effective ventilation and the cooling heterogeneity can be attributed to stacks with large effective ventilation sometimes having a larger distribution of vents. This would have allowed the cooling airflow to penetrate more evenly into the stacks. Vent number may consequently have played a role in the heterogeneity of cooling The results of this study therefore indicate that increasing effective ventilation by making use of cartons with larger vent/hole ratios (0.09-5.31%), as well as using stacking configurations and vent positions that produce ventilation alignment, will improve overall stack cooling uniformity (Baird et al., 1988).

3.1.2 Effects of multi-scale packaging

The presence of polyliner (poly-bag) bags significantly ($p<0.05$) reduced the cooling rate of the stacks without bags (78%), while the presence of thrift bags reduced the cooling rate by only 24% ($p<0.05$; Table 1). The improved cooling rate of the thrift bags over the polyliners can be ascribed to the thrift bags creating more airflow routes through the carton. In addition, more surface area is available for conductive heat exchange in the case of thrift bags compared to the polyliner bags. The cooling rate may also have been influenced by the presence of perforation holes in the thrift bags. Ngcobo et al. (2012a) found that the presence of unobstructed perforation holes can significantly decrease the resistance to airflow of packaging, by improving airflow penetration through the stack. Heat transfer in the stacked packages was therefore largely influenced by the physical barrier created by the plastic bags, resulting in conductive heat transfer between the fruit and the cooling air. However, conductive heat transfer is generally a slower process than convection (Laguerre et al., 2006). This explains why the use of fruit-trays stacks, which made use of mainly convective heat transfer between cold airflow and fruit, resulted in faster cooling rates (Table 1). Although the use of polyliners reduced fruit cooling rates, they have been reported to reduce fruit water loss, which is a desired property during extended storage (Ngcobo et al., 2012c; Tapsoba et al., 2006). The use of polyliner bags should therefore be based on the water permeance characteristics of fruit and the storage or travel period (Maguire et al., 2001).

The relationship between the resistance to airflow of packaging and the rate of cooling can be influenced in several ways. Improved cooling rates could be achieved by increasing the pressure drop in front of the stacks, but this would significantly increase the energy utilization of the fans creating the pressure differential (de Castro et al., 2004; Thompson et al., 2010). Alternatively, packaging resistance to airflow could also be reduced by limiting the use of obstructive multi-scale packaging like polyliner bags and depending on marketing requirements, thrift bags may be utilized instead. Repositioning of ventilation holes may also facilitate airflow to bypass certain high airflow resistance areas inside individual packages. However, adequate heat exchange must still take place between the produce and the airflow to ensure that the cold chain is maintained (de Castro et al., 2004; Ferrua & Singh, 2009).

3.1.3 Stack uniformity of cooling

Irrespective of package design, analysis of the vertical package layers showed no significant differences ($p>0.05$) in cooling rate, cooling uniformity or moisture loss. This can be ascribed to each horizontal layer of the stacked column having the same effective ventilation area, stacking configuration and pressure drop. Across the length (1.2 m side) of the stack, only the Mk4 stack packed with polyliner and fruit trays showed a significant difference ($p<0.05$) in cooling rate (Figure 6b). Specifically, the left and centre packages cooled significantly faster (21%; $p<0.05$) than the packages in the right layer (Figure 2). The significant difference ($p<0.05$) in cooling rate was primarily due to the non-symmetrical package arrangement in combination with the polyliner bags. However, the absence of polyliner bags allowed added airflow penetration into the stack, resulting in a less observable difference between the two sides of the stack.

A gradient in cooling ($p<0.05$) was also present in all the treatments across the width (Figure 6) of the stack (Baird et al., 1988). The gradient had a large cooling rate at the front of the stack, an intermediate cooling rate at the middle of the stack and a low cooling rate at the back (Figure 2). The gradient was ascribed to the cold air progressively increasing in temperature as it flowed through the packaging. A similar gradient has been reported in literature by several researchers (Baird et al., 1988; de Castro et al., 2005b; Xu & Burfoot, 1999), This gradient in thermal performance (gradient) in the airflow direction was the main form of cooling heterogeneity in the present study.

3.1.4 Uniformity of cooling inside a package

The results showed significant differences ($p<0.05$) in cooling rate in all three axes of the packages, and the spatial variation in cooling pattern was influenced by ventilation position and size (Figure 7). The Mk4 fruit-trays and poly-bag packages had ventilations near the top of the carton. This resulted in a larger cooling rate in the fruit samples at the top of the package than at the centre or bottom. The Mk6 fruit-trays package had two obstructed ventilation holes at the vertical middle of the wall. However, airflow was still penetrating the package, as the centre fruit sample had a higher cooling rate than the top and bottom samples. The Mk9 packages showed no significant difference in cooling between the top and bottom samples. This can be attributed to the packages smaller height and limited ventilation area. The results suggest that ventilation position significantly influenced the cooling heterogeneity inside the individual packages (Alvarez & Flick, 1999).

Analysis across the horizontal plane of the packages showed a similar pattern in cooling rate to the stacks (Figure 7). No significant difference ($p>0.05$) in cooling was observed between fruit on the plane perpendicular to the airflow direction. The Mk4 fruit-trays, Mk6 fruit-trays, Mk9 poly-bag and Mk9 packed with thrift bags (thrift-bag) had significant ($p<0.05$) cooling gradients in line with the airflow direction. As with the stack (section 3.1.3), this can be explained by airflow increasing in temperature as it exchanged heat with fruit during movement through the package (Baird et al., 1988).

3.2 Moisture loss

Total moisture loss was significantly affected by the internal packaging (Table 2). The results showed that fruit inside the polyliner stack lost 66% more moisture than those without polyliner bags, while the addition of thrift bags only increased the total moisture loss by 1%. For the fruit-trays stacks, the Mk4 had the lowest total moisture loss (Table 2), whereas the stacks of Mk6 and Mk9 had 18 and 20% larger total moisture loss, respectively. As in the cooling rate results (section 3.1.3), no significant differences ($p>0.05$) were observed between the total moisture loss across the vertical axes. The moisture loss across a 2D geospatial plane is shown in Figure 8. No significant difference ($p>0.05$) was observed across the length (Figure 2) of the stack. However, a significant gradient ($p<0.05$) was observed across the width of the stacks (1.0 m side), which corresponded to the cooling rate gradient observed in Figure 6.

The resistance to airflow of fruit and packaging were the main factors which influenced cooling rate and total moisture loss in the stacks. Similar to the cooling rate (Figure 4), the total moisture loss percentage was correlated ($R^2=98$) to the airflow velocity (Figure 9). This relationship can be attributed to the effects of airflow on the air vapour pressure around the fruit. Areas in the stack with poor airflow distribution increased in temperature, due to heat exchange between the air and the warm fruit (Chourasia & Goswami, 2007). These areas with poor airflow also had a higher VPD and consequently produced larger total moisture loss rates (Nelson, 1978). In addition, fruit with low cooling rates due to low airflow velocity (Figure 4) took longer to reach the endpoint temperature (1°C) and therefore lost even more moisture over the duration (Table 2) of FAC procedures (Maguire, 1998; Mahajan et al., 2008).

