Food Bioprocess Technol (2012) 5:2031–2045
DOI 10.1007/s11947-012-0883-9

REVIEW PAPER

Design of Packaging Vents for Cooling Fresh Horticultural Produce

Pankaj B. Pathare · Umezuruike Linus Opara · Clément Vigneault · Mulugeta A. Delele · Fahad Al-Julanda Al-Said

Received: 12 August 2011 / Accepted: 30 April 2012 / Published online: 16 May 2012

Abstract This review focuses on the design of vents in packages used for handling horticulture produce. The studies on vent designs that are conducted to obtain fundamental understanding of the mechanisms by which different parameters affect the rate and homogeneity of the airflow and the cooling process are presented. Ventilated packages should be designed in such a way that they can provide a uniform airflow distribution and consequently uniform produce cooling. Total opening area and opening size and position show a significant effect on pressure drop, air distribution uniformity and cooling efficiency. Recent advances in measurement and mathematical modelling techniques have provided powerful tools to develop detailed investigations of local airflow rate and heat and mass transfer processes within complex packaging structures. The complexity of the physical structure of the packed systems and the biological variability of the produce make both experimental and model-based studies of transport processes challenging. In many of the available mathematical models, the packed structure is assumed as a porous medium; the limitations of the porous media approach are evident during vented package design studies principally when the container-to-produce dimension ratio is below a certain value. The complex and chaotic structure within horticultural produce ventilated packages during a forced-air precooling process complicates the numerical study of energy and mass transfer considering each individual produce. Future research efforts should be directed to detailed models of the vented package, the complex produce stacking within the package, as well as their interaction with adjacent produce, stacks and surrounding environment. For the validation of the numerical models, the development of better experimental techniques taking into account the complex packaging system is also very important.

Keywords Container · Package · Vents · Cooling process · CFD modelling · Horticultural produce

Introduction

Temperature is one of the most important factors affecting the postharvest life of fruit and vegetables as it influences to a large extent the physiological and biological changes taking place after harvest (Ravindra and Goswami 2008). Respiration is an important metabolic process causing the deterioration of fruits and vegetables after harvest (Caleb et al. 2011; Saenmuang et al. 2011). To minimise the postharvest deterioration, horticultural produce are generally cooled from harvest temperature to their optimal temperature before storage or shipment. As the maintenance of their quality has a fundamental importance on the success of the horticulture marketing industry, it is necessary not only to cool down the produce rapidly but also as soon as possible after harvest (Brosnan and Sun 2001; Castro et al. 2006) and

P. B. Pathare · U. L. Opara (✉) · M. A. Delele
Postharvest Technology Research Laboratory,
Stellenbosch University,
Stellenbosch, South Africa
e-mail: opara@sun.ac.za

C. Vigneault
Postharvest Engineering,
Horticulture Research and Development Centre,
Agriculture and Agri-Food Canada,
Ottawa, Ontario, Canada

F. A. Al-Said
Department of Crop Sciences,
College of Agricultural and Marine Sciences,
Sultan Qaboos University,
Muscat, Oman

maintain this temperature until their transformation or consummation (Castro et al. 2005c). Precooling is the process of cooling down a fresh produce rapidly and immediately after harvest, which involves the rapid removal of field heat from the freshly harvested produce (Ravindra and Goswami 2008).

Many factors affect the precooling process of fruit and vegetables such as ventilation system characteristics, air-to-produce initial temperature difference, air-to-produce final desired temperature difference, relative humidity, produce geometry (size, shape, surface/volume ratio, internal structure, porosity, density, etc), packing configuration, produce thermal properties, respiratory heat generation rate, package vent design (vent size and shape, vent positions, total vent area, etc) and stacking arrangement (Opara 2011). All these factors are important since they affect the heat and mass transfer during the precooling process (Hass et al. 1976; Sastry et al. 1978; Gaffney et al. 1985; Thompson 1996; Becker et al. 1996; Émond et al. 1996; Faubion and Kader 1997; Wills et al. 1998; Ladaniya and Singh 2000; Castro et al. 2004b; Vigneault et al. 2004a, b; Vigneault and Castro 2005a; Cortbaoui et al. 2006). As fruit and vegetables are highly perishable, the packaging technology (Castro et al. 2006; Vigneault et al. 2009a; Vigneault et al. 2009b) plays a critical role in their transportation, preservation and marketing (Hui et al. 2008a, b).

This review focuses on the application of vents in horticultural packaging and especially on research studies contributing to the fundamental understanding of the effects of vent design parameters on the rate and homogeneity of air circulation and cooling of packed horticultural produce. It also discusses the requirements of package strength in ventilated horticultural packaging. Finally, different mathematical modelling approaches that are commonly used in ventilated packaging design and analysis are presented.

Ventilated Packages: Importance and Design Challenges for Horticultural Produce Precooling

Precooling is a critical technology that is applied to rapidly reduce the temperature of horticultural fresh produce inside containers prior to long-term refrigerated storage. Many detailed reviews on precooling techniques and existing systems for horticultural produce have been reported in the literature, highlighting their relative efficacy, their produce specificity and their importance for extending shelf life (Mitchell 1992; Brosnan and Sun 2001; Vigneault and Sobral 2008; Vigneault 2011). The available precooling methods include room cooling, forced-air cooling, vacuum cooling, hydrocooling and package icing. Forced-air cooling is recognised to be the most common commercially applied method (Castro et al. 2004b; Zou et al. 2006a). Forced-air precooling is accomplished by forcing cold air through stacked packages and around each individual piece of produce. Figure 1 shows a typical forced-air cooling system. A pressure gradient is artificially generated across the container using a powerful fan generating the necessary driving force to draw air from the surroundings, through the container openings and around the commodity (Vigneault and Goyette 2002a). Its efficiency may be evaluated in terms of process rapidity using cooling rate or half-cooling time method (Castro et al. 2004b) and temperature uniformity comparing average temperature different among individual produce (Goyette et al. 1996; Castro et al. 2004b).

To obtain uniform cooling processes within packaged horticultural produce, the control of heat and mass (moisture and gas) transfer within the environment is of great importance (Opara 2011; Castro et al. 2004b; Vigneault et al. 2004a, b; Vigneault et al. 2005a; Zou et al. 2006a). Optimal design and efficiency of the forced-air cooling process are vital for minimising postharvest losses of fresh horticultural commodities (Castro et al. 2006). A rapid cooling could also be obtained by increasing the airflow rate, but this directly increases the required energy. The cooling efficiency is also affected by the design of the packaging system (Castro et al. 2005b). For storage and transportation of fruit and vegetables, different types of containers are used for many years (Fraser 1991; Fraser 1998). In early years, wooden boxes or corrugated cartons were used for the storage and shipment of potatoes or oranges (Vigneault et al. 2009a, b). Recently, polymeric individual packages have become more popular, but their use is generally restricted to a high value or fragile produce to justify their cost. Global marketing of fresh produce widely adopts ventilated packaging as one of the most important technological innovations with a minimal amount of internal packaging material to promote rapid, uniform and efficient cooling process of horticultural produce (Castro et al. 2005b; Thompson et al. 2010). Ventilation holes in the container maintain an airflow channel between the surroundings and the inside of the container. This results in reinforcement of the preservation function of the containers (Han and Park 2007). Vents also allow produce respiration heat to escape. Good airflow patterns and appropriate temperature and relative humidity levels are essential for storage stability, good shelf life and quality of fresh produce inside ventilated packages (Opara and Zou 2006). Unfortunately, many of the packages currently used by the industry remain inefficient in promoting rapid and uniform cooling of the packaged produce (Ferrua and Singh 2007). During their studies on forced-air cooling of horticultural produce, Alvarez and Flick (1999a, 2003) observed a strong cooling heterogeneity due to poor temperature management. Commodities located behind blind walls have not been sufficiently cooled, while others exposed to higher velocities were over-cooled, generating freezing, chilling or

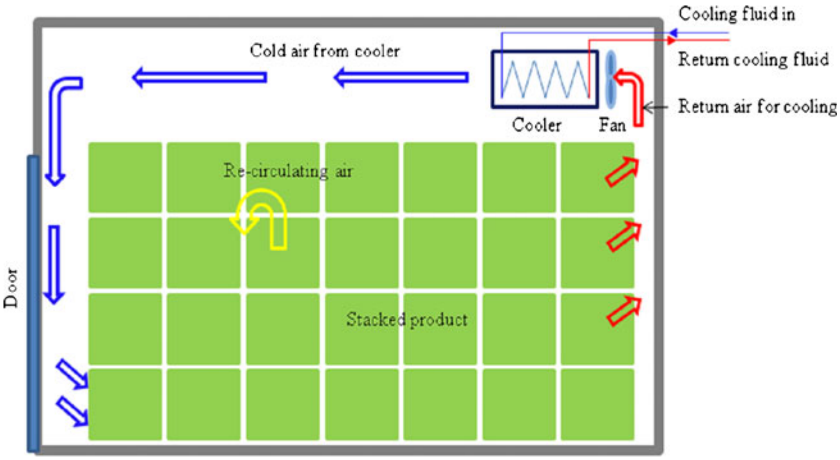

Fig. 1 Typical forced-air cooling system of horticultural products. (Delele et al. 2010)

drying damages. The occurrence of the heterogeneous airflow during forced-air precooling is directly related to the design of the ventilated packages used during the process (Vigneault and Goyette 2003; Castro and Vigneault 2005) and the pressure drop through the mass of produce (Vigneault and Goyette 2005).

