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Forced-convective cooling of citrus fruit: package design

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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.

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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, 2009b; 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 (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 to 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 Figure 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 Figure 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 minutes by the i-buttons and every 60 seconds 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). Figure 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 (Figure 3), were used to create a stack with dimensions 1.2 m x 1.0 m x 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, Figure 3). Twenty-four Ecopack containers, divided over six identically-stacked layers, were used to create a stack with dimensions 1.2 m x 0.8 m x 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 (Figure 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 x 2.77 m x 2.63 m) at -0.5°C and the forced-air cooling experiment was started by switching on the fan. The fan created an underpressure which sucked air from the refrigerator room through the containers after which the air was blown back into the room. Due to the labour- and cost-intensiveness of these experiments, only one experiment was performed for each container type. Note that all containers were evaluated using the same fan system. This makes sense as in reality cooling systems will not be redesigned with respect to airflow, each time a new container is designed. This however implies that the operation point of the system can become suboptimal and that the airflow rate through the stack will change, which will also affect the operational cost.

2.2 Numerical modelling

2.2.1 Numerical model

Computational models of the experimental configurations were made, namely of containers stacked on a pallet, in which the individual oranges were modelled discretely. They are shown in Figure 5, with the dimensions and boundary conditions. Each container contained 64 (CFC's) or 80 oranges (Ecopack) and the stacking was similar as in the experiments. The oranges were modelled as spheres with a diameter of 80 mm. Some simplifications were made to the computational models, to limit the computational cost, amongst others. First, only one of the three layers of containers (Figure 3) was modelled for both CFC's, and only two layers for the RPC, namely the layer(s) in the middle, by assuming symmetry on top and bottom boundaries. The Ecopack container geometry was simplified, by which the total open area was slightly higher than in reality, namely 62% (Table 1). Furthermore, the plastic net was not included due to the high porosity and the plastic foil was also not modelled as it was parallel to the airflow. The upstream and downstream sections were taken sufficiently large to avoid an influence of the boundary conditions at inlet and outlet on the flow in the proximity of the containers. This however induced some differences with the actual configuration (e.g., at the metal casing), but their impact on the results was considered rather limited.

The computational grid was a hybrid grid, consisting of both hexahedral and tetrahedral cells, in total 5.5 x 10^6, 5.4 x 10^6 and 5.5 x 10^6 cells for standard, Supervent and Ecopack containers, respectively. The spatial discretisation error was estimated by means of Richardson extrapolation (Franke et al., 2007; Roache, 1994), and was about 2.5% for the mass flow rate through the containers, and 5% for the heat flow from the oranges.

At the inlet of the domain, the ambient atmospheric pressure was imposed, i.e., the conditions in the refrigerator room. A low turbulence intensity of 0.05% was imposed for flow entering the computational domain. The inlet temperature was taken from temperature measurements in the refrigerator room during cooling, as the set air temperature (-0.5°C) was not reached immediately and fluctuations were present.

At the outlet, an underpressure was imposed, to represent the fan. Its value was determined by the point of intersection between the fan performance curve and the system curve of the entire pallet. This system curve was determined from CFD simulations on the layer of containers (Figure 5), of which the results were converted to represent an entire pallet by considering it as different layers (resistances) in parallel. Here, the pressure drop over the metal casing was considered negligible. The working points were at an underpressure of 572 Pa, 520 Pa and 58 Pa for standard, Supervent and Ecopack containers, respectively. These lead to flow rates of 0.19, 0.65 and 2.12 l $s^{-1}kg^{-1}$ of fruit, respectively, and to an average superficial velocity inside the containers of 0.25, 0.84, 2.11 m s^{-1}, respectively. Typical flow rates of 1 to 2 l $s^{-1}kg^{-1}$ of fruit have been reported as common in industry (Ladaniya, 2008). The evaluated airflow rates are thus representative for forced-convective precooling, except for the standard container.

The bottom and top surfaces and the lateral boundaries upstream and downstream of the containers were modelled as symmetry boundary conditions (slip walls), which assume that the normal velocity component and the normal gradients at the boundary are zero. The cardboard and plastic containers and the fruit surfaces were modelled as no-slip walls with zero roughness. At the sides of the containers, the heat exchange with the room was modelled by means of a convective heat transfer coefficient (CHTC [W $m^{-2}K$]) and the room temperature, to mimic the conditions found in the experiments. The CHTC relates the convective heat flux normal to the wall ($q_{c,w}$ [J $s^{-1}m^{-2}$]), i.e., at the air-material interface, to the difference between the wall temperature (T_w [°C or K]) and a reference temperature (T_{ref} [°C or K]), which was the room temperature in this study: CHTC = $q_{c,w}/(T_w-T_{ref})$. The flux is assumed positive away from the surface. The initial temperature of the fruit and cardboard/plastic was taken equal to the measured average fruit temperature at the start of the experiments (≈ 21°C), and differed slightly for the different experiments.

2.2.2 Numerical simulation

The simulations were performed with the CFD code ANSYS Fluent 13, which uses the control volume method. In the past, CFD has been extensively applied to model fluid flow for several food processing applications (Ambaw et al., 2012; Delele et al., 2008, 2012; Hoang et al., 2003, 2004; Hu and Sun, 2001; Verboven et al., 1997, 2003; Zou et al., 2006a, 2006b). The accuracy of CFD simulations depends to a large extent on the turbulence-modelling and boundary-layer modelling approaches that are used. In this study, steady Reynolds-averaged Navier-Stokes (RANS) in combination with the shear stress transport k-ω model (SST k-ω; Menter, 1994) was applied. It was not feasible to mesh the boundary-layer region fine enough to apply low-Reynolds number modelling (LRNM) to resolve the flow in the boundary layer on the no-slip surfaces (e.g., fruit) since the computational cost would be too large and grid generation would be very challenging. Therefore, the wall-function approach was used.

Wall functions model the flow quantities in the boundary-layer region by calculating them by means of semi-empirical functions (Launder and Spalding, 1974), whereas LRNM explicitly resolves the transport in the boundary layer, which however requires a much finer grid resolution in the boundary layer. Wall functions increase computational economy and facilitate grid generation. Their accuracy is however less than LRNM, particularly for the prediction of convective heat transfer in the boundary layer (Defraeye et al., 2013). A recent study by Defraeye et al. (2013) identified the accuracy of different turbulence and boundary-layer models for flow around a single sphere. They found that the SST k-ω turbulence model performed best, when combined with LRNM. When combined with wall functions, differences in CHTCs up to 35% were found at high sphere Reynolds numbers (Re >

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10^3, where $Re = U_{ref}D/\nu$, with U_{ref} the reference air speed [m s^{-1}], D the sphere diameter [m] and ν the kinematic viscosity of air [m^2 s^{-1}]). At lower air speeds, the accuracy was much better (~10%), and became even comparable to LRNM at very low air speeds ($Re < 10^2$). Based on the superficial velocities reported above, the sphere Reynolds numbers in this study were 1.3 x 10^3, 4.6 x 10^3 and 11.6 x 10^3 for standard, Supervent and Ecopack containers, respectively. Despite being less accurate, wall functions are often the only option as LRNM is not practically applicable for complex 3-D configurations (Kondjoyan, 2006), which was also the case in this study. Other studies also applied the RANS SST k-ω model in combination with wall functions for flow in stacks of food products and found a good agreement with experiments (Ambaw et al., 2012; Delele et al., 2009). In this study, the accuracy of the SST k-ω model with standard wall functions (Launder and Spalding, 1974) will be evaluated by comparison with experiments. Note that the aim of the experiments was not to provide data for detailed CFD validation, which would also require flow-field measurements and a higher spatial resolution of the temperature data. Instead, the experiments were performed to allow comparison of this technique with numerical modelling, and to give a first indication of the accuracy of the CFD simulations.

