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Virtual cold chain method to model the postharvest temperature history and quality evolution of fresh fruit – A case study for citrus fruit packed in a single carton

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ABSTRACT

Fruit quality loss is dependent on the temperature control throughout the postharvest cold chain. Previous research mainly focused on optimizing the cooling performance of single unit operations. However, assessing fruit temperature history throughout the entire cold chain is crucial to determine the end quality. This study proposes a virtual cold chain (VCC) method to predict the temperature history and quality loss of packaged fresh fruit, down to each individual fruit, throughout the entire cold chain. The VCC method is based on computational fluid dynamics and kinetic quality modelling. Results show that the difference in quality loss among individual fruit in a carton could reach 11% for a specific cold chain. The maximum difference in the remaining quality at the end of the cold chain between different cold chain scenarios is 23%. The VCC method has a potential to track temperature history and to estimate quality loss of individual fruit in the cargo throughout a cold chain.

1. Introduction

A general and growing concern in the fruit industry is the loss of quality in supply chains. Postharvest losses, from the point of harvest until fruit reaches the consumer, can be as high as 13–38% (Gustavsson et al., 2011). To reduce the incidence and magnitude of postharvest losses, it is crucial to rapidly remove the field heat of the produce after harvest and to maintain optimum produce temperature throughout the entire supply chain. The reason is that temperature is the most important factor affecting fresh produce quality change, deterioration rates and shelf life (Thompson et al., 2008; Qiu and Wang, 2015). The temperature history of fruit can be directly related to the produce quality loss (Robertson, 1993) and market value. Therefore, tracking the temperature history of fresh fruit is essential to estimate quality evolution throughout the cold chain.

To this end, measuring the pulp temperature of fruit, and not the air temperature, is required. Pulp temperatures are monitored, for example, to decide when to stop the precooling process or to evaluate the state of the cargo during overseas maritime transport in refrigerated containers. The fruit core is the last location to reach the set point temperature. However, in commercial operations, these core temperatures are not that easy to measure for packed fruit throughout the entire cold chain. Temperature sensors, such as point probes, are inserted after fruit have been packed in cartons and stacked on pallets. Hence, core temperature history is often monitored at locations which are easy to access, such as the side of the pallet and carton, and only a limited amount of fruit are monitored. However, fruit in different locations of pallets, e.g., fruit in top and bottom cartons, do not cool in the same way (Pelletier et al., 2011; Defraeye et al., 2013a, 2015). Therefore, the recorded fruit core temperature history, tracked at these selected locations, does not necessarily represent the overall fruit quality evolution of a particular cargo.

An alternative method to obtain fruit temperature data at a much higher spatial resolution in the cargo is to apply numerical modelling by

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computational fluid dynamics (CFD). CFD has been widely applied in postharvest handling and food processing (Ramachandran et al., 2011; Ambaw et al., 2013a; Smith et al., 2014; Tian and Barigou, 2016). The advantage of CFD simulations is that core temperatures of every single fruit in a carton or in a pallet during cooling can be calculated, as heat transfer within the products and their heat exchange with the surrounding airflow are explicitly modelled (Delele et al., 2013; Defraeye et al., 2014). Because of the added insight it provides, CFD has been successfully applied to model cooling of fruit in single unit operations in the cold chain, including precooling (Ferrua and Singh, 2009a, 2009b, 2009c, 2011; Defraeye et al., 2013a), refrigerated transport container (Moureh et al., 2009a, 2009b; Defraeye et al., 2015) and cold storage (Chourasia and Goswami, 2007; Delele et al., 2009). The loss of fruit quality is, however, determined by the fruit temperature history throughout the entire cold chain, where each unit operation is subject to different temperature and ventilation (air speed) conditions. The FRISBEE tool (Gwanpua et al., 2015) is developed to assess food quality along the European cold chain, in which kinetic models are formulated for different quality parameters (e.g., firmness, color, vitamin C) based on overall product temperature. Nevertheless, to the best knowledge of the authors, CFD-based modelling has not been used to study the temperature history of fruit throughout an entire cold chain and to link it to fruit quality evolution.

The objective of this study is, therefore, to develop a virtual cold chain method (VCC) for tracking the temperatures of packed fruit throughout the different unit operations of the entire chain, based on CFD modelling. By transferring the temperature distribution of each individual fruit from one unit operation to the next one, the entire cold chain is simulated. These temperature information of each individual fruit is used to predict fruit quality loss throughout the entire postharvest supply chain. As a case study, the performance of this method is evaluated by simulating the thermal behavior of citrus fruit packed in a single carton for different cold chain strategies.

The unique insights in the obtained temperature history and quality evolution of each individual fruit throughout the entire chain provide new ways to assess different packaging designs and to optimize cold chain strategies, in order to reduce postharvest losses. The current packaging designs are mainly evaluated only for a single unit operation. The optimal package design for one unit operation might show poor performance in another unit operation. With the VCC method, the performance of ventilated packaging can be evaluated in a new and integrated way through multiple cold chain unit operations. Furthermore, another major concern in the postharvest industry is the cooling heterogeneity between individual fruit. The VCC method provide an innovative and simulation-based alternative to assess produce cooling heterogeneity throughout the entire cold chain.