The design of these containers is largely based on the criterion of mechanical strength and ease for manufacturing with minimal consideration of the effect of their venting pattern on the efficiency of the cooling process. This choice of criterions explains the fact of many horticultural packages currently used by the industry which remain inefficient in promoting rapid and uniform cooling of the packaged produce. To provide an efficient and uniform cooling throughout the entire container and throughout the entire stack of containers and to optimise the energy used, the design of these containers should take into consideration the various processes involved in the different precooling methods (Vigneault and Émond 1998). The amount of the energy required to operate any precooling system is also affected by the air pressure drop through the produce (Vigneault et al. 2004a, b) and the opening surface and position of the package (Vigneault and Goyette 2002a; Vigneault et al. 2004a, b; Castro et al. 2004a; Castro et al. 2004b; Castro and Vigneault 2005; Castro et al. 2005b).

Ventilated packages should be designed in such a way that they can provide a uniform airflow distribution and consequently uniform produce cooling. The package must have enough openings to provide a uniform airflow through the entire mass of produce while providing suitable mechanical resistance (Vigneault and Goyette 2002a; Castro et al. 2004a; Vigneault and Castro 2005). Many studies demonstrated that a proper package vent design is necessary to provide any uniform cooling during the forced convection cooling processes. The vent area percentage of the total wall surface of the package is a very critical factor affecting the efficiency of a cooling system (Arifin and Chau 1988; Baird et al. 1988; Castro and Vigneault 2005), the mechanical resistance of the container and the physical support to protect the produce against most of the mechanical damage. Thus, the openings must be well distributed on the package walls in order to provide a uniform airflow distribution during the process (Castro et al. 2004b). A proper package vent design must include not only the total vent area (Brosnan and Sun 2001; Castro et al. 2004b; Smale et al. 2003; Stanley 1989) but also the size and the position of each individual opening to enhance the efficiency of forced-air precooling system while still offering an adequate mechanical support for the produce (Vigneault and Émond 1998). From the studies that have been done so far, designing a vented package that could maximise the cooling and ventilation uniformity and minimise the quality deterioration of the packed produce without affecting the mechanical integrity of the package is a big challenge and results in an even more challenging work if one wishes to design a unique container concept which answers to most of the horticultural produce at the same time.

There is also a continuous development of new packaging systems in the fresh fruit and vegetable industry to meet individual produce and market requirements. The use of ventilated packaging is now a common practice for refrigerated cooling, storage and distribution of fresh horticultural produce (Opara and Zou 2007). However, this development has resulted in panoply of various container footprints, generating produce compression and compaction, bruising, cut and abrasion during mixed load handling since these containers do not often align well on each others. Standardisation of packaging footprint is thus necessary to minimise losses due to improper packaging. A new packaging system should therefore be carefully evaluated to ensure that the container opening areas can be optimised to achieve better and improved cooling process (Vigneault et al. 2006; Vigneault et al. 2009b; Thompson et al. 2010) without affecting the mechanical integrity of the package.

Effect of Vent Size and Position on Cooling Performance

The effect of container vent design parameters on cooling performance has been discussed by several researchers as summarised in Table 1. In order to maximise the uniformity of cooling, the total opening areas should be large enough not to restrict the airflow, the opening positions should cover most of the walls and the bottom (and the top if the container includes a cover) of the container and not affect importantly the container structure (Castro et al. 2004b; Arifin and Chau 1987; Vigneault and Goyette 2002a). In addition, the produce integrity and quality conservation should also be guaranteed (Vigneault et al. 2006). Several experimental studies have been reported in the literature to elucidate the influence of different package vent designs on the efficiency of the forced-air precooling process. The importance of these design criteria does not change with the size of the container since vent openings of individual consumer package, reusable box or standard pallet-size container play all the same major role in the efficiency of the cooling process (Émond et al. 1996)

Vigneault and Goyette (2002a) demonstrated that the effect of the width of opening on pressure loss could be neglected when using an opening width between 3.2 and 12.7 mm for plastic containers. In all cases, the length of the openings was adjusted to a total opening surface of 12,668 mm^2. However, they also demonstrated that there is a large influence on pressure loss during forced-air cooling when the total surface openings on the wall of a plastic container are less than 25 %. Haas et al. (1976) found a similar conclusion that the produce become the greatest contributor to pressure drop, when the surface area of the openings covers 27 % of the container walls. Since other cooling methods such as liquid icing could be desired using the same containers, the opening width should be kept as narrow as possible to ensure that the ice particles remain inside the container (Vigneault et al. 1995). Recently, Dehghannya et al. (2012) reported considerable differences in produce temperature distribution, cooling heterogeneity and cooling time for different package vent configurations. The authors showed that increasing the vent area did not necessarily shorten the cooling time and that this could even increase the time of cooling if the vents are not properly distributed on package walls. These findings suggest that low cooling time and less cooling heterogeneity can be achieved by suitable package vent design for efficient forced convection cooling process.

Castro et al. (2005a) investigated packages with eight different peripheral and central opening configurations during a horticultural produce forced-air cooling process. When the container design options are limited to central or peripheral openings, the bottom and top opening configuration is preferred for a greater cooling performance. Comparing

Table 1 Selected research studies on the effect of vent/opening on cooling performance

Produce or simulator used	Container used	Opening description	Performance criteria	Reference
Broccoli and nylon cylinder	Standard waxed cardboard for that produce	4 holes 30 mm in diameter on each larger side wall	Ice distribution	Vigneault et al. (1995)
Experimental model of strawberry	Individual cup; 5-cup design used	Different percentages of opening	7/8th cooling time, cooling uniformity	Émond et al. (1996)
Corn and rubber balls filled with water/agar-agar solution	Standard waxed cardboard for that produce and plastic containers	4 holes 30 mm in diameter on larger side wall and 30 % surface opening on plastic containers	Water distribution	Maul et al. (1997)
Aluminium spheres	Wind tunnel	Various configurations	Air distribution	Alvarez and Flick (1999a)
Plastic balls filled with water/agar-agar solution	560×280-mm cross section×560-mm length container inside a wooden tunnel 1,700 mm in length, insulated with 12-mm thick rubber foam	13 opening areas and 4 airflow rates	Pressure drop, cooling rate, cooling uniformity	Castro et al. (2004b)
Polymer ball horticultural produce simulator	420-mm^3 container within a forced-air cooling tunnel 1,250-mm long	Holes of 38.6 mm in diameter uniformly distributed on 2 opposite walls and covering 3 opening areas (0.67, 2 and 6 %)	Cooling efficiency, pressure drop, 1/2-cooling time, air distribution uniformity	Castro et al. (2004a)
Strawberry	8 different clamshell and tray combinations were tested	Varied vent-hole designs	7/8th cooling time, cooling coefficient	Anderson et al. (2004)
25 different horticultural produce in separate containers	Wooden, container with an inside dimension of 587×387×305 mm, 6.5-mm thick	Venting areas of 25 and 88 %	Pressure drop	Vigneault et al. (2004a, b)
Polymer ball horticultural produce simulator	420 mm^3, within a forced-air cooling tunnel 1,250-mm long	8 opening configurations	Air pressure drop, cooling rate, cooling uniformity	Castro et al. (2005a)
Polymer ball horticultural produce simulator	420-mm^3 container within a forced-air cooling tunnel 1,250-mm long	3 package opening areas and 6 airflow rates	Half-cooling time	Vigneault et al. (2005a)
Polymer ball horticultural produce simulator	420-mm^3 container within a forced-air cooling tunnel 1,250-mm long	3 total opening areas evaluated using a central hole, a central line of holes or 9 holes	Cooling rate, cooling index	Vigneault et al. (2007)
Strawberries of uniform size	Clamshells	Vent area of the clamshell	Cooling rate uniformity, pressure drop	Ferrua and Singh (2011)

packages with the same number and position of openings, those with larger holes produced higher air velocity, cooling rate and air velocity uniformity and smaller air pressure drop. This improvement in cooling performance was explained by the increase in total vented area and could be also obtained by increasing the airflow rate. However, Vigneault et al. (2005b) showed that the presence of gravity force also affected the uniformity of air distribution at the minimum airflow rate studied. The combination among high airflow rate, large vented area and holes covering most of the container surface was revealed as most advantageous for increasing the cooling rate.

The resistance to airflow of horticultural produce in boxes is important for the design of the cooling process (Verboven et al. 2004b). Arifin and Chau (1987) reported that the effect of opening area is significant for cooling uniformity and pressure drop responses; thus, they should be considered when designing a container or regarding the cooling efficiency. The negative effect of the lower opening area could be compensated by increasing the airflow rate, which would also increase the pressure drop through the container and, consequently, the energy required for the process. Haas and Felsenstein (1987) reported that carton opening is the main factor which affects the pressure drop. Recent studies by Ngcobo et al. (2011) on multi-layer packaging of fresh table grapes showed that perforation (micro vents) of liners improved fruit cooling rates but significantly reduced relative humidity (RH) around fruit. The authors also found that the low RH in perforated liners resulted in a significant increase in stem dehydration and browning compared to non-perforated liners.