Furthermore, second-order discretisation schemes were used throughout. The SIMPLE algorithm was used for pressure-velocity coupling. Pressure interpolation was second order. Buoyancy effects were considered negligible and were not taken into account in the simulations, which implies forced-convective flow and passive scalar (heat) transfer. Radiation was also not considered in the simulations, since the radiation exchange between the fruit inside the stack was considered small compared to convective heat transfer. Heat of respiration was not included in the model since it is unlikely to have a significant impact on the cooling rate of fresh horticultural produce during forced-convective precooling (Gowda et al., 1997) and it is quite low for oranges (~ 50 W/tonne; ASHRAE, 1994). Mass loss from the fruit, and the resulting latent heat of evaporation were also not included in the model since the mass loss was very small (measured as < 1% after 3 days at -0.5°C, of which one day with air flow, not reported). Iterative convergence of the numerical simulation was assessed by monitoring the velocity, turbulent kinetic energy and temperature on specific locations in the flow field, and the heat fluxes (surface-averaged values) on the fruit surfaces. Following thermal properties of the oranges were used in the simulations: a density of 960 kg m^{-3}, a thermal conductivity of 0.386 W $m^{-1}K^{-1}$ and a specific heat capacity of 3850 J $kg^{-1}K^{-1}$.

Before simulating the transient cooling process, steady simulations were performed to obtain the flow field and the initial temperature conditions. During these simulations, the temperature of the containers and the fruit was fixed to the initial values specified in section 2.2.1 (≈ 21°C) and the initial inlet temperature was taken equal to the room temperature at the start of the experiment. After the steady simulations, transient simulations of the cooling process were performed. Since the flow field was steady over time, amongst others since no buoyancy was included in the model, the flow field did not need to be resolved anymore during the transient simulations, and thus the flow equations were switched off. Since only the energy equation needed to be solved, the computational cost was reduced. The transient simulations were run for 14h, with a time step of 60s, which was determined from a temporal sensitivity analysis. The simulations took about 24h on a 12 core Intel Xeon processor (2.66GHz) with 48GB RAM memory.

3. Results

3.1 CFD vs. experiments

Before comparing the cooling performance of the three containers, the accuracy of the CFD simulations was assessed by comparison with experimental data in Figure 6-8. Here, the temperatures in the centre of the oranges are given as a function of time for all sensors of a certain type (experiments: thermocouples or i-buttons®) and for all virtual sensors (CFD), averaged over a specific row (*y*-direction, see Figure 3), for the three container designs. In addition, the temperatures at the inlet of the stack (i.e., in the refrigerator room) are also shown. Since the inlet temperature data of the experiments were only available up to 10h, the inlet temperature imposed in the CFD simulations was taken constant from that point on. As the data of the i-buttons® compared very well with the thermocouple data, only the i-button® data are shown for standard and Ecopack containers. For the CFD simulations, the virtual sensors are located in the centre of an orange in the central part of a specific container. Due to the large spread found in the temperature profiles between the containers in a certain row for the CFD simulations of the standard container, in contrast to the experiments, the profiles of CFD of the individual containers are also given in Figure 6. For Supervent and Ecopack, this spread was very limited for CFD, and is therefore not shown. In the experiments, the variation in temperature between the different oranges in a row was limited for all containers. As an indication of this variability, the standard error (which holds the standard deviation) on the temperature was calculated at each moment in time, by considering all sensors in the same row.

These standard errors of each row, averaged over the entire experimental duration, are given in Table 2. The standard errors are clearly limited (≤ 0.3 °C) and lie within the experimental accuracy of the sensors.

These temperature profiles however depend to some extent on the initial fruit temperature and the inflow temperature conditions, which differed slightly for the three experiments. Therefore, comparing dimensionless parameters which are less dependent on these conditions might be more appropriate. For this purpose, the cooling rate was described in terms of the fractional unaccomplished temperature change *Y*, which could be determined from the temperature profiles:

$$Y = \frac{T - T_a}{T_i - T_a} \qquad (1)$$

where the subscripts *i* and *a* represent the initial temperature of the fruit and the set cooling air temperature (-0.5°C), respectively. The half cooling time (HCT) and the seven-eighths cooling time (SECT) are the times required to reduce the temperature difference between the fruit and the cooling air by half (Y = 0.5) or seven eighths (Y = 0.125). The SECT is particularly interesting in commercial cooling operations because the fruit temperature is then acceptably close to the required storage temperature. At this point, the fruit can be transferred to storage facilities where the remaining heat load can be removed with less energy costs (Brosnan and Sun, 2001). Both the HCT and SECT of each row are presented in Table 3 for experiments and CFD for each container, and were directly determined from the temperature profiles of Figure 6-8.

For the Supervent container, but especially for the Ecopack container, the temperature profiles from CFD almost exactly agree with the experiments, and lie predominantly within the experimental uncertainty. Also the HCT and SECT agree well for Ecopack and Supervent. Large discrepancies are however found for the standard container, i.e., with differences up to almost 100% for the HCT. These discrepancies are due to the fact that between row 2 and row 3 in the CFD model, there is no direct connection between several vent holes of the containers. The locations where the vent holes are closed by another container are indicated in Figure 3 by black dots. Hence airflow occurs predominantly via the outer containers of rows 2 and 3 in the CFD model by which the resulting cooling rate of the fruit inside the central containers in rows 2 and 3 is very low. The large variation in cooling rate between the individual containers (central and outer) is indicated in Figure 6, and is a consequence of a (too) idealised CFD model, where multiple vents are closed. In reality, some airflow will always pass via these vents, due to imperfect stacking. This however identifies that the standard container is not designed to be placed with its long side against its short side on a pallet. For the Supervent container on the other hand, the holes on the short side were designed to always align with two of the holes on the long side. Apart from this mismatch between computational model and reality for the standard container, the accuracy of CFD for this forced-convective cooling study was shown to be satisfactory. The accuracy of the simulations could perhaps be increased even more by using periodic boundary conditions on top and bottom boundaries (see section 2.2.1), instead of symmetry, which could be explored in the future. In addition, the CFD model of the standard container could be adjusted to allow airflow via the central vents in the last row, but this was not pursued since these adjustments would have been rather arbitrary.

