Journal of Food Engineering 118 (2013) 8–18

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

# Forced-convective cooling of citrus fruit: Package design

Thijs Defraeye[a,*], Rutger Lambrecht[a], Alemayehu Ambaw Tsige[a], Mulugeta Admasu Delele[c], Umezuruike Linus Opara[c], Paul Cronjé[d], Pieter Verboven[a], Bart Nicolai[a,b]

[a] *MeBioS, Department of Biosystems, KU Leuven, Willem de Croylaan 42, 3001 Heverlee, Belgium*
[b] *VCBT, Flanders Centre of Postharvest Technology, Willem de Croylaan 42, 3001 Heverlee, Belgium*
[c] *Postharvest Technology Research Laboratory, South African Research Chair in Postharvest Technology, Stellenbosch University, Stellenbosch 7602, South Africa*
[d] *Citrus Research International, Department of Horticultural Sciences, Stellenbosch University, Stellenbosch 7602, South Africa*

ARTICLE INFO

*Article history:*
Received 23 December 2012
Received in revised form 6 March 2013
Accepted 23 March 2013
Available online 1 April 2013

*Keywords:*
Orange
Container
Computational fluid dynamics
Precooling
Vent hole
Packaging

ABSTRACT

Optimisation of package design for citrus fruit is required to increase the throughput, by reducing the precooling time, and to enhance fruit quality by providing fast and uniform cooling without inducing chilling injury. The cooling performance of an existing container and of two new containers (Supervent and Ecopack), as stacked on a pallet, was evaluated experimentally and numerically with computational fluid dynamics (CFD). The accuracy of the CFD simulations was confirmed by a good agreement with experiments. The best cooling performance was found for Ecopack, but removing airflow short circuits in this container may enhance the cooling performance even more. Also with respect to uniformity of cooling of the fruit and the magnitude of the convective heat transfer coefficients, in a specific container and between different containers on the pallet, the Ecopack container performed best, followed by the Supervent and the standard container. The new container designs thus clearly showed significant improvements in cooling performance.

## 1. Introduction

The worldwide production of citrus fruit has risen significantly in the past decades. For oranges, which account for more than half of the recent global citrus fruit produced, production increased over 70% compared to 1980 (FAOSTAT, 2012). Apart from an increase in cultivated area and consumer demand, an important reason for this increase are the improvements made in packaging, transportation and storage, as they maintain postharvest quality and extend shelf life, by which economic losses are reduced. Since preservation of citrus fruit quality is mainly determined by temperature, a critical step in the postharvest cold chain is the rapid precooling after harvest to remove field heat. Forced-convective cooling is the most commonly used precooling method (Dehghannya et al., 2010). Here, cool air is forced through a stack of produce (e.g., in containers stacked on a pallet) by applying a pressure difference over the stack.

The forced-convective cooling process can be optimised with respect to the cooling system and the resulting fruit quality. Cooling system optimisation involves determining the optimal working point of the system (i.e., the required flow rate) that minimises the cooling time of the fruit, to increase throughput, and limits operational costs and energy losses in the system. Fruit quality should be optimised by providing fast cooling without introducing chilling injury (Thompson, 2003), and homogeneous cooling of individual fruit in different parts of the package to ensure uniform fruit quality, hence avoiding undercooling or overcooling (Dehghannya et al., 2010; Nahor et al., 2005). The cooling rate is dependent on the size, shape and thermal properties of the fruit but also on cooling temperature, airflow rate and accessibility of the airflow to fruit. The latter is determined by the fruit stacking pattern in the containers, the design of the packaging (location of vent holes and total vent area; Pathare et al., 2012) but also by the stacking of individual containers on a pallet, as vent holes might be closed or the airflow can bypass the fruit through openings between individual containers.

Package design is a subject of active research in the food industry due to its importance in the forced-convective cooling process and its complexity (de Castro et al., 2004, 2005; Dehghannya et al., 2010, 2011, 2012; Ferrua and Singh, 2009a,b; Pathare et al., 2012; Verboven et al., 2006). Optimal package design is very product-specific because of the large variety in size and shape and thermal properties of different produce. Often, a compromise has to be made between optimal ventilation and mechanical strength of the containers, which is required for stacking them and for protecting the fruit. Previous studies on package design have used both experimental and numerical techniques, such as computational fluid dynamics (CFD). Particularly the use of numerical modelling is becoming more popular, as airflow patterns and temperatures can be obtained at a high spatial and temporal resolution

---

* Corresponding author. Tel.: +32 016321618; fax: +32 016322966.
*E-mail address:* thijs.defraeye@biw.kuleuven.be (T. Defraeye).

0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.03.026

(Dehghannya et al., 2010; Smale et al., 2006). Such information is invaluable for the evaluation and interpretation of package performance and for proposing design changes. Although numerical modelling can be used as a design tool by itself, a priori comparison with experiments is strongly advised in order to assess the accuracy of the numerical models used.

In this study, the performance of an existing corrugated fibreboard container (CFC) for forced-convective cooling of orange fruit is compared with two new container designs, namely the Supervent CFC and the Ecopack reusable plastic container (RPC), as stacked on a pallet. Both experiments and CFD are used for the analysis of the three container designs, by which the accuracy of CFD modelling could be evaluated. This study deals with several features which are of particular interest to researchers and practitioners involved in the fruit postharvest cold chain. First of all, the performance of new container designs for fruit is evaluated. Furthermore, containers are evaluated as stacked on a pallet, by which not only the performance and uniformity in cooling of an individual container can be assessed, but also heterogeneities between different containers, e.g., located more downstream on the pallet. Finally, the individual orange fruit are modelled discretely with CFD, thus avoiding the use of the porous-medium approach to model flow in the containers (Verboven et al., 2006), based on the Darcy–Forchheimer–Brinkman equation. This discrete approach allows assessing the heterogeneity of fruit cooling inside a single container, identifying local extremes, and is inherently more accurate, but has a higher computational cost (Dehghannya et al., 2010).