The effect of produce shape and size, box design and air penetration slots on overall pressure drop have been correlated experimentally (Hass et al. 1976; Chau et al. 1985; Fikiin et al. 1999; Van der Sman 2002; Smale et al. 2003; Verboven et al. 2004a; Vigneault et al. 2004a, b). These correlations often have little physical background, while some try to relate the observed pressure drops to physical parameters and phenomena other than only airflow rate. In few cases, there has been numerical verification by use of theoretical models (van der Sman 2002; Verboven et al. 2004a, b). Relationships between airflow and pressure drop have been reported for different types of produce for lima bean, snap bean and snow pea (Wilhelm et al. 1983), sweet potato and green pepper (Gaffney and Baird 1977), oranges (Chau et al. 1985; Staley and Watson 1961) and potato (Abrams and Fish 1982). Vigneault et al. (2004a, b) measured the pressure drop through 25 different fruits and vegetables in separate containers during forced-air ventilation. The results demonstrated that the geometry of the produce and their particular characteristics play a significant part in pressure drop during forced-air ventilation. The authors found that a 25 % venting area of the container wall showed a greater pressure drop than venting area of 88 %, indicating that the percentage of opening was more important than the opening configuration. Based on their extensive studies, Vigneault et al. (2004a, b) recommended that the openings on the sides of containers used in forced-air cooling should be designed to provide the most uniform distribution of air possible.

Arifin and Chau (1988) studied strawberry precooling and established a relationship between the cooling rate, the air flow rate and the vent hole designs on a cardboard flat. Results showed that an increase in the flow rate reduced the cooling time, but not with a linear relationship. Indeed, the decrease in the cooling time was more significant in the lower flow rate range than in the high flow rate range. Baird et al. (1988) noted the importance of percentage of openings, airflow, air and produce temperature and dimensions of produce on precooling time. The authors also reported that an opening area below 10 % increases the cooling time. Castro et al. (2005a) reported that the mean air velocity and pressure drop decreased as more holes were added to the package. The decrease of air velocity and pressure drop as the total opening area increases explains the fact that the lowest values of air velocity and pressure drop were obtained with the fully open configuration.

In most studies, produce simulators have been used instead of real horticultural produce (Table 1) because of the difficulty of maintaining similar thermal properties and produce positioning pattern when replicating experiments with packed fresh produce. Produce simulators seem to be the most appropriate method to measure the effect of the different parameters on air distribution through porous medium, such as the container opening (Vigneault and Castro 2005).

Optimal Vent Size and Configuration

A well-designed container should protect horticultural produce against damage during transportation and distribution as well as having enough venting/opening for rapid and uniform heat transfer during precooling and storage. Effective container venting is essential to maximise the efficiency of cooling produce during forced-air cooling (Vigneault and Goyette 2002a). Combining a certain percentage of container opening area and vent positioning with airflow rate enhances forced-air cooling efficiency up to a certain point (de Castro et al. 2004a, b). The container opening area and position, rather than the shape, play an important role in cooling efficiency (Arifin and Chau 1988; Baird et al. 1988; Edeogu et al. 1997; Hass et al. 1976; Kader 2002; Vigneault and Goyette 2002a, b). Total opening area of less than 25 % of the container surface restricts airflow considerably (Vigneault and Goyette 2002a, b). Properly distributed vents on package walls with enough opening area provide a uniform produce cooling with less cooling time (Dehghannya et al. 2012). Studies by Castro et al. (2004b) showed that total opening area of 14 % generated a maximum cooling efficiency, with beneficial effects on product cooling rate and uniformity and energy costs. A summary of the recommended optimal vent size and configurations on containers for different types of fresh horticultural produce is presented in Table 2.

Table 3 presents optimal vent size and configurations on containers based on artificial horticultural produce simulators. As live organisms, fruits and vegetables exhibit physiological changes after harvest. Produce from the same variety can present considerable differences in physical and chemical properties (ASHRAE 2002; Leyte and Forney 1999). These factors, added to the variability of produce positioning due to the packing procedure, can affect the cooling efficiency. It is very difficult to maintain similar produce positioning patterns and thermal properties when replicating experiments with packed produce. Uniform produce and stacking condition are necessary to generate replicable results and allow comparisons between opening configurations or airflow rates. These replicated data can also be attained by representing horticultural produce with stable simulators (Alvarez and Flick 1999a, b; Émond et al. 1996; Vigneault and Goyette 2002a, b). Such tools allow a more accurate evaluation of the airflow and temperature distributions through packages during forced-air cooling, aiding container and equipment design. The recommendations that have been given by different studies about the appropriate vent designs are different (Tables 2 and 3). This shows the need for a more compressive study that takes into consideration the produce type, package material, atmospheric condition and product quality. The package opening area must be optimised to guarantee produce integrity and quality conservation and compensate for any costs derived from additional material required for structural support.

Compromise Between Cooling Efficacy and Mechanical Resistance

The design of these vented packages is largely based on their mechanical strength; their ability to promote rapid and uniform cooling of the packaged produce is often deficient. Effective container venting is essential to maximise the efficiency of cooling produce during forced-air cooling. Ferrua and Singh (2009a) reported that the homogeneity of the cooling process is largely influenced by the structure and design of the packaging system. Thus, until recently, finding an acceptable compromise between the optimal vent area and the mechanical integrity of the container has been considered as a big challenge. Little venting does not affect the structure resistance but restricts the airflow and generates cooling heterogeneity; too much venting weakens the carton container. A reasonable compromise appears to be about 5 to 6 % side or end-wall venting (Mitchell 1992) with cardboard. However, Vigneault and Goyette (2002a) demonstrated the important effect of total opening area on airflow until this open surface reach 25 % of the walls of a plastic container. During more recent research, the same research group demonstrated that the best air cooling efficacy is obtained using an open surface area between 8 and 16 % of the container walls (Castro et al. 2005b).

Table 2 Recommended optimal vent size and configurations on containers for different types of fresh produce

Produce type	Container/package type with dimensions	Recommended vent characteristics	Reference
Citrus	Corrugated fibre board (50×30×30 cm)	Up to 6 % vent area	Ladaniya and Singh (2002)
'Nagpur' mandarin	Corrugated fibre board cartons (50×30×30 cm)	Side area of 4–5 %, end area of 1.65 %	Ladaniya (2008)
Mandarins and sweet oranges	Polyethylene bag	0.5–1 % of the area of the PE bag	Ladaniya (2008)
'Shamouti' orange	Cartons	Openings cover 27 % of the container walls	Hass et al. (1976)
Nectarines	Various corrugated fibre board containers	5–6 % side vent area	Mitchell et al. (1971)
Peach	Polyethylene bags (500 g)	2.5 % opening	Singh et al. (2003)
Table grape	Corrugated cardboard (5/10 kg)	Approximately 5 % of the surface area	Aswaney (2007)
Strawberry	Different clamshell and tray combinations	Positioning of the vent-hole near the centre of the package	Anderson et al. (2004)
Strawberry	Clamshell basket-type (36×50 cm) tray	13 % or more side area venting	Thompson and Knutson (1997)
Strawberries	Clamshells	Higher vent area and uniform cooling air distribution	Ferrua and Singh (2011)
Apple and onion	Plastic containers of 400–600-mm footprint and 250-mm high	25 % of the container walls	Vigneault and Goyette (2002a, b)
Highbush blueberry	Clamshells	Vents across the top	Leyte and Forney (1999)
25 different horticultural produce[a]	Wooden container with an inside dimension of 587×387×305 mm, 6.5-mm thick	Uniform distribution of vents on the sides of the container	Vigneault et al. (2004a, b)

[a] List the types of produce reported/studied (leafy: celery, Chinese cabbage, Romaine lettuce, iceberg lettuce, leafy lettuce; spherical: potato, apple, plum, peach, turnip, bell pepper, tomato, cantaloupe; with leaves/peel: onion, green cabbage (bulk), green cabbage (placed), radish; long: cucumber (in bulk), cucumber (placed), corn, carrot, asparagus (bundle); complex: cauliflower, broccoli; in bulk: mushroom, snow pea, snap bean)

Table 3 Recommended optimal vent size and configurations on containers based on horticultural produce simulation

Type of produce simulator	Container/ package type with dimensions	Recommended vent characteristics	Reference
Plastic ball	Cartons	Openings cover 27 % of the container walls	Hass et al. (1976)
Solid polymer balls	Acrylic plates to form 42-cm^3 container within a forced-air cooling tunnel 125-cm long	5 vents (12.1 % vent area)	Dehghannya et al. (2008)
Polymer ball	Acrylic plates to form 420-mm^3 container within a forced-air cooling tunnel 1,250-mm long	Open area above 2.4 % (slat width larger than 200 mm)	Vigneault et al. (2006)
Polymer ball	Acrylic plates to form 420-mm^3 container within a forced-air cooling tunnel 1,250-mm long	Peripheral and central opening positions and large vent area	Castro et al. (2005a)
Polymer ball	Acrylic plates to form 420-mm^3 container within a forced-air cooling tunnel 1,250-mm long	Opening area should be more than 6 %	Castro et al. (2004a)
Plastic balls filled with water/agar-agar solution	Tunnel having 560×280-mm cross section and 1,700-mm length, insulated with 12-mm thick rubber foam	A total opening area of 14 % for the container design	Castro et al. (2004b)
Polymer ball	Acrylic plates were assembled in a tunnel containing the ball mat	Opening area between 8 and 16 %, avoid corner holes	Castro et al. (2005b)
Polymer ball	Acrylic plates to form 420-mm^3 container within a forced-air cooling tunnel 1,250-mm long	Larger opening area	Vigneault et al. (2005a, b)
Sphere	Container having a dimension of 620×420×355 mm	Increase the opening area at the side and bottom faces	Tutar et al. (2009)

From a structural point of view, Mitchell (1992) also recommends fewer large vents as opposed to many smaller vents. However, containers made of plastic materials have become more common in the agri-food industry and appropriate designs allow for the maintenance of adequate structural resistance even when using many small vents through these materials. Proper width of the openings on the sides and the bottom of containers is also important. The shape of the hole has a critical impact on the loss of compression strength (Singh et al. 2008).