3.2 Comparison of container designs

The cooling performance of different container designs is compared by grouping the data of Figure 6-8 for all containers over each row, for experiments and CFD separately in Figure 9. The standard container clearly performs worst (see also Table 3), as expected due to the low area of vent holes, and the central positioning of these holes. The Supervent container shows a slightly higher cooling rate than the Ecopack container, which is seemingly contra-intuitive, since the airflow rate of the Ecopack container is much higher (2.12 l $s^{-1}kg^{-1}$ compared to 0.65 l $s^{-1}kg^{-1}$ for the Supervent container). At first sight, the lower cooling rate of Ecopack could be attributed to the presence of open air spaces on either side of the container, i.e. next to the plastic foil, as a result from the construction of the carry handles (see Figure 2 and Figure 5). Because of the low airflow resistance in this region, a preferential pathway is created where air can easily bypass the fruit and, in turn, reduce the airflow rate through the fruit. For the standard and Supervent containers on the other hand, all air needs to pass via the fruit as no airflow short circuits are present. Several studies have revealed the existence of preferential pathways in RPCs, where up to 80% of the air can bypass the produce (Vigneault and Goyette, 2003; Vigneault et al., 2004). The presence of these preferential pathways was confirmed by the CFD simulations, as high air speeds were found in these regions.

However, when comparing the average CHTC of the oranges in Supervent and Ecopack containers resulting from steady CFD simulations for each row (see Table 4 and section 3.3), the highest convective heat transfer rates are found for the Ecopack container. This contradicts its lower cooling rate, compared to the Supervent container, seen in both experiments and CFD (Figure 9). Further research identified that the lower cooling rate of Ecopack was related to the fact that the temperature in the refrigerator room during the experiments (thus also during the CFD simulations) decreased slightly slower than for the Supervent experiments (see Figure 6-8), leading to higher inlet temperatures for the Ecopack stack (<1°C difference). Additional simulations with the Ecopack container, but with the initial thermal conditions and inlet temperature from the Supervent experiments showed a (slightly) higher cooling rate for Ecopack (Figure 10). The difference between both is however smaller than expected, based on the differences found in CHTCs. This is related to the fact that the temperature in the refrigerator room, and thus also that imposed in the CFD simulations, did not decrease immediately to -0.5°C (see Figure 6-8). Thereby, the cooling rate kinetics are not mainly governed by convection (CHTC), but also by the inlet temperature, and the conduction in the fruit. If the inlet temperature does not decrease rapidly, as was the case for the experiments (and thus also for the simulations), a quasi-equilibrium state can be found at the fruit surface, with a small convective flux. Preliminary CFD simulations where the temperature in the room was reduced immediately to -0.5°C showed a larger difference between Supervent and Ecopack (results not shown).

In conclusion, the cooling performance of Ecopack is thus the best, but not yet optimal due to the presence of airflow short circuits. Note however that these conclusions are based on a specific fan configuration, i.e., with a much larger flow rate for Ecopack. Since its better performance did not came forward in the experiments, the need for high-quality design of experiments (with detailed temperature and airflow control, amongst others) with a high accuracy is emphasised, as well as the need for more repetitions of the same experiment. Here, also the usefulness of CFD simulations for such studies is apparent: with CFD, inlet conditions can be set exactly the same, and convective heat transfer rates can be quantified at a high spatial resolution, including surface-averaged values.

Given the large differences in flow rates through the different containers and thus in CHTCs (Table 4), the differences in cooling performance between the container designs are actually quite limited. This is related, amongst others, to the fact that the forced-convective precooling process is mainly conduction driven, and is thereby less sensitive to convective heat transfer (Dehghannya et al., 2010, 2011; Ferrua and Singh, 2009a, 2009b), but also, as discussed, to the rather slow temperature decrease in the refrigerator room.

3.3 Cooling heterogeneity of fruit

The heterogeneity of convective heat loss from oranges within a specific container and between individual containers is evaluated in this section since uniform (homogeneous) cooling of the individual fruit is desired in each container to ensure constant fruit quality and to minimise the risk of chilling injury. For this purpose, the CHTCs at the surface of the oranges, resulting from steady CFD simulations (see section 2.2.2), are analysed. These CHTCs are based on the initial fruit temperature and the initial inlet air temperature. The CHTC of each computational cell on the surface of the oranges was determined and their relative frequency distribution is shown in Figure 11 for each individual container, for the three container designs, where the containers in the same row are indicated by the same colour. These CHTCs are scaled with the average CHTC per container ($CHTC_{avg}$). The average value of the CHTC for each row, and the corresponding coefficient of variation (standard deviation, scaled with the average CHTC of that row) are presented in Table 4 for all three designs. Preferably, the variation of the CHTC within an individual container should be as small as possible, as well as the variation of the CHTC between the individual containers (rows).

The standard container clearly shows a large spread in the CHTC distributions, including very low values and a coefficient of variation of 1 or higher; also the variation between different containers is remarkable. The Supervent container exhibits a more homogeneous distribution, both within each individual container as between different containers. The Ecopack container shows the most uniform distribution. Furthermore, the highest CHTCs are found for the Ecopack container, followed by the Supervent and standard container. Note that the convective transfer at the surface (CHTC) was chosen in this study to evaluate cooling heterogeneity, instead of the interior fruit temperature (e.g., as in section 3.1, Figures 6-8). As the latter is also determined by conduction in the fruit, differences and heterogeneities in cooling rate will appear less pronounced here. Fruit quality and internal disorders, such as chilling injury, are however not only related to the temperature in the centre of the fruit, by which evaluating the cooling heterogeneity by means of CHTCs makes more sense.

Such an evaluation of the cooling heterogeneity (at the fruit surface) was only feasible with CFD, as it is very challenging experimentally, clearly indicating the added value of CFD as a tool for evaluation and optimisation of forced-convective cooling processes. CFD was also found to be less labour- and resource-intensive in the present study, and even allowed to identify and resolve the reasons for the differences in cooling behaviour of Supervent and Ecopack containers (see section 3.2). So once its accuracy was evaluated with experimental data, CFD was shown to be a viable alternative for experimental work. Furthermore, an assessment of the cooling heterogeneity and an identification of local extremes required discrete modelling of the oranges. Since containers were evaluated as stacked on a pallet, heterogeneities between different containers could also be assessed, and distinct differences with containers located more downstream on the pallet were identified. Modelling such larger, more complex systems, compared to single containers, has been already raised as a focus point for future studies (Smale et al., 2006).

The main impact of package design on optimisation of the cooling process to remove field heat, is a reduction of the cooling time. Thereby the throughput is increased which reduces the process time and costs. Furthermore, fast cooling leads to better fruit preservation by reduced respiration and contamination by pathogens. However, during cooling of citrus fruit, chilling injury can occur. As such, an optimal container design with respect to cooling is not necessarily the best with respect to fruit quality. Hence the cooling performance of a new container design should preferably be evaluated together with chilling injury. In contrast to cooling performance, an evaluation of chilling injury is very challenging numerically. Hereto, experiments on chilling injury were performed for the three containers. The details of these experiments are not presented but the largest percentage of oranges which showed (minor) symptoms of chilling injury was observed for the standard container (24.1%), followed by the Ecopack (17.8%) and the Supervent containers (11.6%). As no clear trend was observed between the incidence of chilling injury and the convective cooling rate (CHTCs), or the homogeneity thereof inside the containers, further research on the influence factors of chilling injury is required.