The Mk4 poly-bag samples had a larger moisture loss rate than the Mk4 fruit-trays stacks (Table 2). This can be explained by the fact that each polyliner bag package had only 2 apples amongst the 88 fruit (apples and produce simulators). With more apples, the air inside the package would have humidified faster, which would have reduced the VPD resulting in lower rate of moisture loss. In contrast to the Mk4 stack, the Mk9 poly-bag stack had a lower moisture loss rate than the Mk9 fruit-trays, while the Mk9 thrift-bag stack had the highest rate of moisture loss. This may be attributed to a combination of fruit cooling rates and airflow patterns. Airflow can remove the boundary layer around a fruit, which can also alter the VPD and therefore lead to a possible increase in the rate of moisture loss (Maguire et al., 2001). The ventilations at the upper and lower sides of the cartons and perforations in the thrift bags may have produced turbulence inside the fruit-trays and thrift bags, respectively, producing a larger VPD than in the poly-bag stack. Further studies are warranted to verify this.

4. Conclusions

Experimental assessment of fruit cooling rate and moisture loss when stacked were evaluated for different apple package designs during forced-air cooling. Results obtained showed that ventilation area of the packages were often highly obstructed after stacking, resulting in lower effective ventilation (0.09-1.53%) compared to even the most restrained recommendation of 5-6% (Kader, 2002). Fruit cooling rate (R^2=0.82) and total moisture loss (R^2=0.98) were correlated to the superficial airflow velocity. In addition, the cooling uniformity was also correlated (R^2=0.99) to the total ventilation area of the stack.

The stack of Mk4 packages packed with fruit trays had the fastest cooling rate and highest cooling homogeneity, when airflow was perpendicular to the 1.2 m side of the pallet. The use of polyliner bags in the package stacks produced a high resistance to airflow through the stack and reduced fruit cooling rate by 78%. Previous researchers have also reported the negative influence of non-perforated plastic liners on cooling rate (Ngcobo et al., 2012a). However, the use of thrift bags resulted in a better cooling rate and lower moisture loss, presumably due to the ability of airflow to move easily between the thrift bags, thereby promoting better heat transfer between warm fruit and cold air. Thrift bags may therefore offer a more rapid cooling solution for fruit with high permeance (Maguire et al., 2001), which would normally require polyliner bags.

A distinctive cooling gradient formed through the packages, which was a result of the airflow progressively increasing in temperature as it progressed through the packaging (de Castro et al., 2005b). In addition, the observed gradient in cooling rate was mimicked by a gradient in moisture loss.

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Table 1: Mean seven-eighth cooling time and cooling rate data for each of the stacks.

Stacked package type	Momentary Cooling rate (°C/hour)	Seventh-eighth cooling time (hours)	Heterogeneity index
Mk4 fruit-trays	4.18 ± 0.18^{a}	6.28	9.10 ± 0.29^{a}
Mk4 poly-bag	0.86 ± 0.03^{e}	30.70	13.17 ± 0.75^{a}
Mk6 fruit-trays	3.28 ± 0.30^{b}	7.99	13.77 ± 3.91^{a}
Mk9 fruit-trays	3.78 ± 0.75^{ab}	6.94	35.17 ± 3.19^{b}
Mk9 poly-bag	0.93 ± 0.07^{d}	28.15	12.38 ± 3.17^{a}
Mk9 thrift-bag	3.00 ± 0.01^{c}	8.74	25.27 ± 2.23^{b}

Data shown are mean and standard deviation of the mean. Superscript letters indicate statistically significant differences between the stacks ($p<0.05$).

Table 2: Rate of moisture loss and duration of FAC procedure for the examined stacks.

Stacked package type	Moisture loss (%)	Moisture loss rate (Δ%/week)	Time required to cool to 0.5°C(hours)
Mk4 fruit-trays	0.049 ± 0.002^{a}	0.393 ± 0.023^{b}	20.9
Mk4 poly-bag	0.181 ± 0.008^{c}	0.406 ± 0.038^{b}	75
Mk6 fruit-trays	0.058 ± 0.002^{a}	0.528 ± 0.019^{a}	18.3
Mk9 fruit-trays	0.059 ± 0.002^{a}	0.398 ± 0.075^{b}	24.9
Mk9 poly-bag	0.139 ± 0.004^{b}	0.304 ± 0.001^{c}	77
Mk9 thrift-bag	0.060 ± 0.002^{a}	0.445 ± 0.033^{b}	22.5

Data shown are mean and standard deviation of the mean. Superscript letters indicate statistically significant differences between the stacks ($p<0.05$).

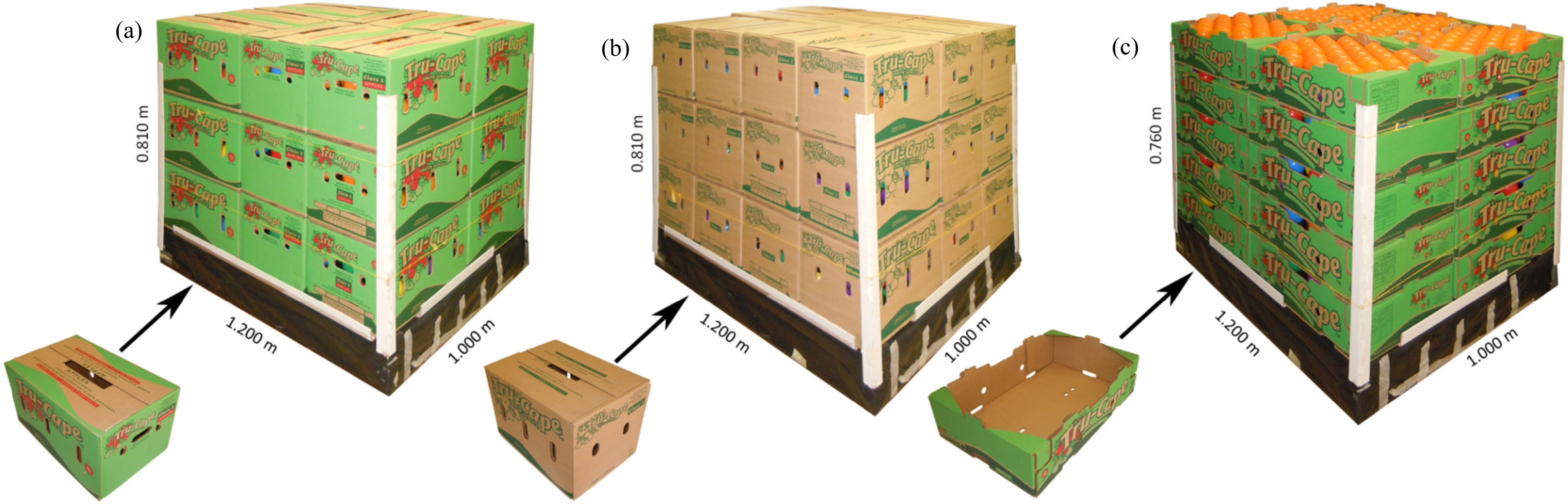

Figure 1: Photos of the (a) Mark 4, (b) Mark 6 and (c) Mark 9 palletised stacks and individual packages.