Han and Park (2007) used finite element analysis (FEA) to predict the loss of compression strength due to vent and hand holes. They used actual testing on 15 different styles of boxes and hole patterns. The study used double-walled corrugated boxes with dimensions of 41×30×25 cm, and the surface area occupied by the holes was approximately 2 % of the total surface area of the vertical faces of the boxes. The study reported a compression strength loss of less than 10 % based on FEA and experimental data. They also found that an increase in the radius of curvature at both ends of the hand hole provided better stress relaxation and lower stress. The decrease in compression strength of the box could be minimised with identical area of the ventilation holes if the length of the major axis of the ventilation hole is less than 1/4 of the depth of the box and the ratio of the minor axis to the major axis is 1/3.5–1/2.5, provided that even-numbered holes are located symmetrically.

Recently, Singh et al. (2008) initiated to understand the loss of compression strength in corrugated containers as a function of size, shape and location of ventilation and hand holes. They found that the presence of ventilation and hand holes can cause strength reduction between 20 and 50 % in single-wall corrugated shipping containers. Vertical holes that are rectangular or parallelogram in shape are better in retaining corrugated box strength as compared to circular holes. Also, they found a linear relationship between the loss of strength and the total area of the holes made for venting or handling. This relationship does not stay linear when over 40 % of the face material is removed.

In terms of water cooling (hydrocooling), the containers should also be designed to provide an efficient and uniform cooling throughout the entire volume of container and throughout an entire stack of containers. This could be obtained using small openings distributed over the entire surface and totalizing an opening area of 5.2 % of the container floor surface (Vigneault et al. 2004a, b). In terms of uniform water distribution, the width of the openings on the bottom of containers is also important. While using the water flow rate recommended in the literature for an efficient hydrocooling system and testing width between 2.6 to 17 mm, Vigneault and Goyette (2002b) showed the apparition of water vortex above the bottom openings of the container when the width of these openings reached 6.4 mm. The presence of a vortex decreased the water flow by about 50 %, generating important heterogeneity in the water distribution (Vigneault and Goyette 2002b). These authors then recommended using bottom openings with a maximum width of 3.2 mm.

Application of Mathematical Modelling in Ventilated Packaging Design and Analysis

Nowadays, mathematical modelling technique is becoming an alternative to the difficult, time-consuming and expensive experiments because more powerful computers are less expensive, software is readily available and it is an important tool to study the effects of different operating and design parameters once the model is validated (Delele et al. 2010). However, it is fairly difficult to validate any model without any experimental data. Different mathematical modelling techniques have been applied to study, optimise and design processes that are related to horticultural produce cooling, storage and handling. To understand and optimise horticultural produce package design, computational methods have been extensively used (Table 4). Mathematical models are capable of predicting the airflow field, heat and mass transfer within packaged commodities during forced-air cooling (Talbot 1988; Xu and Burfoot 1999; Tanner et al. 2002b; Tanner et al. 2002c; Van der Sman 2002; Hoang et al. 2003; Alvarez et al. 2003; Verboven et al. 2006; Zou et al. 2006a; Zou et al. 2006b; Ferrua and Singh 2007). In general, due to the limitations in computational resources, these models required simplification of the geometrical characteristics of the system. Talbot (1988) introduced the idea of using a porous media approach to numerically predict the pressure and velocity field within a three-dimensional package and used this information along with a suitable heat transfer model to predict the cooling response of individual produce in packages with different vent designs. This assumption has been extensively used since 1970 to elucidate the relationship between the pressure drop and the rate of airflow forced through a bulk of horticultural produce (Wang and Tunpun 1969; Neale and Messer 1976; Gaffney and Baird 1977; Wilhelm et al. 1978; Wilhelm et al. 1983).

In many of the available models, the packed structure is assumed as a porous medium. This assumption cannot be justified for vented package design studies and when the container-to-produce diameter ratio is below 10, which is a common occurrence in the case of individual packages of horticultural produce. In these cases, the heterogeneity in the local airflow pattern within the horticultural packages has a major impact on the heat and mass transport phenomena during the forced-air cooling process and the continuous medium assumption is not valid anymore (Alvarez and Flick 1999a; Alvarez and Flick 1999b). Van der Sman (2002) presented a model based on the Darcy–Forchheimer–Brinkman theory of flow through a confined porous media. The model can reproduce experimental data on pressure drop over vented boxes quite accurately. The model confirmed the hypothesis of a power law relationship between the pressure drop and the percentage of the surface area of the box covered by vent opening. Given the good comparison with experimental data, one can conclude that the model describes the airflow inside the box reasonably well, and when coupled to convection–diffusion models describing heat and water vapour transport, it can be used to present the direction for improving the design of vented package of horticultural produce. However, the study did not reflect variation of the local velocity at different positions inside the ventilated packages to investigate air velocity heterogeneity. Zoned model approach to predict heat and mass transfer processes within refrigerated horticultural packages was used (Tanner et al. 2002a; b; c). It requires much less computing effort, and it is easy to write computer codes for model solution. As the airflow patterns were estimated from measured data for certain packages or cool stores, this approach limits the model application under different

Table 4 Selected journal papers since 2000 on applications of numerical modelling techniques on ventilated packaging

Approach	Study criteria	References
Zoned approach	Predict heat and mass transfer processes within refrigerated horticultural packages	Tanner, Cleland and Opara (2002a, b, c)
Simultaneous aerodynamic and thermal analysis	Airflow pattern and temperature profiles	Dehghannya et al. (2008)
CFD and turbulence model	Airflow patterns and temperature profiles in ventilated containers including stacked layers of spheres	Tutar et al. (2009)
Darcy–Forchheimer–Brinkman theory of flow through porous media.	Airflow, pressure drop	Van der Sman (2002)
Darcy–Forchheimer porous media models	Heat and mass transfer in food bulks	Verboven et al. (2006)
CFD	Airflow patterns and heat transfer inside ventilated packaging systems based on the porous media approach	Zou et al. (2006a)
CFD	Solve mathematical models for both layered and bulk packaging systems and a user-friendly software package (CoolSimu) integrating a modelling system	Zou et al. (2006b)
CFD	Sensitivity analysis of modelling for refrigerated air-cooling system for apple inside of carton	Opara and Zou (2007)
CFD	Airflow distribution within individual packages of strawberries (clamshells) during forced-air cooling processes	Ferrua and Singh (2009a)
Discrete element and CFD modelling	Local and average airflow through stacks of horticultural produce	Delele et al. (2008)
Direct numerical simulation	Airflow field in a package with a container-to-produce diameter ratio of less than 10	Ferrua and Singh (2008)
Simultaneous airflow and heat transfer	Simulate velocity and temperature profile	Dehghannya et al. (2011)

package designs or cool store arrangements. Although a wide range of correlations have been suggested to predict these effective parameters, a lack of consensus among them has prevented a reliable solution.

Computational fluid dynamics (CFD) modelling technique is the primary method of choice for modelling transport processes during postharvest handling of horticultural products (Smale et al. 2006). CFD is a technique where the appropriate geometry is discretised and the governing partial differential equations (Navier–Stokes equations) for conservation of mass, momentum and energy are solved on a discrete mesh on the geometry using numerical methods such as the finite volume method or the finite element method (Becker et al. 1996; Allais and Alvarez 2001; Hoang et al. 2003; Verboven et al. 2006; Norton and Sun 2006; Ferrua and Singh 2009a; Ferrua and Singh 2009b; Ferrua and Singh 2009c). The governing Reynolds-averaged Navier–Stokes equations are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u_i) = S_{\mathrm{m}} \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij} - \rho\,\overline{u'_i u'_j}\right) + S_{\mathrm{u}} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_j}(\rho u_j h) = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j} - \rho\,\overline{u'_j h'}\right) + S_{\mathrm{e}} \tag{3}$$

where ρ is the density (in kilograms per cubic metre), u_i and u_j are flow velocities (in metre per second), t is the time (in second), x_i and x_j are the Cartesian coordinates (in metre), p is pressure (in Pascal), τ_{ij} is the molecular stress tensor, $u_i^{'}$ and $u_j^{'}$ are the fluctuating velocity parts, T is the temperature (in Kelvin), h is the enthalpy (in Joules per kilogram), h' is the fluctuating enthalpy, λ is the thermal conductivity (in Watts per metre Kelvin), $\rho\overline{u_i^{'} u_j^{'}}$ is the Reynolds stress term and $\rho\overline{u_j^{'} h'}$ is the Reynolds flux term. S_{m}, S_{u}, and S_e represented the mass, momentum and energy source terms, respectively. The momentum loss of the flow in ventilated packages is expressed using Darcy–Forchheimer equation:

$$\nabla p = -\frac{\mu}{K}u - \beta\rho|u|u \tag{4}$$

where K is the Darcy permeability (in square metre), μ is the dynamic viscosity (in kilograms per metre second) and β is the Forchheimer drag coefficient (in per metre).