4. Conclusions

Defraeye T., Lambrecht R., Ambaw A., Delele M.A., Opara U.L., Cronjé P., Verboven P., Nicolai B. (2013), Forced-convective cooling of citrus fruit: package design, *Journal of Food Engineering* 118 (1), 8-18.
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The cooling performance of an existing corrugated fibreboard container (CFC) for forced-convective precooling of orange fruit was compared with two new container designs, namely the Supervent CFC and the Ecopack reusable plastic container, for containers stacked on a pallet. Both experiments and numerical modelling (CFD) were used, which allowed to identify the advantages and limitations of each technique.

CFD results showed a good agreement with experiments, except for the standard container, which was not related to CFD flow modelling itself, but rather to a mismatch between an idealised geometrical model of the stacking of the containers on the pallet (CFD) and the actual imperfections in stacking present in reality.

The cooling performance of the standard container was clearly the worst. Although experiments and CFD identified the best performance for the Supervent container, these results were misleading to some extent: this seemingly better performance was attributed to a difference in inlet temperatures between Supervent and Ecopack containers. This anomaly could be identified by means of CFD. As such, the Ecopack container performed best, but the presence of airflow short circuits, leading to a preferential airflow pathway around the fruit, however decreased the cooling performance. Closing these pathways could enhance the Ecopack cooling performance.

A detailed comparison, by means of CFD, of the cooling heterogeneity in a specific container, and between different containers on the pallet, identified that the Ecopack container showed the most uniform cooling with the highest convective heat transfer coefficients, followed by the Supervent and the standard container. For the standard container, very low convective heat transfer coefficients were found, with a coefficient of variation over the container of 1 or higher.

For forced-convective cooling studies, e.g., for package design, experiments provide realistic cooling rates, together with the possibility of assessing chilling injury, but require a well-designed and well-controlled setup to allow a proper comparison of different container designs. CFD on the other hand allows controlling all parameters and boundary conditions, as well as an exact quantification of flow and heat transfer rates. Nevertheless, prior to CFD-based design studies, comparison with experiments is imperative to evaluate the accuracy of the models used. In conclusion, the use of both techniques is advised, as they provide complementary information.

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Acknowledgements

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Figures

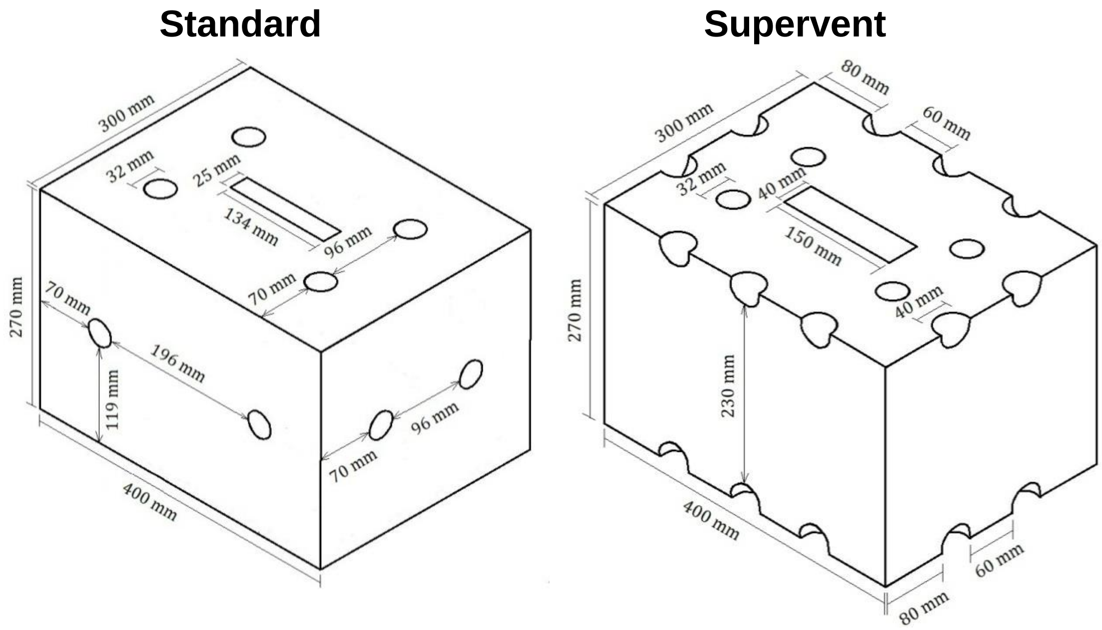

Figure 1. Geometry and dimensions of corrugated fibreboard containers: standard and Supervent container.

Defraeye T., Lambrecht R., Ambaw A., Delele M.A., Opara U.L., Cronjé P., Verboven P., Nicolai B. (2013), Forced-convective cooling of citrus fruit: package design, *Journal of Food Engineering* 118 (1), 8-18.
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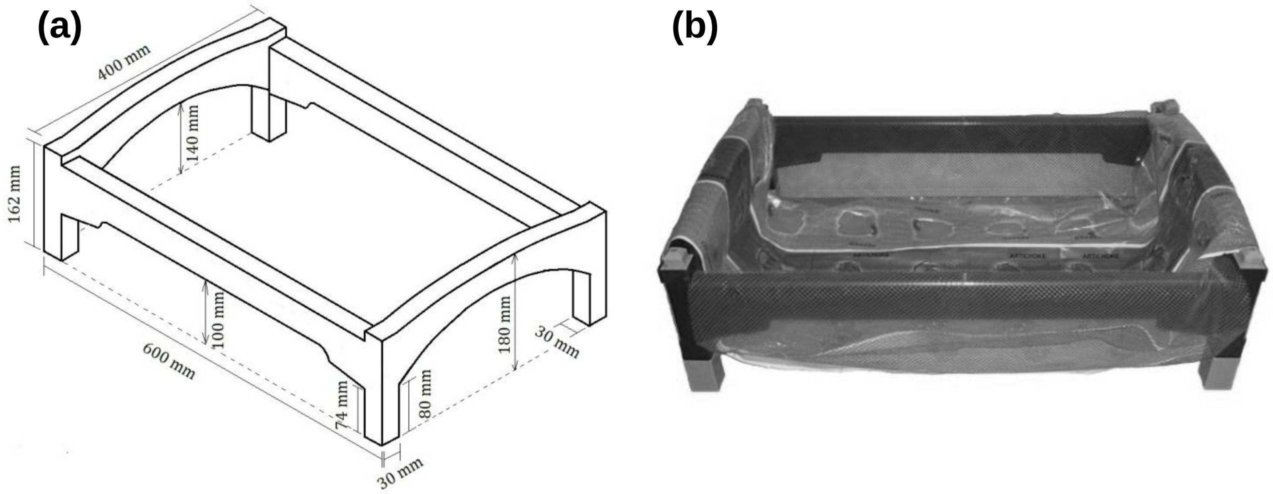

Figure 2. (a) Geometry and dimensions of the Ecopack reusable plastic container; (b) fully assembled Ecopack container.