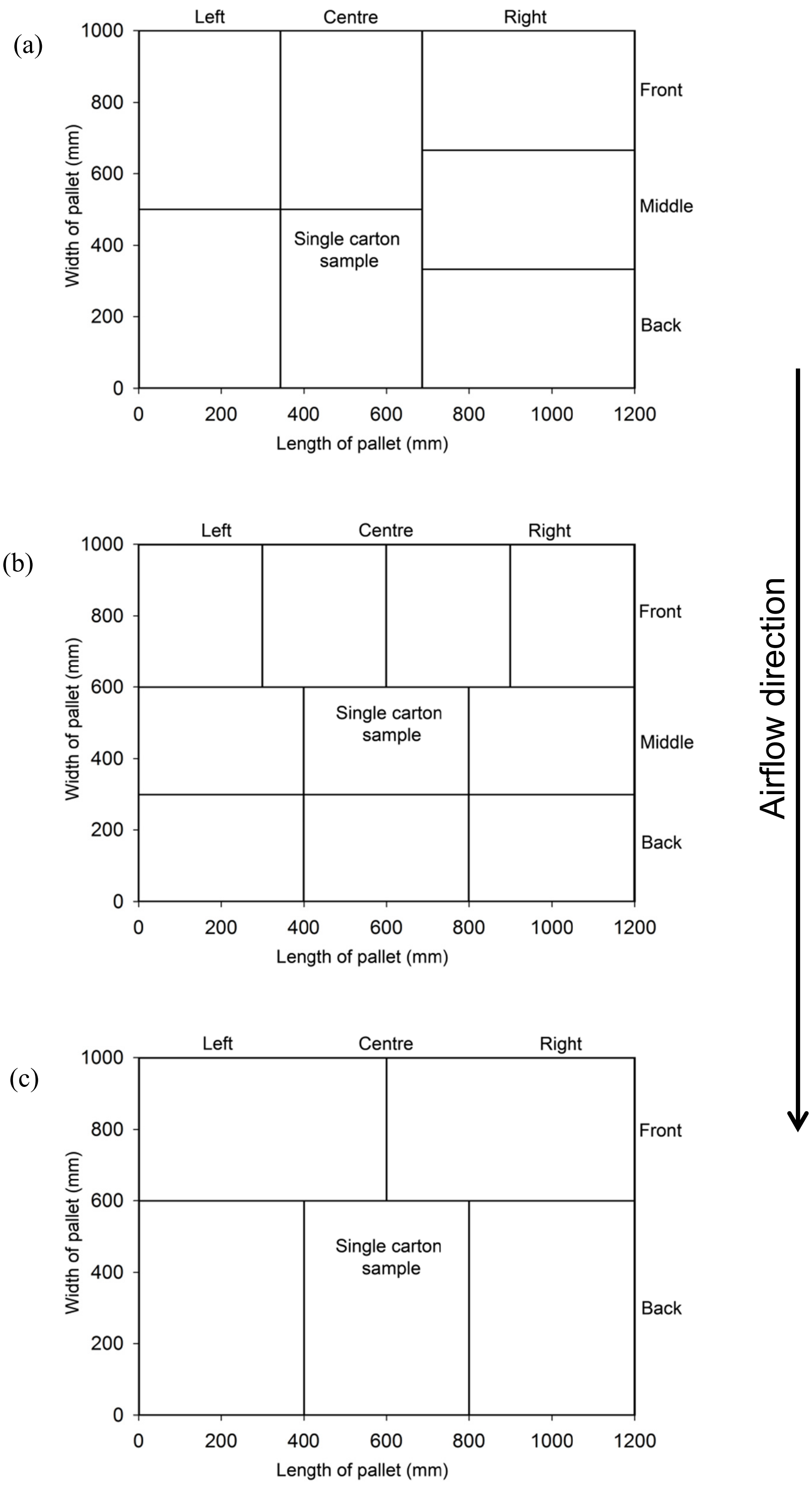

Figure 2: Layout of the individual packages in a single horizontal layer for the (a) Mark 4, (b) Mark 6 and (c) Mark 9 stacks.