2. Materials and methods

2.1. The virtual cold chain (VCC) method

The VCC method is illustrated for a typical cold chain for citrus fruit, consisting of three unit operations – precooling, refrigerated transport and cold storage (Fig. 1). In the first step, computational models for each different unit operations are created, which include the detailed geometrical model of the package and individual fruit. Secondly, all unit operations in the cold chain are calculated sequentially, where the temperature condition of each fruit is transferred from one operation, e.g., forced air precooling, to the other, e.g., transport. Then the temperature history of each individual fruit is extracted from unit operations throughout the entire cold chain and this information is used in a fruit quality model, which calculates the produce quality evolution.

2.2. Different cold chains

The concept and performance of the VCC method is illustrated by evaluating cooling and quality evolution of citrus fruit packed in a single carton for five cold chain scenarios (see Fig. 3). Although a single carton is used for calculation in this study, it is sufficient to show the ability of the VCC method, which can be later extended to more comprehensive computational models (e.g. pallet). During forced air precooling, the carton is ventilated with horizontal airflow (See Fig. 2(a)) at high flow rates, typically 0.5–3 $\mathrm{L\,kg^{-1}\,s^{-1}}$ (Thompson et al., 2008). During refrigerated transport, the carton is ventilated with vertical airflow (See Fig. 2(a)). In a refrigerated container, the airflow rate is typically 0.02–0.06 $\mathrm{L\,kg^{-1}\,s^{-1}}$ (Defraeye et al., 2015). During cold storage, the carton is assumed here to be ventilated with horizontal airflow with low airflow rates, which are typically 0.001–0.002 $\mathrm{L\,kg^{-1}\,s^{-1}}$ (Thompson et al., 2008). Different combinations of these three types of unit operations are evaluated to mimic different postharvest cold chain strategies used in the citrus fruit industry. The baseline cold chain used in this study consists of precooling (1 d at 3 °C), transport (24 d at −1 °C) and cold storage (14 d at 4 °C). This baseline case is chosen as a representative scenario used currently in the citrus export industry. This case simulated partial precooling to remove the majority of the fruit field heat and then further heat removal during transport. The second cold chain – 'cold-disinfestation precooling' – consists of precooling (3 d at −1 °C), transport (24 d at −1 °C) and cold storage (14 d at 4 °C). These lower temperatures are often required for markets demanding a cold disinfestation protocol to kill insect larvae in fruit. The third cold chain – 'ambient cooling' – does not include precooling. Instead, fruit are held in static cold storage for 5 d at 3 °C before shipment, which induces a slow cooling process. Afterwards, the fruit go through refrigerated transport (24 d at −1 °C) and cold storage (14 d at 4 °C) after shipment. In the fourth cold chain, called 'ambient loading' (Defraeye et al., 2015), the fruit are directly loaded (warm) to the refrigerated container after being packed. After 24 d of transport at −1 °C, fruit are held in cold storage for 14 d at 4 °C. Such ambient loading is used in the South African citrus industry to shorten the cold chain and to avoid the use of precooling facilities as there are several regions where they are not present or where there is insufficient precooling capacity. The last cold chain scenario – 'holding time after precooling' includes four unit operations: precooling (1 d at 3 °C), cold storage before shipment (5 d at 3 °C), transport (24 d at −1 °C) and cold storage (14 d at 4 °C) after shipment. This cold chain simulates the case where fruit are kept for a few days after precooling at storage set point temperature (3 °C) before being loaded into the container.

2.3. Computational model

2.3.1. Model development

A telescopic corrugated fibreboard carton is used (0.4 m × 0.3 m × 0.27 m, see Fig. 2a). The carton has two circular vents on each lateral side, at half height. During precooling and storage, these side vents enable horizontal airflow. The carton has four circular vents and a rectangular slot on top and bottom, respectively, which enable vertical airflow during transport. The carton is filled with 64 orange fruit according to a predetermined staggered pattern and fruit are discretely modelled as spheres with a diameter of 75 mm. The total weight of the fruit in a carton is 13.6 kg. To avoid the generation of highly skewed cells near the contact point of two fruit, a gap of about 3 mm is left between the fruits.

Three separate computational models are constructed for precooling, transport and storage (Fig. 2b). In the models for precooling and storage, the carton is ventilated horizontally (Fig. 2a and b), while in the model for transport, the carton is ventilated vertically (Fig. 2a and b). The upstream and downstream sections are extended long enough to reduce the impact of inlet and outlet boundary conditions on the flow near the proximity of the box.

At the outlet, a volumetric flow rate is imposed, with a flow direction going out of the domain. This boundary condition mimics the