Defraeye T., Lambrecht R., Ambaw A., Delele M.A., Opara U.L., Cronjé P., Verboven P., Nicolai B. (2013), Forced-convective cooling of citrus fruit: package design, *Journal of Food Engineering* 118 (1), 8-18.
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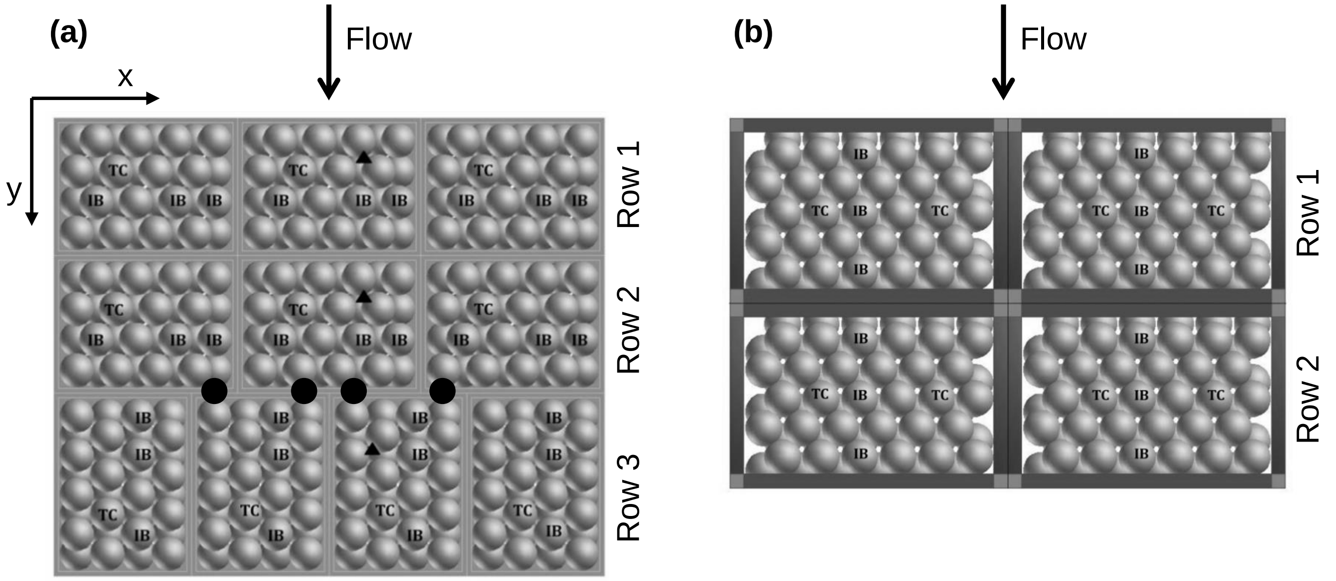

Figure 3. Stacking pattern, sensor positions (in second layer) and airflow direction for (a) standard and Supervent containers; (b) Ecopack container (IB: i-button® in centre of the fruit; TC: thermocouple in centre of the fruit; top view where only the bottom and second layer of fruit in each container are shown).

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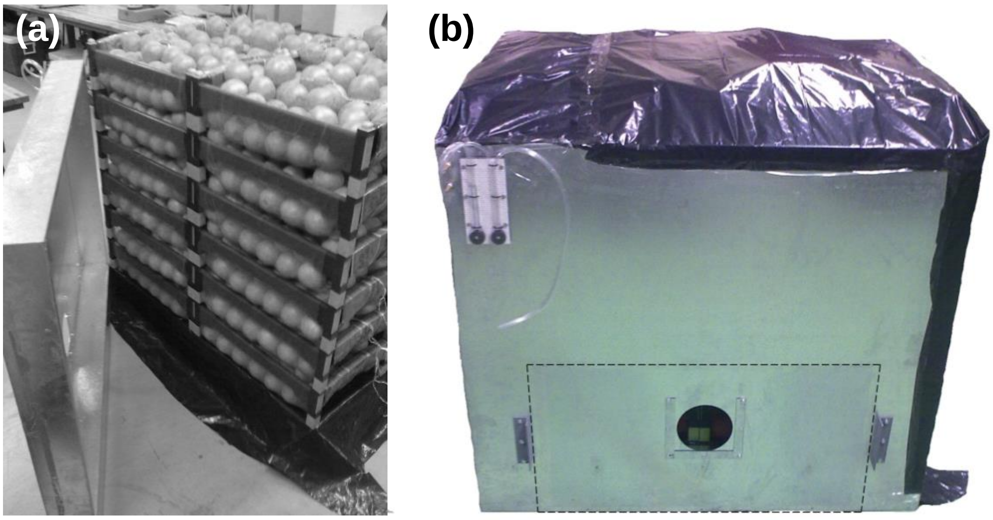

Figure 4. (a) Alignment of stack of (Ecopack) containers with metal casing, (b) Connection between metal casing and centrifugal fan (round opening).

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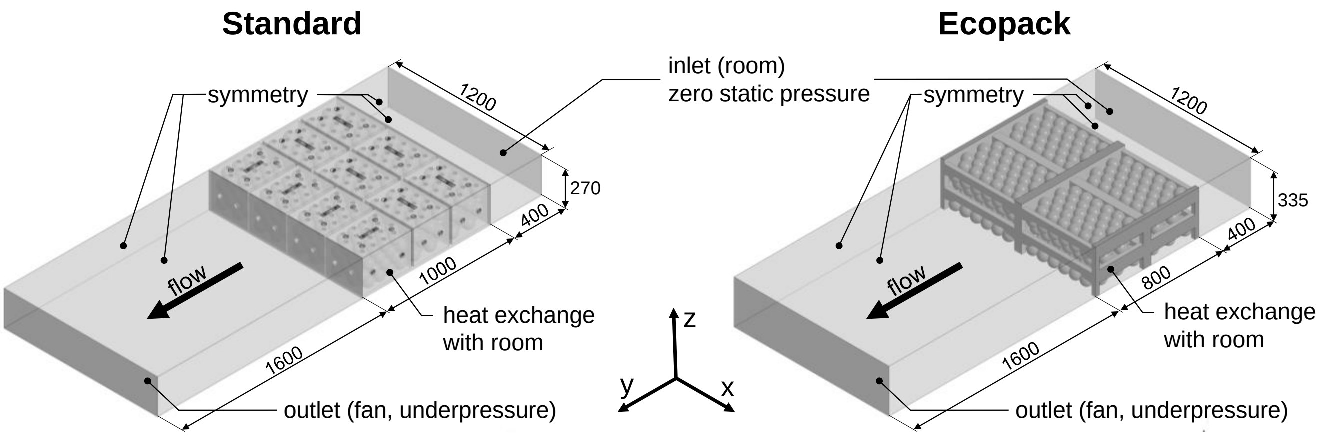

Figure 5. Computational model and boundary conditions for standard (similar to Supervent) and Ecopack containers.