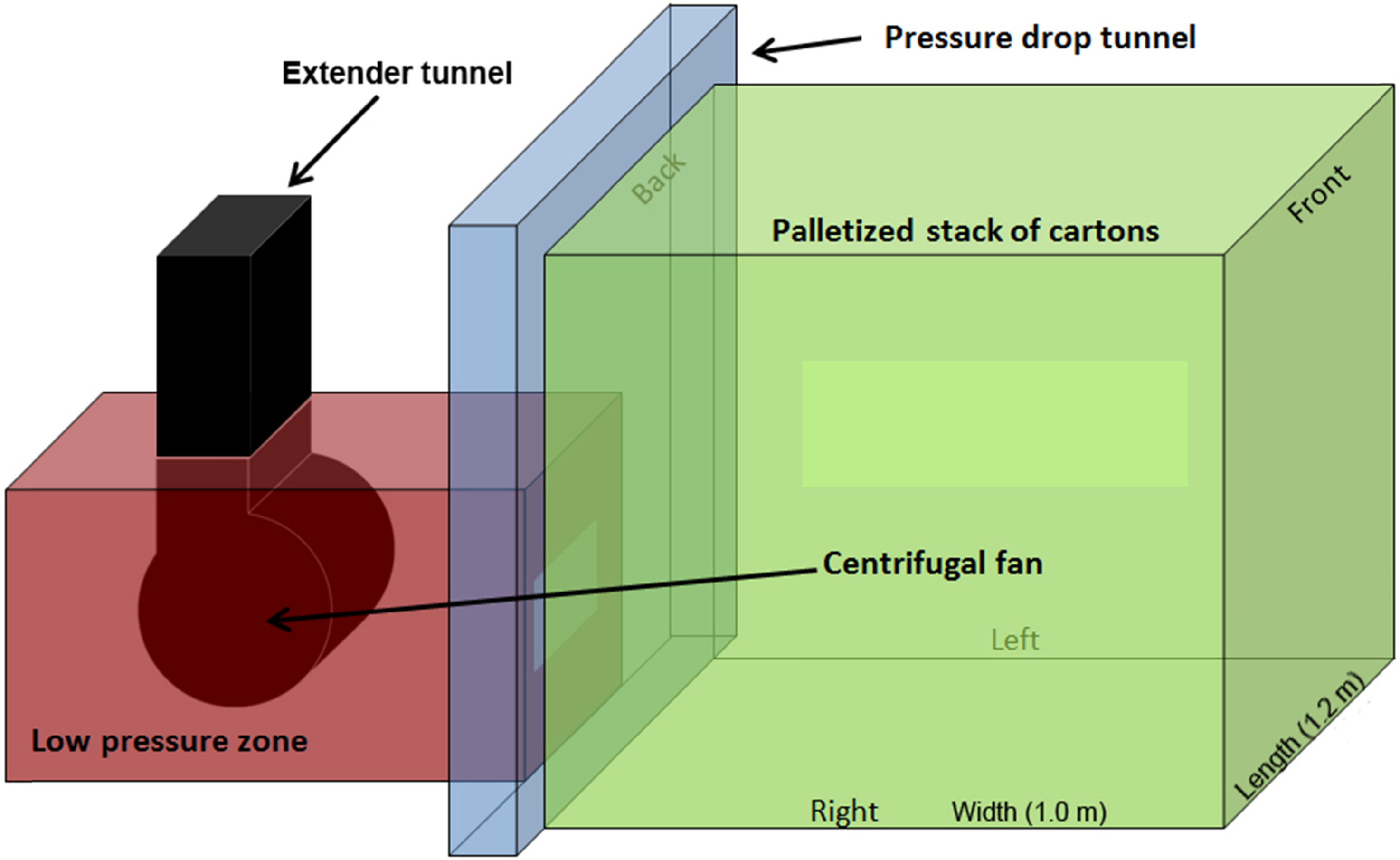

Figure 3: Schematic diagram of the FAC equipment and stack used in the study. Airflow progressed from the front of the stack to the back and into the pressure drop tunnel.

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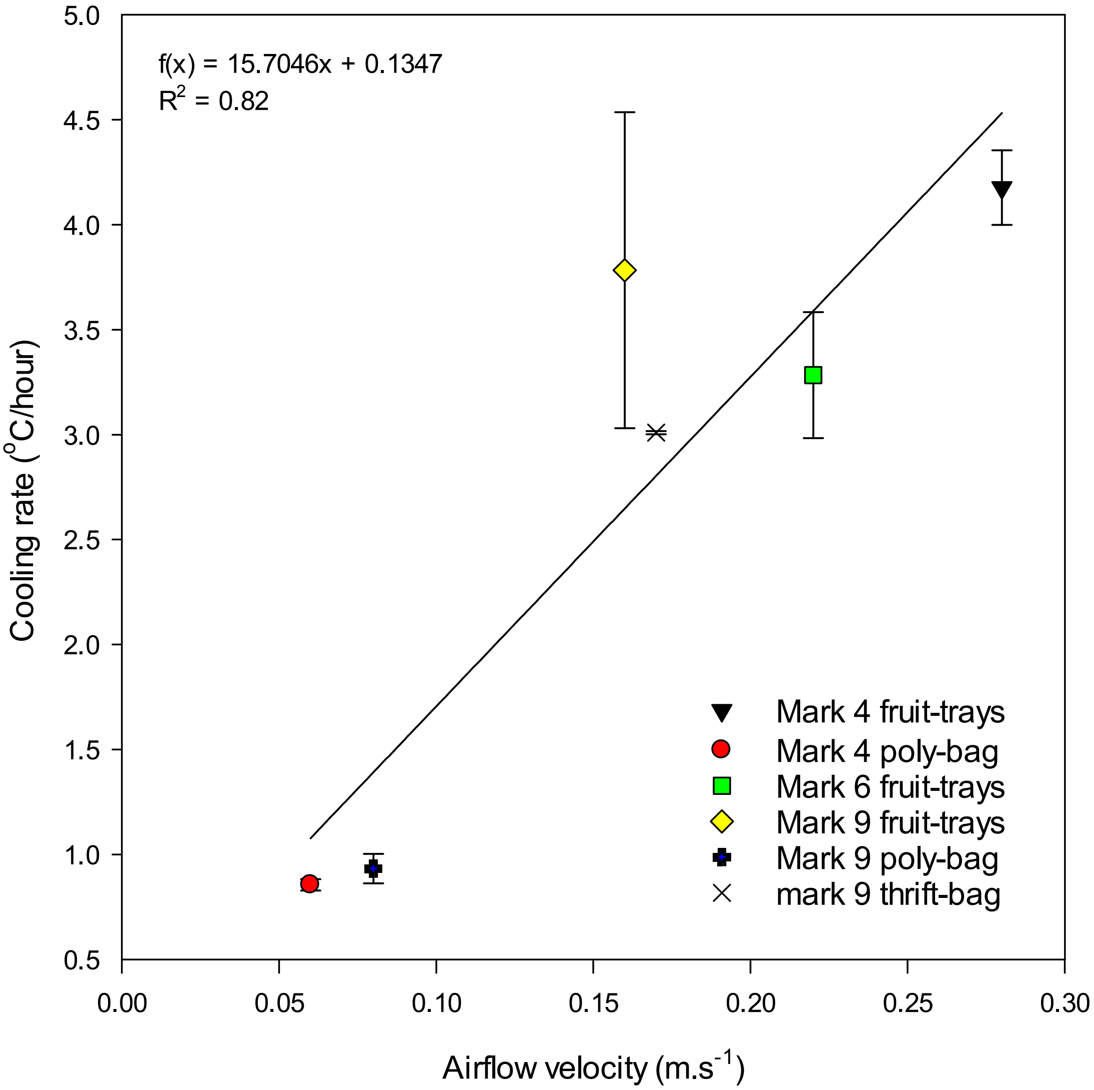

Figure 4: Superficial airflow rate through stacks versus stack cooling rate. Error bars indicate standard deviation of the mean.