Recent advances in CFD codes and computational resources have provided powerful tools to develop detailed simulations of the local airflow field and heat transfer process within complex packaging structures (Logtenberg et al. 1999; Freund et al. 2003; Nijemeisland and Dixon 2004; Guardo et al. 2005). The integration of modern CFD codes and new experimental flow field measurements offer a promising approach to improve the understanding of the flow field and heat transfer process within packages of fresh produce in forced-air coolers. For example, Fig. 2 shows an isometric view of a clamshell model of strawberry fruit packaging.

Zou et al. (2006a) presented a comprehensive CFD modelling system to simulate the airflow and heat transfer processes inside ventilated packages of horticultural produce. The ventilated packages divided into two types, bulk and layered packages (Fig. 3). The areas inside the packages were categorised as produce air, plain air and solid region. The produce air regions inside the bulk packages or between trays in the layered packages were treated as porous media, in which volume averaged transport equations were employed. This approach avoids the dealing with the situation-specific and complex geometries inside the packaging systems and therefore facilities the development of a general modelling system suitable for a wide range of packaging design, produce type and stalking arrangement inside cool stores. Zou et al. (2006b) applied the CFD model to numerically solve this mathematical model of a range of ventilated fruit packaging and found good correlation between the predicted and experimental data for produce centre temperatures. A lack of fit was found at certain locations inside the package, which was attributed to inaccurate temperature measurements and uncertainty in model input data.

Subsequently, Opara and Zou (2007) applied sensitivity analysis to the modelling system under refrigerated air cooling of apples inside a ventilated cardboard carton. The inaccuracy in the measurement of inlet air velocity had a small but noticeable effect on the prediction accuracy while the predicted produce temperature was insensitive to the variation in the air velocity along the outside package walls. Variations in vent areas on both front and back walls of the package within ±20 % did not significantly alter the model predictions in the near-inlet region but had noticeable effects at the package centre and near-outlet regions. The changes in vent position had considerable effects on the model predictions, as it alters the airflow distribution among the produce layers and consequently affects the heat transfer between air and produce items. To facilitate the use of the generalised modelling system reported by Zou et al. (2006a, b) for ventilated and bulk packaging of fresh horticultural produce undergoing refrigerated cooling, Opara and Zou (2006) developed a CFD-based software ('CoolSimu') which incorporated various interfaces that enable the user to interact with simulation process to specify packaging structural properties, produce attributes, as well as the thermal operating conditions. Results obtained provided accurate prediction and visualisation of airflow patterns and heat transfer in the horticultural packages tested.

Delele et al. (2008) employed a discrete element method to generate a random stacking of spherical produce in the

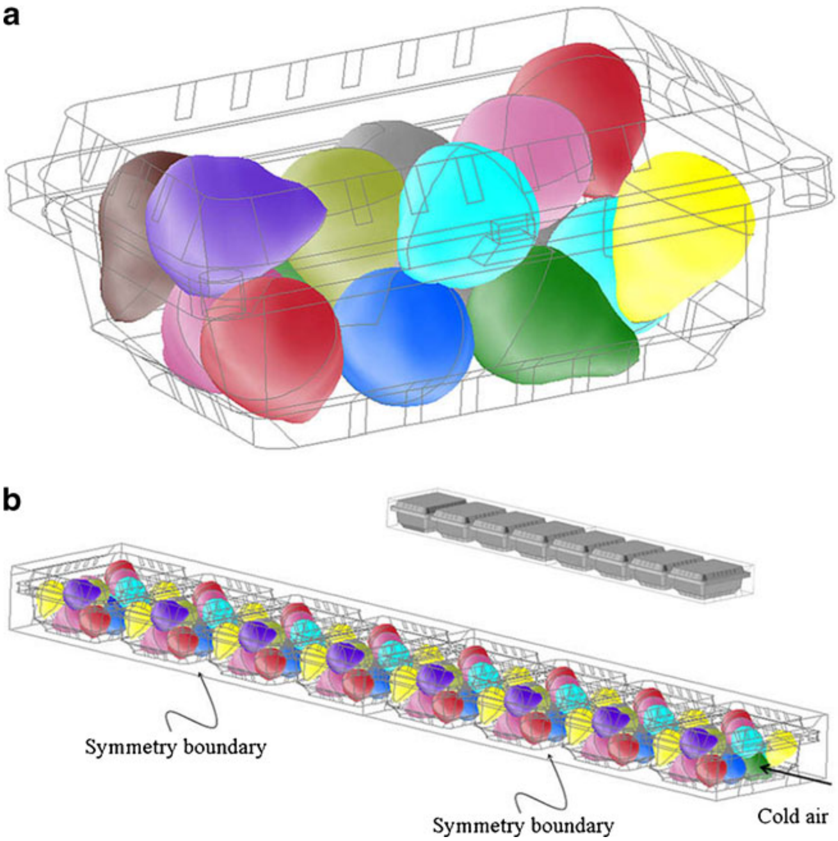

Fig. 2 **a** Isometric view of the packaging structure developed within clamshells. **b** Final geometrical model of the packaging structure. (Ferrua and Singh 2009a)

box, and CFD model was then applied to study explicitly the airflow through the air gaps in the box and in the voids between the stacks of different random fillings. The flow resistance was affected by the confinement ratio, produce size, porosity, box-to-vent ratio and much less by the random filling. The airflow inside the stack was very heterogeneous (Fig. 4). The methodology was used to obtain a more accurate pressure drop correlation for stacks of vented boxes that can be used in large-scale simulations of cool rooms. Using the same combined discrete element–CFD method, Delele et al. (2012) studied airflow and fungicide flow through bin vent holes and void spaces of the stack and deposition behaviour of fungicide particle. The validated model was used to investigate the effects of air rate and bin-handling parameters.

Tutar et al. (2009) studied the airflow patterns and temperature distribution in ventilated containers including stacked layers of spheres using CFD and turbulence model. The effects of flow dimensionality, turbulence intensity, opening size and ratios for venting and air inflow rate were investigated, which showed that there was a slight improvement on cooling performance with the inclusion of 20 % opening on the side surface area of packaging.

Ferrua and Singh (2008) used a non-intrusive flow measurement technique (particle image velocimetry) to determine the airflow field in a package. The container-to-produce diameter ratio was 2.96. The complexity and uneven distribution of the measured flow field supported the requirement of a geometrical and mathematical model capable of describing the geometry and physics of flow within the package. Using novel CFD codes, an accurate model of the packed structure was developed and the three-dimensional Navier–Stokes equations were solved. A good agreement was obtained between experimental and predicted velocities. The detailed insight on the airflow pattern provided by the CFD analysis makes this approach an ideal tool to analyse the effect of different vent designs in the airflow field distribution in complex packaging systems. Particle image velocimetry (PIV) provided an experimental insight of the flow field behaviour within the complex structure.

The complex and chaotic structure within horticultural produce packages during the forced-air precooling process complicates the numerical study of the thermal repartition around each individual produce within ventilated packages. The main obstacle that has limited this analysis is the determination of the airflow distribution around particles. Even in the case of uniformly distributed produce in a package, measurement of fluid flow around individual produce, by means of traditional methods, is difficult without disturbing the packaging arrangement itself (Ferrua and Singh 2007). The development of better environment measurement techniques and sensors suitable for data acquisition inside complex packaging structures and configuration is also needed to assist in the validation of mathematical model predictions.

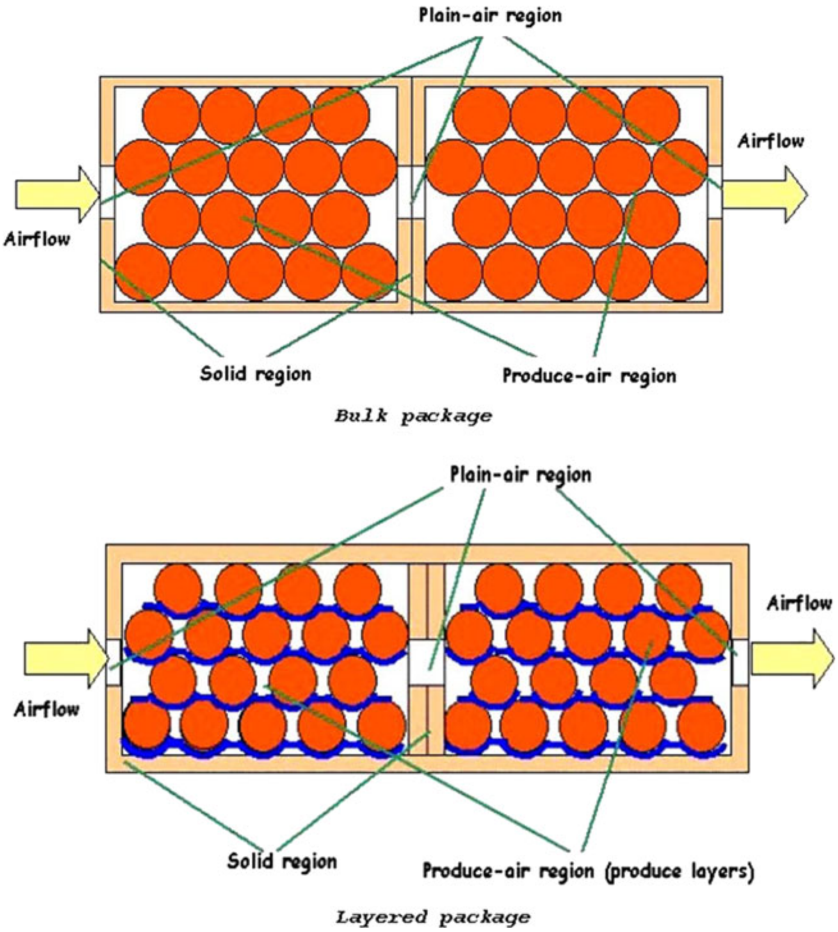

Fig. 3 Regions in layered and bulk packages for fresh produce. (Zou et al. 2006a)