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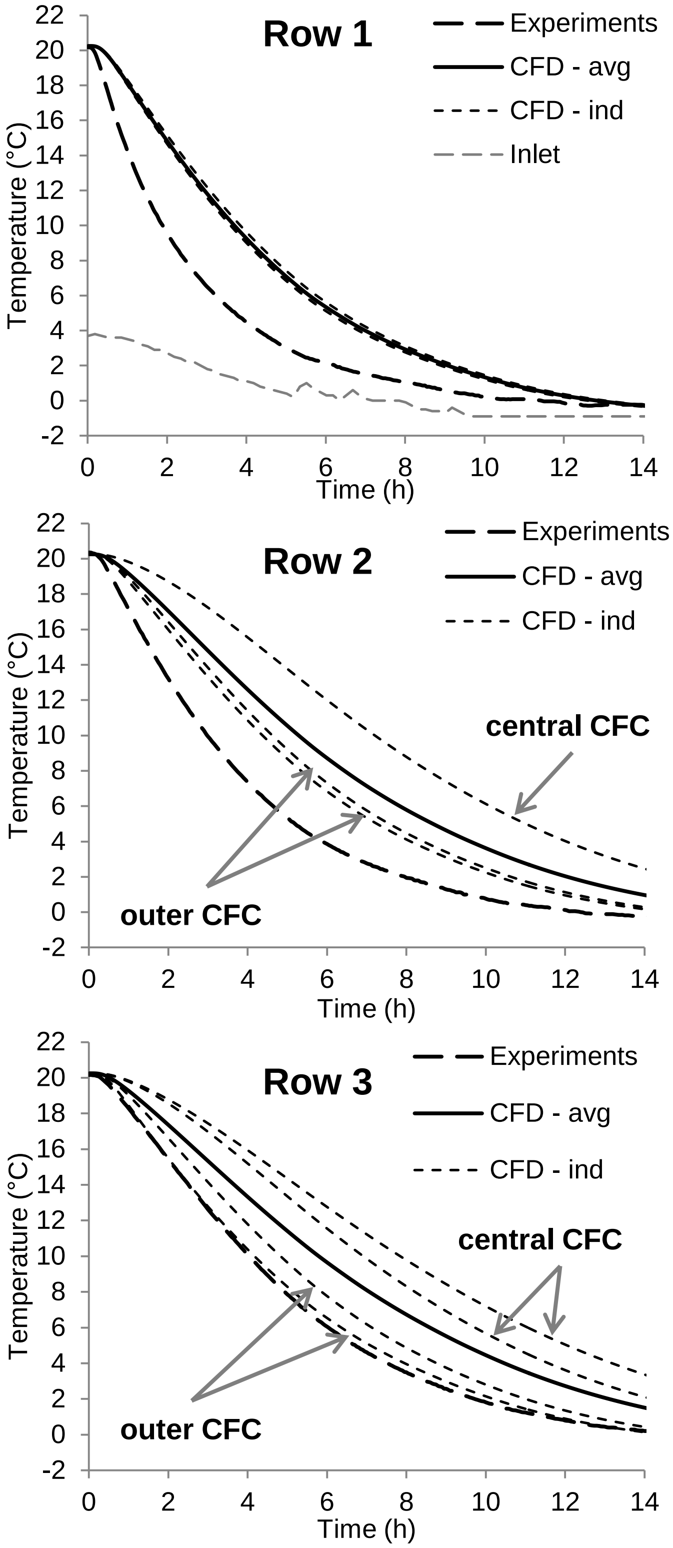

Figure 6. Temperatures in the centre of the oranges in each row of containers (averaged over all (virtual) sensors in the row, *y*-direction) from experiments and CFD for the standard container (CFD - avg: the average temperature over all containers in that row; CFD - ind: the temperature for the individual containers in that row), and temperature at inlet (refrigerator room).

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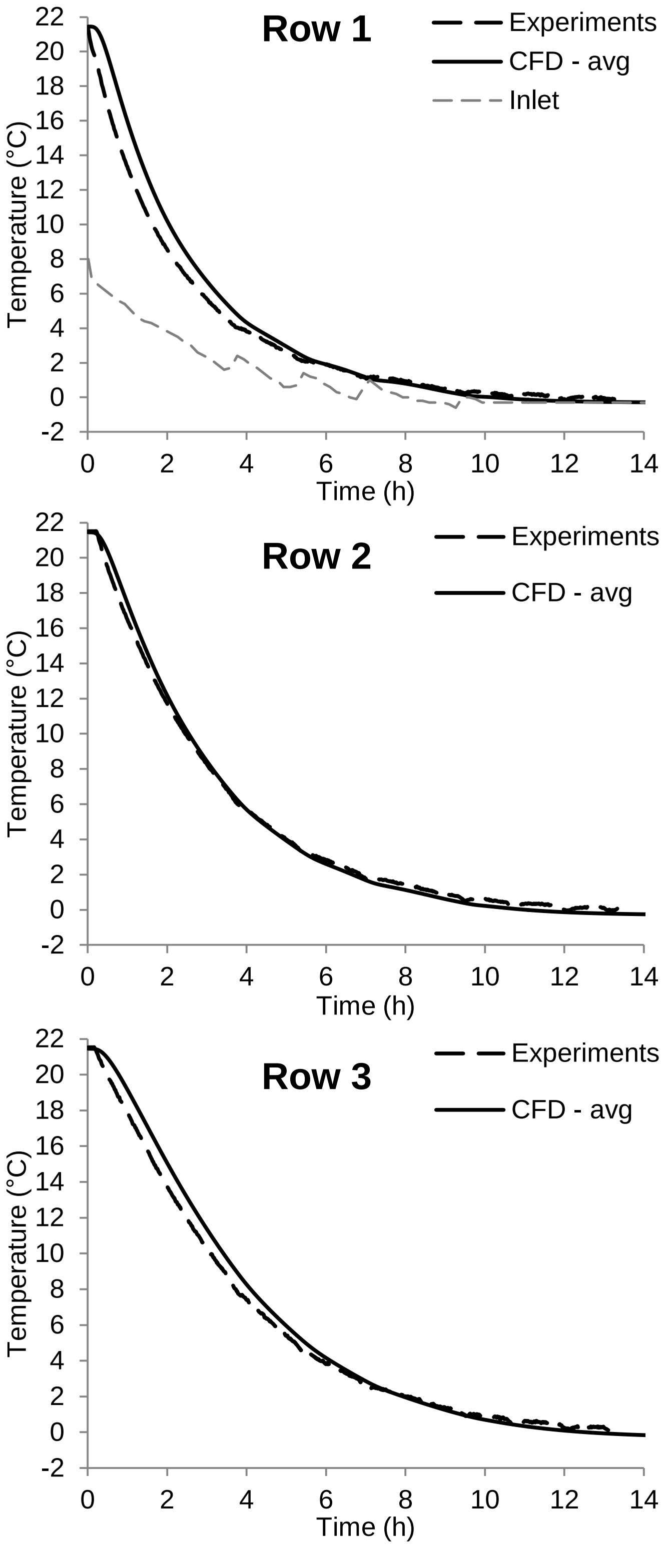

Figure 7. Temperatures in the centre of the oranges in each row of containers (averaged over all (virtual) sensors in the row, *y*-direction) from experiments and CFD for the Supervent container (CFD - avg: the average temperature over all containers in that row), and temperature at inlet (refrigerator room).