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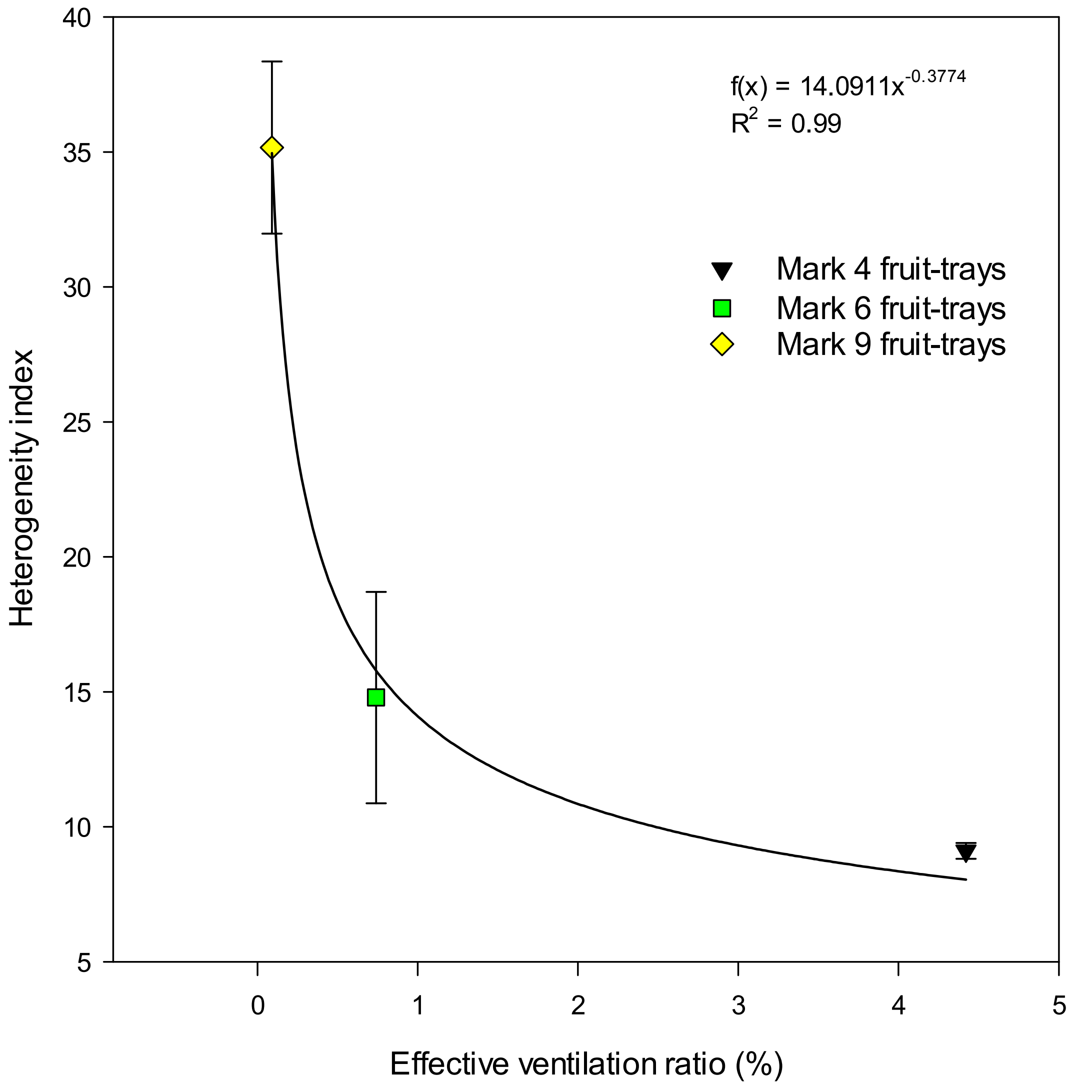

Figure 5: Total ventilated area versus the heterogeneity (HI) of cooling in stack. Error bars indicate standard deviation of the mean.

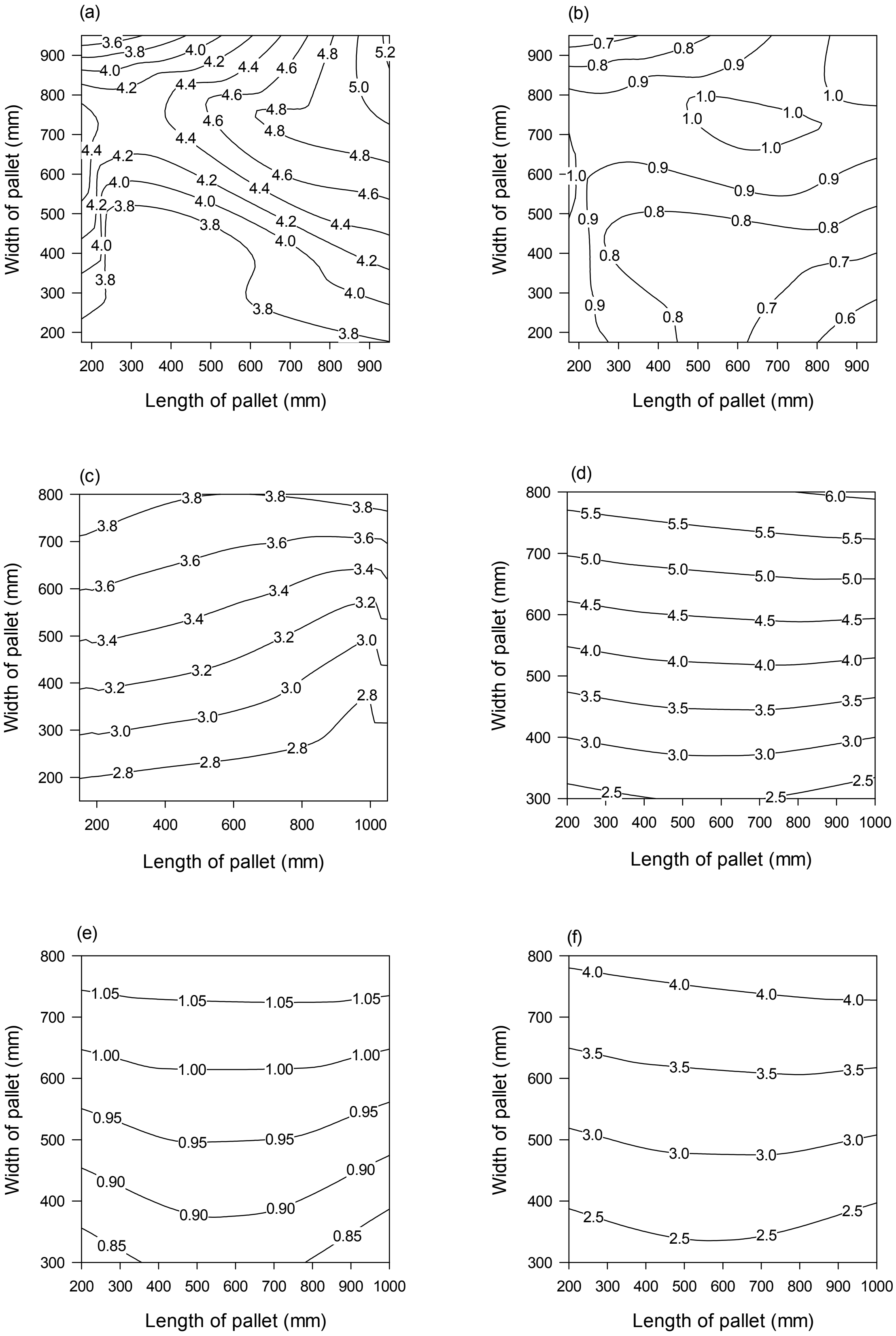

Figure 6: 2D geospatial contour graph of cooling rate (°C/hour) for (a) Mark 4 fruit-trays, (b) Mark 4 poly-bag, (c) Mark 6 fruit-trays, (d) Mark 9 fruit-trays, (e) Mark 9 poly-bag and (f) Mark 9 thrift-bag stacks.