Conclusions and Future Prospects

Packaging plays a critical role in the postharvest handling and distribution of fresh and processed food and other biomaterials. For horticultural fresh produce, package/containers are usually provided with opening/vents. A major function of the ventilation holes in the container is to maintain an airflow channel between the surroundings and the inside of the containers. Strength and ventilation capability are heavily dependent on the geometric location, sizes and shapes of the ventilation holes. Non-intrusive image-based experimental techniques such as Laser–Doppler velocimetry and PIV have been identified as possible methods to determine the flow field inside complex packed structures. The use of non-intrusive image-based techniques in combination with novel CFD models to develop a mathematical model capable of accurately predicting the airflow field within a complex packed structure is still part of the wish list of the scientific and industrial communities, but not part of the reality. Many researchers have recommended specific vent

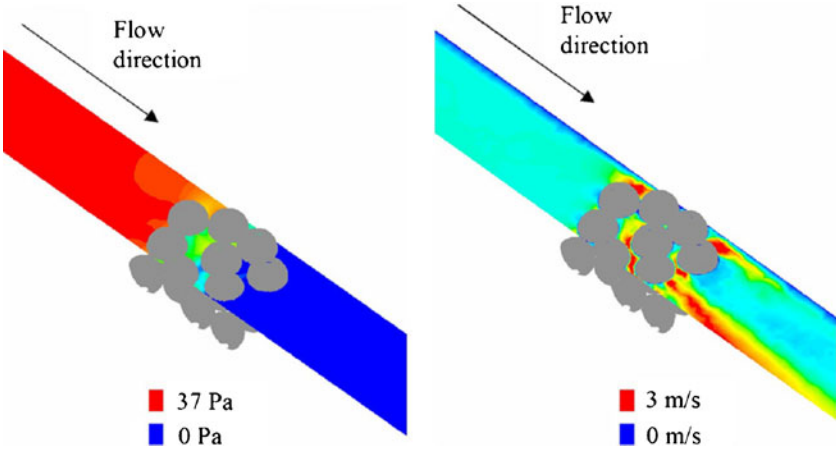

Fig. 4 Simulated pressure (*left*) and velocity (*right*) contours of the airflow through a con fined bulk of 32 spheres of 75-mm diameter, superficial velocity=1 m/s. (Delele et al. 2008)

sizes and vent/package area ratio for different types of packaging applicable to a particular type of produce. However, to date, there is no universal scientific guideline on the selection of optimum dimensions and configuration of vents on horticultural packaging. Optimising ventilated packaging design (size, shape, number and location) to maintain the cold chain and produce quality offers an opportunity to reduce the amount of packaging materials and the environmental impact of packaging in the food industry. Optimising packaging vents for cold chain performance offers a new opportunity to reduce the energy requirement for cooling (Opara 2011); however, this must be balanced with the requirements for robust mechanical handling and transportation along the supply chain.

Future research efforts should be directed towards the development of models that include stacks of packages as well as their interaction with adjacent stacks and the surrounding environment. Balancing the needs for adequate resistance to mechanical strength and proving optimum ventilation for airflow to maintain the cold chain is a primary challenge in the design and development of packaging in the fresh food industry. FEA simulation offers a useful tool to the mechanical design of ventilated packaging, taking into account factors such as the shape, location and size of the vents and hand holes. Combining FEA and CFD modelling offers a powerful tool for cost-effective ventilated packaging to meet the structural requirements of packaging and cold chain requirements of fresh horticultural produce.

Acknowledgments This work is based upon the research supported by the South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation. The financial support of the Postharvest Innovation Programme (PHI-2) and Hortgro$^{\text{Science}}$ through the award of a project on ‘Packaging of the Future’ is gratefully acknowledged.

References

Abrams, C., Jr., & Fish, J., Jr. (1982). Air flow resistance characteristics of bulk piled sweet potatoes. *Transactions of ASAE, 25*(4), 1103–1106.

Allais, I., & Alvarez, G. (2001). Analysis of heat transfer during mist chilling of a packed bed of spheres simulating foodstuffs. *Journal of Food Engineering, 49*(1), 37–47.

Alvarez, G., & Flick, D. (1999a). Analysis of heterogeneous cooling of agricultural products inside bins part I: aerodynamic study. *Journal of Food Engineering, 39*(3), 227–237.

Alvarez, G., & Flick, D. (1999b). Analysis of heterogeneous cooling of agricultural products inside bins: part II: thermal study. *Journal of Food Engineering, 39*(3), 239–245.

Alvarez, G., Bournet, P. E., & Flick, D. (2003). Two-dimensional simulation of turbulent flow and transfer through stacked spheres. *International Journal of Heat and Mass Transfer, 46*(13), 2459–2469.

Anderson, B., Sarkar, A., Thompson, J., & Singh, R. (2004). Commercial-scale forced-air cooling of packaged strawberries. *Transactions of ASAE, 47*, 183–190.

Arifin, B., & Chau, K. (1987). Forced-air cooling of strawberries. *American Society of Agricultural Engineers (USA)*.

Arifin, B., & Chau, K. (1988). Cooling of strawberries in cartons with new vent hole designs. *ASHRAE Transactions, 94*(1), 1415–1426.

ASHRAE. (2002). *Methods of precooling fruits, vegetables, and cut flowers* (pp. 14.1–14.10). Atlanta: ASHRAE.

Aswaney M. (2007). Forced-air precooling of fruits and vegetables. *Air Conditioning and Refrigeration Journal*, 57–62

Baird, C., Gaffney, J., & Talbot, M. (1988). Design criteria for efficient and cost effective forced-air cooling systems for fruits and vegetables. *ASHRAE Transactions, 94*(1), 1434–1454.

Becker, B. R., Misra, A., & Fricke, B. A. (1996). Bulk refrigeration of fruits and vegetables. Part I: theoretical considerations of heat and mass transfer. *H V A C & R Research, 2*(2), 122–134.

Brosnan, T., & Sun, D. (2001). Precooling techniques and applications for horticultural products - a review. *International Journal of Refrigeration, 24*(2), 154–170.

Caleb, O. J., Opara, U. L., & Witthuhn, C. R. (2011). Modified atmosphere packaging of pomegranate fruit and arils: a review. *Food and Bioprocess Technology*. doi:10.1007/s11947-011-0525-7.

Chau, K., Gaffney, J., Baird, C., & Church, G. (1985). Resistance to air flow of oranges in bulk and in cartons. *Transactions of ASAE, 28* (6), 2083–2088.

Cortbaoui, P., Goyette, B., Gariépy, Y., Charles, M. T., Raghavan, G. S. V., & Vigneault, C. (2006). Forced air cooling system for *Zea mays*. *International Journal of Food, Agriculture and Environment, 4*(1), 101–104.

de Castro, L. R., & Vigneault, C. (2005). Effect of container openings and airflow rate on energy required for forced-air cooling of horticultural produce. *Canadian Biosystems Engineering, 47*(3), 1–9.

de Castro, L. R., Vigneault, C., & Cortez, L. A. B. (2004a). Effect of container opening area on air distribution during precooling of horticultural produce. *Transactions of ASAE, 47*(6), 2033–2038.

de Castro, L. R., Vigneault, C., & Cortez, L. A. B. (2004b). Container opening design for horticultural produce cooling efficiency. *Journal of Food, Agriculture and Environment, 2*(1), 135–140.

de Castro, L. R., Vigneault, C., & Cortez, L. A. B. (2005a). Cooling performance of horticultural produce in containers with peripheral openings. *Postharvest Biology and Technology, 38*(3), 254–261.

de Castro, L. R., Vigneault, C., & Cortez, L. A. B. (2005b). Effect of container openings and airflow on energy required for forced air cooling of horticultural produce. *Canadian Biosystems Engineering, 47*, 3.1–3.9.

de Castro, L. R., Vigneault, C., Charles, M. T., & Cortez, L. A. B. (2005c). Effect of cooling delay and cold-chain breakage on Santa Clara tomato. *International Journal of Food, Agriculture and Environment, 3*(1), 49–54.

de Castro, L. R., Cortez, L. A. B., & Vigneault, C. (2006). Effect of sorting, refrigeration and packaging on tomato shelf life. *International Journal of Food, Agriculture and Environment, 4*(1), 70–74.

Dehghannya, J., Ngadi, M., & Vigneault, C. (2008). Simultaneous aerodynamic and thermal analysis during cooling of stacked spheres inside ventilated packages. *Chemical Engineering and Technology, 31*(11), 1651–1659.

Dehghannya, J., Ngadi, M., & Vigneault, C. (2011). Mathematical modeling of airflow and heat transfer during forced convection cooling of produce considering various package vent areas. *Food Control, 22*(8), 1393–1399.

Dehghannya, J., Ngadi, M., & Vigneault, C. (2012). Transport phenomena modelling during produce cooling for optimal package design: thermal sensitivity analysis. *Biosystems Engineering*. doi:10.1016/j.biosystemseng.2012.01.001.