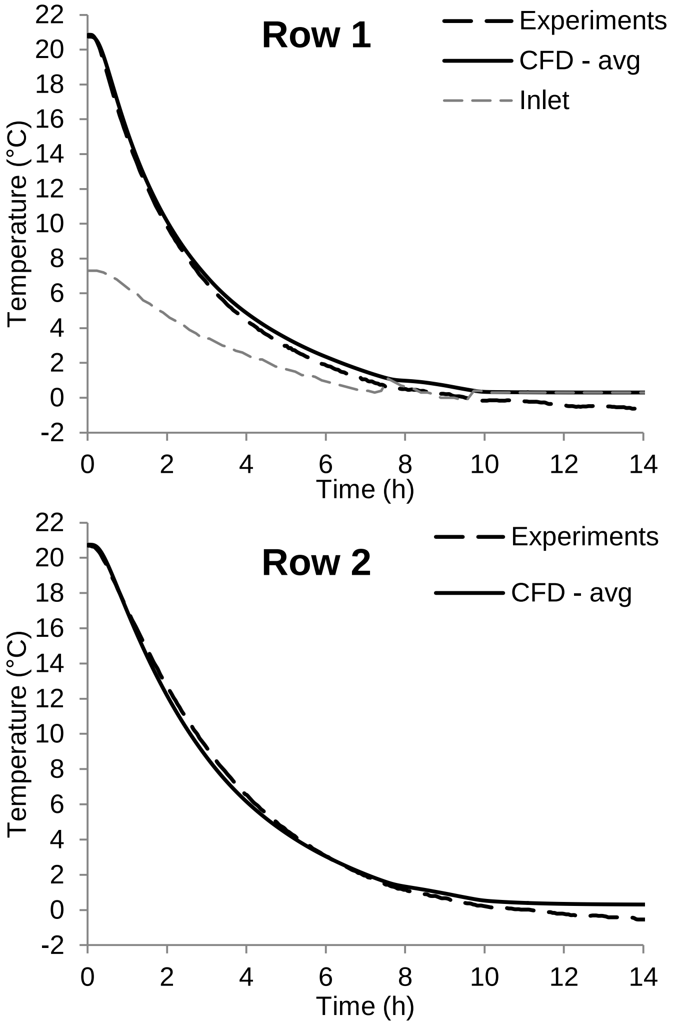

Figure 8. Temperatures in the centre of the oranges in each row of containers (averaged over all (virtual) sensors in the row, *y*-direction) from experiments and CFD for the Ecopack container (CFD - avg: the average temperature over all containers in that row), and temperature at inlet (refrigerator room).

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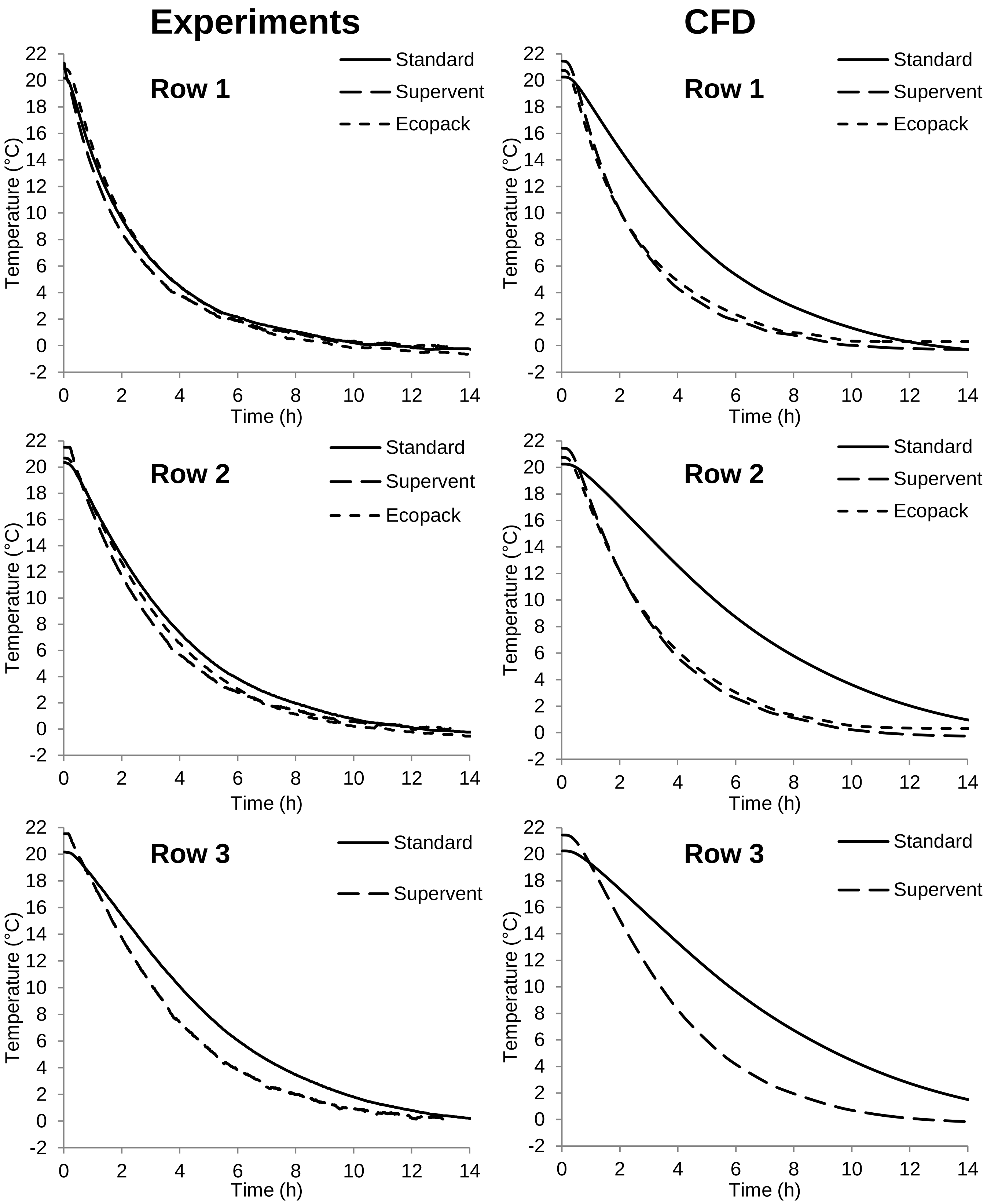

Figure 9. Temperatures in the centre of the oranges in each row of containers (averaged over all (virtual) sensors in the row, *y*-direction) from experiments and CFD: comparison between different container designs.