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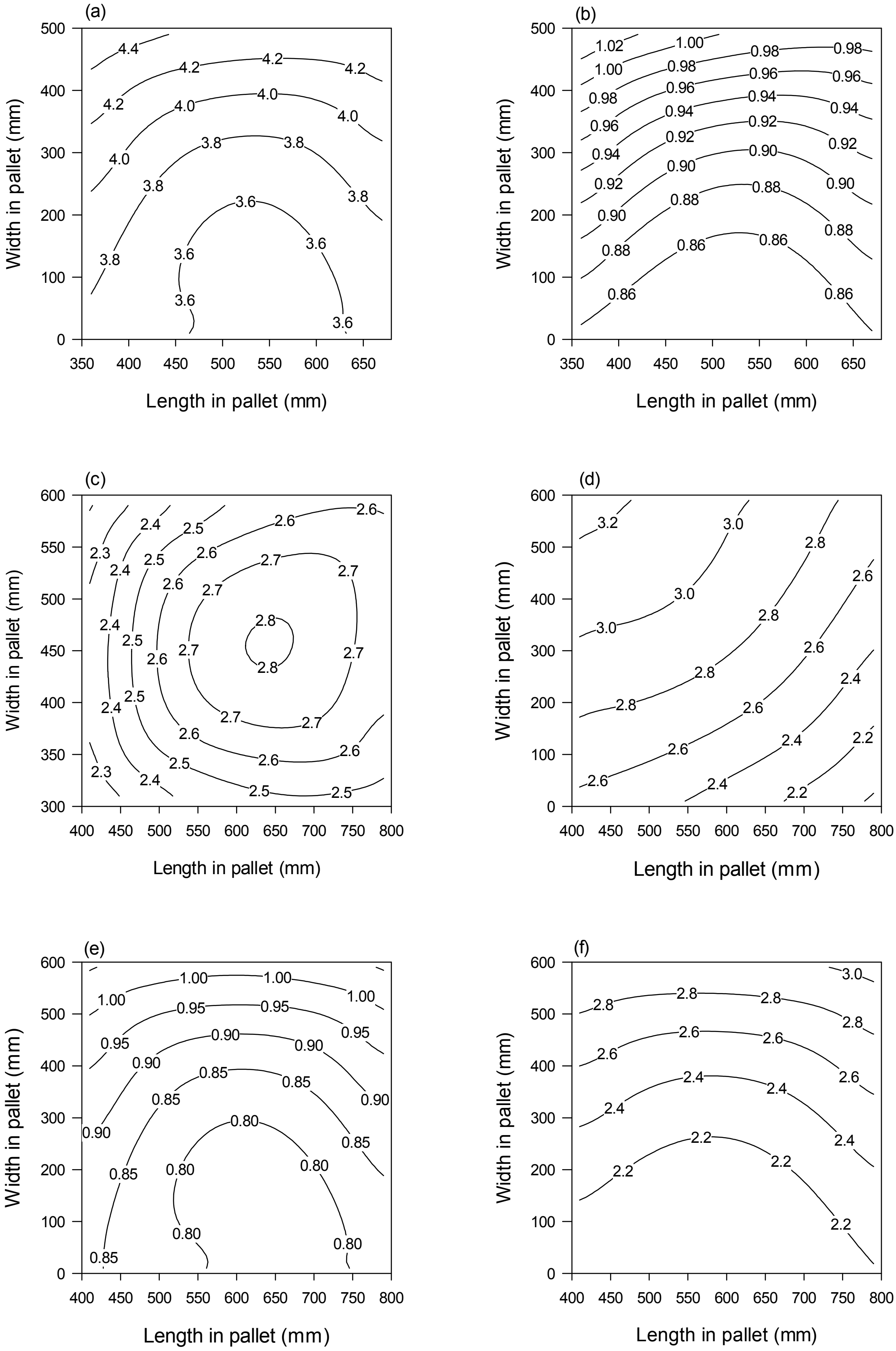

Figure 7: 2D geospatial contour graph of cooling rate (°C/hour) of single package for (a) Mark 4 fruit-trays, (b) Mark 4 poly-bag, (c) Mark 6 fruit-trays, (d) Mark 9 fruit-trays, (e) Mark 9 poly-bag and (f) Mark 9 thrift-bag cartons.

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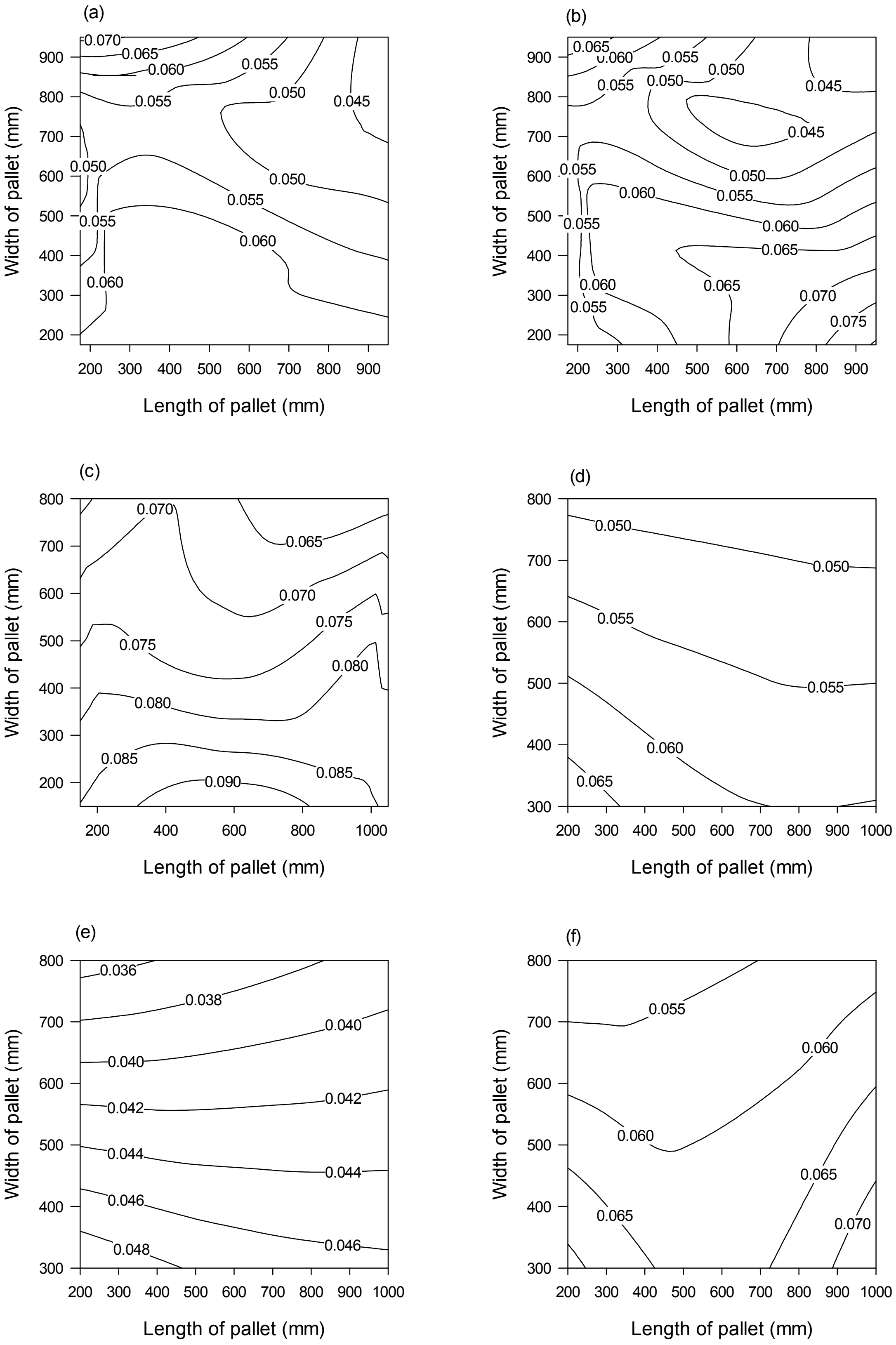