Delele, M., Tijskens, E., Atalay, Y., Ho, Q., Ramon, H., Nicolaī, B., & Verboven, P. (2008). Combined discrete element and CFD modelling of airflow through random stacking of horticultural products in vented boxes. *Journal of Food Engineering, 89*(1), 33–41.

Delele, M., Verboven, P., Ho, Q., & Nicolai, B. (2010). Advances in mathematical modelling of postharvest refrigeration processes. *Stewart Postharvest Review, 6*(2), 1–8.

Delele, M., Vorstermans, B., Creemers, P., Tsige, A. A., Tijskens, E., Schenk, A., Opara, U. L., Nicolaī, B., & Verboven, P. (2012). CFD model development and validation of a thermonebulisation fungicide fogging system for postharvest storage of fruit. *Journal of Food Engineering, 108*(1), 59–68.

Edeogu, I., Feddes, J., & Leonard, J. (1997). Comparison between vertical and horizontal air flow for fruit and vegetable precooling. *Canadian Agricultural Engineering, 39*(2), 107–112.

Émond, J. P., Mercier, F., Sadfa, S., Bourré, M., & Gakwaya, A. (1996). Study of parameters affecting cooling rate and temperature distribution in forced-air precooling of strawberry. *Transactions of ASAE, 39*(6), 2185–2191.

Faubion, D. F., & Kader, A. A. (1997). Influence of place packing or tray packing on the cooling rate of palletized Anjou pears. *HortTechnology, 7*(4), 378–382.

Ferrua, M. J., & Singh, R. P. (2007). Modelling airflow through vented packages containing horticultural products. In D. W. Sun (Ed.), *Computational fluid dynamics in food processing*. Florida: CRC.

Ferrua, M. J., & Singh, R. P. (2008). A nonintrusive flow measurement technique to validate the simulated laminar fluid flow in a packed container with vented walls. *International Journal of Refrigeration, 31*(2), 242–255.

Ferrua, M. J., & Singh, R. P. (2009a). Modeling the forced-air cooling process of fresh strawberry packages, part I: numerical model. *International Journal of Refrigeration, 32*(2), 335–348.

Ferrua, M. J., & Singh, R. P. (2009b). Modeling the forced-air cooling process of fresh strawberry packages, part II: experimental validation of the flow model. *International Journal of Refrigeration, 32*(2), 349–358.

Ferrua, M. J., & Singh, R. P. (2009c). Modeling the forced-air cooling process of fresh strawberry packages, part III: experimental validation of the energy model. *International Journal of Refrigeration, 32*(2), 359–368.

Ferrua, M. J., & Singh, R. P. (2011). Improved airflow method and packaging system for forced-air cooling of strawberries. *International Journal of Refrigeration, 34*(4), 1162–1173.

Fikiin, A. G., Fikiin, K. A., & Triphonov, S. D. (1999). Equivalent thermophysical properties and surface heat transfer coefficient of fruit layers in trays during cooling. *Journal of Food Engineering, 40*(1–2), 7–13.

Fraser, H. W. (1991). *Forced-air rapid cooling of fresh Ontario fruits and vegetables (factsheet order no. 91−070, October edn.)*. Ottawa, Ontario, Canada: Ontario Ministry of Agriculture and Food and Rural Affairs.

Fraser, H. W. (1998). *Tunnel forced-air coolers for fresh fruits and vegetables*. Ottawa, Ontario, Canada: Ontario Ministry of Agriculture, Food and Rural Affairs.

Freund, H., Zeiser, T., Huber, F., Klemm, E., Brenner, G., Durst, F., & Emig, G. (2003). Numerical simulations of single phase reacting flows in randomly packed fixed-bed reactors and experimental validation. *Chemical Engineering Science, 58*(3–6), 903–910.

Gaffney, J., & Baird, C. (1977). Forced air cooling of bell peppers in bulk. *Transactions of ASAE, 20*(6), 1174–1179.

Gaffney, J., Baird, C., & Chau, K. (1985). Influence of airflow rate, respiration, evaporative cooling, and other factors affecting weight loss calculations for fruits and vegetables. *ASHRAE Transactions, 91*(1), 690–707.

Goyette, B., Vigneault, C., Panneton, B., & Raghavan, G. S. V. (1996). Method to evaluate the average temperature at the surface of horticultural crop. *Canadian Agricultural Engineering, 38*(4), 291–295.

Guardo, A., Coussirat, M., Larrayoz, M., Recasens, F., & Egusquiza, E. (2005). Influence of the turbulence model in CFD modeling of wall-to-fluid heat transfer in packed beds. *Chemical Engineering Science, 60*(6), 1733–1742.

Haas, E., & Felsenstein, G. (1987). Factors affecting resistance to air flow through avocados packed in fiberboard crates. In Proc. 17th international congress of refrigeration. *International Institute of Refrigeration*, pp 125–130, Paris, France.

Han, J., & Park, J. M. (2007). Finite element analysis of vent/hand hole designs for corrugated fibreboard boxes. *Packaging Technology and Science, 20*(1), 39–47.

Hass, E., Felsenstein, G., Shitzer, A., & Manor, G. (1976). Factors affecting resistance to air flow through packed fresh fruit. *ASHRAE Transactions, 82*(2), 548–554.

Hoang, M. L., Verboven, P., Baelmans, M., & Nicolaï, B. (2003). A continuum model for airflow, heat and mass transfer in bulk of chicory roots. *Transactions of ASAE, 46*(6), 1603–1611.

Hui, K. P. C., Vigneault, C., de Castro, L. R., & Raghavan, G. S. V. (2008a). Effect of different accessories on airflow pattern inside refrigerated semi-trailers transporting fresh produce. *Applied Engineering in Agriculture, 24*(3), 337–343.

Hui, K. P. C., Vigneault, C., Sotocinal, S. A., de Castro, L. R., & Raghavan, G. S. V. (2008b). Effects of loading and air bag bracing patterns on correlated relative air distribution inside refrigerated semi-trailers transporting fresh horticultural produce. *Canadian Biosystems Engineering, 50*(3), 27–35.

Kader, A. A. (2002). *Postharvest technology of horticultural crops*. Davis, California: University of California, Department of Agriculture and Natural Resources, Cooperative Extension.

Ladaniya, M. S. (2008). *Citrus fruit: biology, technology and evaluation*. USA: Academic Press.

Ladaniya, M., & Singh, S. (2000). Influence of ventilation and stacking pattern of corrugated fibre board containers on forced-air precooling of 'Nagpur' mandarins. *Journal of Food Science and Technology-Mysore, 37*(3), 233–237.

Ladaniya, M., & Singh, S. (2002). Packaging of horticultural produce with special reference to citrus fruits. *Packaging India, 34*(5), 9–22.

Leyte, J. C., & Forney, C. F. (1999). Optimizing flat design for forced-air cooling of blueberries packaged in plastic clamshells. *Hort Technology, 9*(2), 202–205.

Logtenberg, S., Nijemeisland, M., & Dixon, A. (1999). Computational fluid dynamics simulations of fluid flow and heat transfer at the wall-particle contact points in a fixed-bed reactor. *Chemical Engineering Science, 54*(13–14), 2433–2439.

Maul, F., Vigneault, C., Sargent, S. A., Chau, K. V., & Caron, J. (1997). Nondestructive sensor system for evaluation of cooling efficiency. *Proceeding of sensors for nondestructive testing international conference and tour, 18–21*, 351–360.

Mitchell, F. G. (1992). Cooling methods. In A. A. Kader (Ed.), *Postharvest technology of horticultural crops* (2nd ed.). Davis, California, USA: University of California.

Mitchell, F., Parsons, R., & Mayer, G. (1971). Cooling trials with plastic tray pack nectarines in various containers. *California Agriculture, 25*(9), 13–15.

Neale, M., & Messer, H. (1976). Resistance of root and bulb vegetables to airflow. *Journal of Agricultural Engineering Research, 21*(3), 221–231.

Ngcobo, M. E. K., Opara, U. L., & Thiart, G. (2011). Effects of packaging liners on cooling rate and quality attributes of table grape (cv. *regal seedless*). *Packaging Technology and Science*. doi:10.1002/pts.961.

Nijemeisland, M., & Dixon, A. G. (2004). CFD study of fluid flow and wall heat transfer in a fixed bed of spheres. *AICHE Journal, 50* (5), 906–921.

Norton, T., & Sun, D. W. (2006). Computational fluid dynamics (CFD)—an effective and efficient design and analysis tool for the food industry: a review. *Trends in Food Science & Technology, 17*(11), 600–620.

Opara, U. L. (2011). *From hand holes to vent holes: what's next in innovative horticultural packaging? Inaugural Lecture* (p. 24p). South Africa: Stellenbosch University.

Opara, L. U., & Zou, Q. (2006). Novel computational fluid dynamics simulation software for thermal design and evaluation of horticultural packaging. *International Journal of Postharvest Technology and Innovation, 1*(2), 155–169.

Opara, L. U., & Zou, Q. (2007). Sensitivity analysis of a CFD modelling system for airflow and heat transfer of fresh food packaging: inlet air flow velocity and inside-package configurations. *International Journal of Food Engineering, 3*(5), 1263.