## 2. Materials and methods

### 2.1. Experimental study

#### 2.1.1. Materials

'Valencia late' orange fruit [*Citrus sinensis* (L.) Osb.] were harvested and packed at Cederpack packhouse in Citrusdal (Western Cape, South Africa) on September 7th 2011. Before transportation to the experimental facility, all fruit received standard commercial treatments (thiabendazole, 500 mg, l-1; imazalil, 500 mg, l-1; 2,4-dichlorophenoxyacetic acid, 125 mg, l-1). Also, a polyethylene citrus wax (Citrushine®, Johannesburg, South Africa) was applied. Fruit of similar size were used (calibre 5), which had an average weight of about 250 g and a diameter of 78–80 mm. Between the time of arrival of the oranges and the start of the cooling experiments (~5 days), the oranges were stored at 4 °C to maintain their overall quality and avoid excessive moisture loss that could affect the thermal and physical properties of the fruit. Before the cooling experiments, the fruit was brought to room temperature (≈21 °C). Due to small fluctuations of air temperature in the room, the initial flesh temperature was not exactly identical in every experiment. Three experiments were performed, i.e., one for each container design. For each experiment, 1920 oranges were used, whether in 30 containers of 64 oranges for the two CFC types or in 24 containers of 80 oranges for the Ecopack RPC.

#### 2.1.2. Container types

Two types of telescopic CFC's were compared (see Fig. 1), where telescopic indicates that the top part of the box slides over the bottom part. The outer component of the containers consists of a flute construction of type "C" (4 mm thickness), whereas the inner component consists of a double "B" and "C" flute construction (6 mm thickness). The only difference between the two CFC's is the number, size and positioning of the different vent holes: the standard container, with a conservative design, has two circular vents on each side, at half height; the Supervent container has half-circular vent holes, located at the top and bottom of the sides. A horizontal ventilation pathway is formed by these vent holes, when several containers are stacked on a pallet. As forced-convective cooling was performed by horizontal airflow, the impact of the large horizontal openings on the bottom and top of the CFC containers on the cooling process was assumed negligible.

The third type of container was a reusable plastic container called Ecopack (see Fig. 2). The fruit is kept in position by means of a net and a plastic foil. For this container, horizontal flow should always be perpendicular to the long side, as the short side is almost completely blocked by the plastic foil. Table 1 summarizes the total open area (TOA) of the sides for both CFC types and for the Ecopack RPC.

#### 2.1.3. Cooling experiments

The temperature inside individual fruit during forced-air cooling was measured at different positions in the containers, loaded on a pallet. The temperature profiles allowed to compare the cooling performance of the different containers but also to evaluate the accuracy of the CFD model for predicting the cooling behaviour. Two different types of temperature sensors were used: DS1921Z Thermocron® i-buttons® (Maxim, CA, USA), which are disk-shaped sensors (diameter = 16.30 mm, height = 5.9 mm) with an accuracy of ±1 °C; T-type thermocouples, with an accuracy, after calibration, of ±0.3 °C. These sensors were inserted in the centre of the fruit via an incision. The influence of the difference in heat capacity and mass of both sensors on the temperature measurements was considered limited, as they were inserted in the centre of the fruit and as their mass was low compared to that of the fruit. Data were collected every 3 min by the i-buttons and every 60 s by the thermocouples.

For the CFC's, individual containers were filled according to a predetermined staggered pattern, which was the same for both containers. Four oranges per container were used for temperature monitoring: three were inserted with an i-button® and one with a thermocouple. These four oranges were located in the second layer of oranges inside the container (*z*-direction). Fig. 3 shows the position of the temperature sensors in this layer of the container. Note that for the Supervent container, only thermocouples were used, thus one per container. Thirty containers, divided over three identically-stacked layers (Fig. 3), were used to create a stack with dimensions 1.2 m × 1.0 m × 0.81 m on a standard wooden pallet.

The individual Ecopack containers were filled, where the bottom layer in the container contained 36 oranges, the second layer 30 and an additional 14 oranges were added in a random way to fill the container where possible. Because of the open character of the plastic container, it was not evident to fill all containers in the exact same way. Five oranges per container were used for temperature monitoring: three were inserted with an i-button® and two with a thermocouple. These five oranges were located in the second layer of oranges inside the container (*z*-direction, Fig. 3). Twenty-four Ecopack containers, divided over six identically-stacked layers, were used to create a stack with dimensions 1.2 m × 0.8 m × 0.99 m.

After stacking, all sides that were parallel to the airflow direction (i.e., *xy*- and *yz*-planes) were sealed with low-density polyethylene (LDPE) plastic foil to ensure that only airflow in the positive *y*-direction was allowed through the stacks. Also, the vertical slots between two neighbouring containers, perpendicular to the airflow, were taped with LDPE plastic to prevent air bypassing the containers. Next, the loaded pallet was aligned with a metal casing, where an airspace of 120 mm was present between the last row of containers and the back plate (Fig. 4). The metal casing contained a circular opening (diameter 150 mm), on which a centrifugal fan was mounted. The pallet, attached to the metal casing, was then transferred to a refrigerator room (2.79 m × 2.77 m × 2.63 m) at