Figure 8: 2D geospatial contour graph of moisture loss percentage for (a) Mark 4 fruit-trays, (b) Mark 4 poly-bag, (c) Mark 6 fruit-trays, (d) Mark 9 fruit-trays, (e) Mark 9 poly-bag and (f) Mark 9 thrift-bag stacks.

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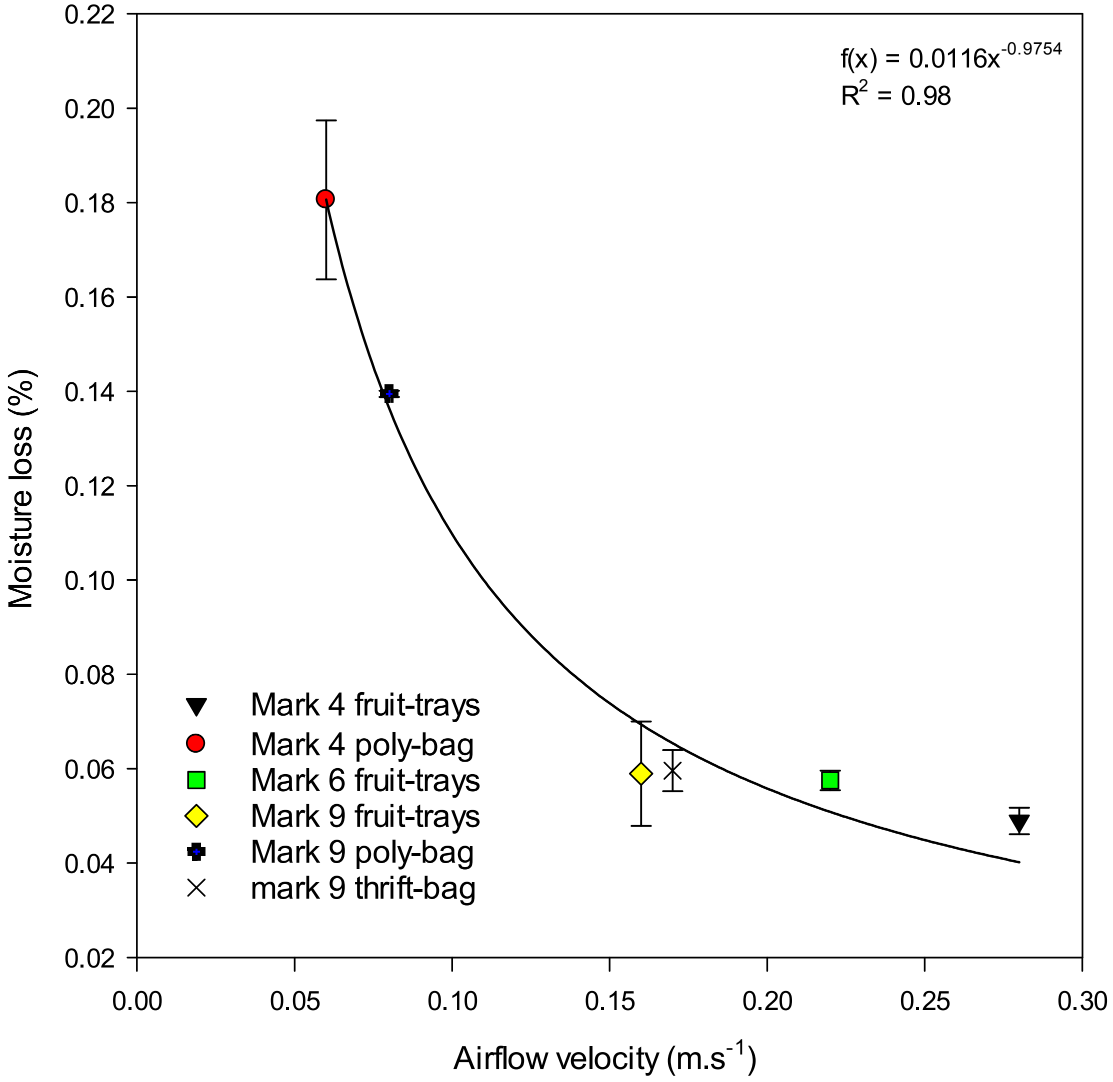

Figure 9: Total moisture loss versus superficial airflow velocity. Error bars indicate standard deviation of the mean.

GENERAL CONCLUSIONS

Cooling is the most effective and significant tool available in the quality preservation of fresh produce (Brosnan & Sun, 2001). Properly cooled fruit have a reduced respiration rate, which slows the onset of senescence and therefore prolongs the storage period. In addition, chilled fruit are less susceptible to spoilage and have a lower rate of moisture loss. Cooling also impedes the growth of microorganisms and therefore inhibits fruit decay. Fruit cooling in the cold chain is primarily achieved through a process of heat transfer to refrigerated air (convective heat transfer). A common method of accelerating heat transfer in apples and pears is to therefore make use of forced-air cooling (FAC). However, the presence of packaging limits airflow penetration, which necessitates the addition of ventilation openings.

The South African fruit cold chain uses numerous variations in apple and pear (pome) package designs, most of which make use of internal packaging. After careful examination, eleven unique design types were identified. Within these design types, the cartons were categorized into either ‘display’ or ‘telescopic’. The telescopic designs (Mark 4 and Mark 6) represented 54% and the display designs (Mark 7 and Mark 9) represented 27% of the pome fruit packaging exported from South Africa.