Ravindra, M. R., & Goswami, T. (2008). Comparative performance of precooling methods for the storage of mangoes (*Mangifera indica* L. CV. *amrapali*). *Journal of Food Process Engineering, 31*(3), 354–371.

Saenmuang, S., Al-Haq, M. I., Samarakoon, H. C., Makino, Y., Kawagoe, Y., & Oshita, S. (2011). Evaluation of models for spinach respiratory metabolism under low oxygen atmospheres. *Food and Bioprocess Technology*, Article in press.

Sastry, S., Baird, C., & Buffington, D. (1978). Transpiration rates of certain fruits and vegetables. *ASHRAE Transactions, 84*(2), 237–255.

Singh, D., Mandal, G., & Jain, R. (2003). Effect of ventilation on shelf life and quality of peaches. In VII International symposium on temperate zone fruits in the tropics and subtropics. Part two 696. References

Singh, J., Olsen, E., Singh, S., Manley, J., & Wallace, F. (2008). The effect of ventilation and hand holes on loss of compression strength in corrugated boxes. *Journal of Applied Packaging Research, 2*(4), 227–238.

Smale, N. J., Tanner, D. J., Amos, N. D., & Cleland, A. C. (2003). Airflow properties of packaged horticultural produce—a practical study. *Acta Hort., 599*, 443–450.

Smale, N. J., Moureh, J., & Cortella, G. (2006). A review of numerical models of airflow in refrigerated food applications. *International Journal of Refrigeration, 29*(6), 911–930.

Staley, L., & Watson, E. (1961). Some design aspects of refrigerated potato storages. *Canadian Agricultural Engineering, 3*(1), 20–22.

Stanley, R. (1989). The influence of temperature and packaging material on the post harvest quality of iceberg lettuce. *Acta Hort. (ISHS), 244*, 171–180.

Talbot M (1988) An approach to better design of pressure-cooled produce containers. In Proceedings of the Florida State Horticultural Society 101, 165–175.

Tanner, D. J., Cleland, A. C., & Robertson, T. (2002a). A generalised mathematical modelling methodology for design of horticultural food packages exposed to refrigerated conditions: part 3, mass transfer modelling and testing. *International Journal of Refrigeration, 25*(1), 54–65.

Tanner, D. J., Cleland, A. C., & Opara, L. U. (2002b). A generalised mathematical modelling methodology for the design of horticultural food packages exposed to refrigerated conditions part 2. Heat transfer modelling and testing. *International Journal of Refrigeration, 25*(1), 43–53.

Tanner, D. J., Cleland, A. C., Opara, L. U., & Robertson, T. R. (2002c). A generalised mathematical modelling methodology for design of horticultural food packages exposed to refrigerated conditions: part 1, formulation. *International Journal of Refrigeration, 25* (1), 33–42.

Thompson, A. K. (1996). *Postharvest technology of fruit and vegetables*. Oxford: Blackwell.

Thompson, J., & Knutson, J. (1997). Forced air cooling of strawberries in clamshell baskets. *Perishables Handling Newsletter, 90*, 29–30.

Thompson, J., Mejia, D., & Singh, R. (2010). Energy use of commercial forced air coolers for fruit. *Applied Engineering in Agriculture, 26* (5), 919–924.

Tutar, M., Erdogdu, F., & Toka, B. (2009). Computational modeling of airflow patterns and heat transfer prediction through stacked layers' products in a vented box during cooling. *International Journal of Refrigeration, 32*(2), 295–306.

Van der Sman, R. (2002). Prediction of airflow through a vented box by the Darcy–Forchheimer equation. *Journal of Food Engineering, 55*(1), 49–57.

Verboven, P., Hoang, M., Baelmans, M., & Nicolaī, B. (2004a). Airflow through beds of apples and chicory roots. *Biosystems Engineering, 88*(1), 117–125.

Verboven, P., Tijskens, E., Ramon, H., & Nicolaï, B. M. (2004b). Virtual filling and airflow simulation of boxes with horticultural products. In International conference postharvest unlimited downunder 2004. *ISHS Acta Horticulturae, 687*, 47–54.

Verboven, P., Flick, D., Nicolaī, B., & Alvarez, G. (2006). Modelling transport phenomena in refrigerated food bulks, packages and stacks: basics and advances. *International Journal of Refrigeration, 29*(6), 985–997.

Vigneault, C. (2011). Vorkühlungsverfahren von Obst und Gemüse. In: Geyer M (ed) Lagerung von Obst und Gemüse. Chapter 3, Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt, Germany.

Vigneault, C., & de Castro, L. R. (2005). Produce-simulator property evaluation for indirect airflow distribution measurement through horticultural crop package. *Journal of Food, Agriculture & Environment, 3*(2), 67–72.

Vigneault, C., & Émond, J. P. (1998). Reusable container for the preservation of fresh fruits and vegetables. *United States Patent number :, 5*, 727,711.

Vigneault, C., & Goyette, B. (2002a). Design of plastic container opening to optimize forced-air precooling of fruits and vegetables. *Applied Engineering in Agriculture, 18*(1), 73–76.

Vigneault, C., & Goyette, B. (2002b). Largeur des ouvertures au fond de contenants de plastique utilisés pour la manutention des produits horticoles frais. *Canadian Biosystems Engineering, 44*(3), 7–10.

Vigneault, C., & Goyette, B. (2003). Effect of tapered wall container on forced-air circulation system. *Canadian Biosystems Engineering, 45*(3), 23–26.

Vigneault, C., & Goyette, B. (2005). Paramètres affectant le débit d'air à travers une masse de poireaux et leur taux de refroidissement. *Cahiers Agricultures, 14*(4), 383–389.

Vigneault, C., & Sobral, D. (2008). Pré-resfriamento e refrigeração em pós-colheita de citros. In : Nascimento LM, de Negri JD & de Mattos Jr D. Topicos em qualidade e pós-colheita de frutas / Topicos en calidad y postcoscha de frutos. pp111-132. Centro APTA Citros Sylvio Moreira– IAC, Cordeirópolis, SP, Brasil.

Vigneault, C., Goyette, B., & Raghavan, G. S. V. (1995). Continuous flow liquid-ice system tested on broccoli. *Canadian Agricultural Engineering, 37*(3), 225–230.

Vigneault, C., Goyette, B., Markarian, N., Hui, C., Côté, S., Charles, M. T., & Émond, J. (2004a). Plastic container opening area for optimum hydrocooling. *Canadian Biosystems Engineering, 46* (3), 41–44.

Vigneault, C., Markarian, N. R., Da Silva, A., & Goyette, B. (2004b). Pressure drop during forced-air ventilation of various horticultural produce in containers with different opening configurations. *Transactions of ASAE, 47*(3), 807–814.

Vigneault, C., de Castro, L. R., & Cortez, L. A. B. (2005a). A new approach to measure air distribution through horticultural crop packages. *ISHS Acta Horticulturae., 682*, 2239–2245.

Vigneault, C., de Castro, L. R., & Cortez, L. A. B. (2005b). Effect of gravity on forced-air precooling. *IASME Transactions., 3*(2), 459–463.

Vigneault, C., Goyette, B., & de Castro, L. R. (2006). Maximum slat width for cooling efficiency of horticultural produce in wooden crates. *Postharvest Biology and Technology, 40*(3), 308–313.

Vigneault, C., de Castro, L., Goyette, B., Markarian, N., Charles, M. T., Bourgeois, G., Foot, E. T. L., & Cortez, L. A. B. (2007). Indirect airflow distribution measurement method for horticultural crop package design. *Canadian Biosystems Engineering, 49*(3), 13–22.

Vigneault, C., Thompson, J., Wu, S., Hui, K. P. C., & LeBlanc, D. L. (2009a). Transportation of fresh horticultural produce. In N. Benkeblia (Ed.), *Postharvest technologies for horticultural crops (Vol 2)* (pp. 1–24). Kerale, India: Research Signpost.

Vigneault, C., Thompson, J., & Wu, S. (2009b). Designing container for handling fresh horticultural produce. In N. Benkeblia (Ed.), *Postharvest Technologies for Horticultural Crops (Vol 2)* (pp. 25–47). Kerale, India: Research Signpost.

Wang, J. K., & Tunpun, K. (1969). Forced-air precooling of tomatoes in cartons. *Transactions of ASAE, 12*(6), 804–806.

Wilhelm, L., Jones, D., & Mullins, C. (1978). Air flow resistance of snap beans. ASAE Paper 78–3058.

Wilhelm, L., Tompkins, F., & Mullins, C. (1983). Air flow resistance of bean and pea pods. *Transactions of ASAE, 26*(3), 946–949.

Wills, R., McGlasson, W., Graham, D., & Joyce, D. (1998). *Postharvest: an introduction to the physiology and handling of fruit, vegetables and ornamentals* (4th ed.). Sydney: UNSW Press Ltd.

Xu, Y., & Burfoot, D. (1999). Simulating the bulk storage of foodstuffs. *Journal of Food Engineering, 39*(1), 23–29.

Zou, Q., Opara, L. U., & McKibbin, R. (2006a). A CFD modeling system for airflow and heat transfer in ventilated packaging for fresh foods: I. Initial analysis and development of mathematical models. *Journal of Food Engineering, 77*(4), 1037–1047.

Zou, Q., Opara, L. U., & McKibbin, R. (2006b). A CFD modeling system for airflow and heat transfer in ventilated packaging for fresh foods: II. Computational solution, software development, and model testing. *Journal of Food Engineering, 77*(4), 1048–1058.