The large variation in packaging designs is in part due to the many cultivars, grades of quality and sizes of apples and pears that are available. The export markets have a wide range of aesthetic preferences and specifications for packaging, which need to be met by the cold chain industry to be internationally competitive. Many of the mechanisms and technologies used in the industry have been developed to accommodate the more common pallet designs (1.2×1.0 m) as well as the dimensions of the currently used packages. For example, many UK retail shelves have been designed to accommodate a 600×400 mm display packages. Recommendations for future packaging should therefore be consistent with the limitations of the current market and industry.

The total ventilation area (TVA; effective ventilation) of stacked packaging plays an important role in the rate of cooling and energy efficiency during FAC (Faubion & Kader, 1997; Thompson et al., 2010; Vigneault & Goyette, 2002). Packaging ventilation holes need to be aligned in a palletized stack for optimal airflow rate (Parsons et al., 1972). The physical design of a FAC facility will generally determine which stack orientation will be perpendicular to airflow during FAC. In the study, the Mark 4 had 100% ventilation alignment across the length (1.2 m), while the Mark 6 and Mark 9 had 100% ventilation alignment across the width (1.0 m) of the pallet stacks. This was

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attributed to stacking configurations which resulted in carton alignment. When FAC was performed across the alternative orientations, all of the packaging designs showed some misalignment of ventilation holes, resulting in a mean ventilation area reduction of 71%. The effective ventilations of the package designs tested, therefore ranged between 0.09 and 4.42% (side walls), which is below the 5% TVA recommended by the industry (Hortgro, 2013) as well as evidence in the scientific literature (de Castro et al., 2005a; Kader, 2002).

Two possible methods can be used to increase total ventilation area. First, each of the stacking configurations can have an orientation in which all the cartons are aligned with one another in the direction of airflow. Secondly, ventilation holes can be moved to strategic positions on the cartons that will allow maximum alignment when stacked, irrespective of carton alignment. Ventilation design recommendations, however, need to consider the importance of structural strength since the addition of ventilation holes can significantly reduce the structural stability of the package (Han & Park, 2007; Kader, 2002; Singh et al., 2008). Using these recommendations, ventilated package designs with increased effective ventilation area would decrease resistance to airflow of the packaging and thus improve cooling performance and energy efficiency during FAC (Delele et al., 2008; Ngcobo, 2013).

The relationship between pressure drop and the superficial airflow velocity through ventilated packages used in the apple industry was successfully characterised by the Darcy-Forchheimer (Forchheimer, 1901) and Ramsin (Chau et al., 1985) equations. The β (Darcy-Forchheimer) and *a* (Ramsin) coefficients were used to characterise resistance to airflow and was correlated (R^2=0.70) to stack effective ventilation (Delele et al., 2008; Ngcobo et al., 2012; Smale, 2004; van der Sman, 2002). However, the degree of correlation was significantly influenced by the use of different combinations of package designs, internal packaging and stacking configurations (Chau et al., 1985; Delele et al., 2008; van der Sman, 2002).

When examining the effect of carton, fruit trays and polyliner bag combinations on total pressure drop when packages were stacked, it was shown that the carton and fruit trays components contributed 11% of the total pressure drop, while polyliner bag contributed 89%. However, the combination of carton and fruit filled thrift bags resulted in a total pressure drop contribution of 24% by the carton and 66% by the thrift bags.

The resistance to airflow by the packaging resulted in the fruit packed with polyliner bags cooling four times slower than fruit with trays and three times slower in thrift bags (Ngcobo et al.,

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2012; Smale et al., 2006). Fruit cooling rates and patterns thus suggested that heat transfer in stacks packed without polyliners was dominated by convection compared with conduction in packages with polyliner film.

The position of ventilation holes played an important role in the rate of cooling in the stacks. Ventilation holes near the middle of the carton walls resulted in higher pressure drop contribution by the produce, due to more interaction between the package contents and the airflow. Ventilation holes near the top and bottom of the package resulted in reduced contact between the airflow and packaging contents (de Castro et al., 2005a; Vigneault et al., 2005). Several relationships were observed during FAC of the stacks. For instance, the mean cooling rate (R^2=82%) and total moisture loss (R^2=98%) of fruit in the stacks were correlated to airflow velocity (Baird et al., 1988). Additionally, the uniformity of cooling was correlated (R^2=99%) to the total stack ventilation area (effective ventilation).

Some researchers have reported that TVA was correlated to the cooling rate (Chau et al., 1985). However, this observation may have been due to the relationship between the TVA and airflow velocity. In contrast, this study showed a better correlation between TVA and heterogeneity of cooling than cooling rate. Although, the difference in observations may be due to the smaller range of ventilation sizes tested, in addition to the use of multi-scale packaging in the present study. The relationship between the TVA and the heterogeneity of cooling in this study may have been attributed to a relationship between an increase in ventilation holes and a larger TVA on the packages, indicating that vent number can positively influence uniformity of cooling (de Castro et al., 2004). Further research should be conducted on this phenomenon, specifically under stacking conditions, as this may provide a possible recommendation to the fruit packaging industry to reduced pressure drop during FAC.

A temperature gradient was observed through the stack during FAC. The temperature gradient was ascribed to the airflow progressively increasing in temperature as it flowed from the front to the back (airflow direction) of the stack. In addition, the observed temperature gradient corresponded with a gradient of increasing moisture loss through the stack. This result may be explained by the positive relationship between fruit temperature, extended cooling period and moisture loss (Maguire et al., 2001). The temperature and moisture loss gradients found in this study highlighted the need to carefully monitor and control airflow velocity during FAC. High airflow velocities may not sufficiently exchange heat with the fruit during the short period of contact between the air and

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produce, while low airflow velocities may result in the air increasing in temperature too rapidly at the front, resulting in less heat exchange being possible at the back of the stack (Baird et al., 1988; de Castro et al., 2005b; Xu & Burfoot, 1999). The incorrect airflow velocity would therefore result in low energy efficiency or extended cooling rates.

The use of polyliner bags had a significant effect in increasing moisture loss due to the effect of the bags reducing fruit cooling rate. Fruit inside stacks with polyliner bags cooled up to four times slower than the non-polyliner stacks. This resulted in the fruit inside the bags spending longer periods under a warm environment and thus losing more moisture (Maguire et al., 2001). However, the limited number of real fruit in each carton may have reduced the ability to effectively humidify the environment and therefore rendered the plastic liner ineffective in reducing the rate of moisture loss. Further research is recommended in this area.

In conclusion, the study has provided new and better understanding of the cooling performance of some of the key packaging designs used in the South African fruit industry. The study has also characterised the effects of stacking on resistance to airflow, cooling and moisture loss of fruit inside ventilated packaging during forced-air cooling. These findings provide new baseline information to assist in the optimal design of ventilated packaging to maintain the cold chain.

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