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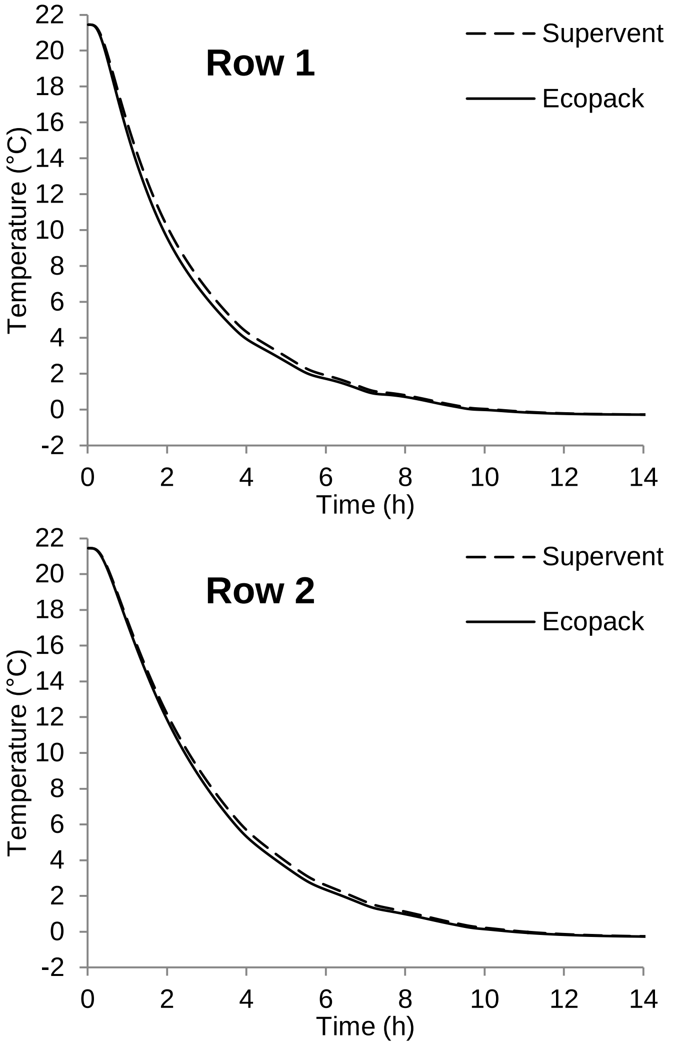

Figure 10. Temperatures in the centre of the oranges in each row of containers (averaged over all virtual sensors in the row, *y*-direction) from CFD for Supervent and Ecopack containers. For the Ecopack container, the same initial thermal conditions and inlet temperature are imposed as for Supervent.

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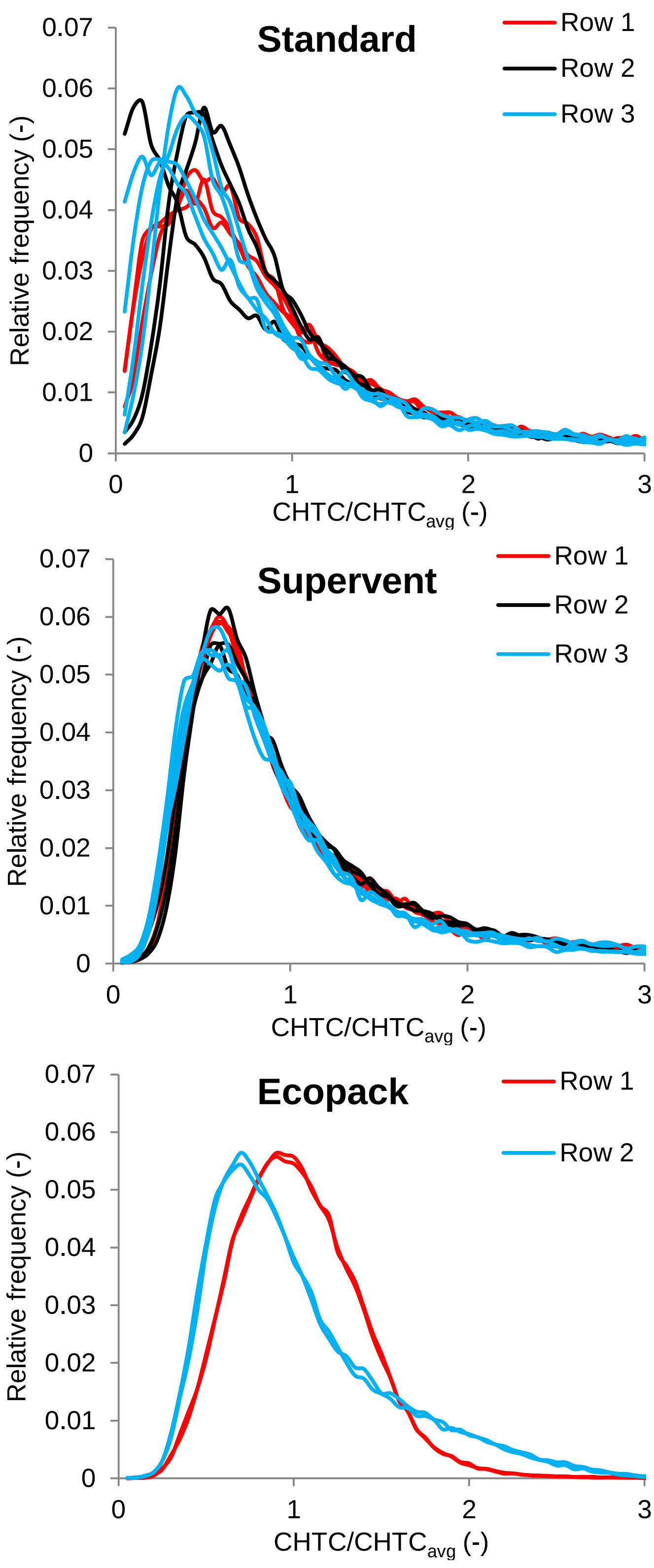

Figure 11. Relative frequency distribution of the convective heat transfer coefficient (CHTC) for each of the containers from CFD, for three container designs. The CHTCs are scaled with the average CHTC per container (CHTC$_{avg}$).

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Tables

Table 1. Total open area of standard, Supervent and Ecopack containers.

	Short side	Long side
Standard	2.0%	1.5%
Supervent	3.1%	3.5%
Ecopack	not relevant	57.9%

Table 2. Standard error (°C) on experimental temperatures inside oranges for each row for three container designs, averaged over the entire experimental duration (obtained from temperature profiles of Figure 6-8).

	Row 1	Row 2	Row 3
Standard error			
Standard (i-buttons®)	0.21	0.24	0.22
Supervent (thermocouples)	0.3	0.21	0.26
Ecopack (i-buttons®)	0.23	0.17	

Table 3. HCT and SECT (min) of each row for three container designs for experiments and CFD (obtained from temperature profiles of Figure 6-8).

	Experiments			CFD			**Difference**		
	Row 1	Row 2	Row 3	Row 1	Row 2	Row 3	**Row 1**	**Row 2**	**Row 3**
HCT (min)									
Standard	116	181	247	225	321	352	**94%**	**78%**	**43%**
Supervent	93	139	176	117	145	196	**26%**	**4%**	**12%**
Ecopack	115	164		120	153		**4%**	**7%**	
SECT (min)									

Standard	364	468	576	538	714	776	**48%**	**53%**	**35%**
Supervent	317	396	457	333	384	457	**5%**	**3%**	**0%**
Ecopack	342	407		373	411		**9%**	**1%**	

Table 4. Average CHTCs of the oranges and their coefficient of variation for different rows for three container designs.

	Average CHTC (W $m^{-2}K^{-1}$)			Coefficient of variation of CHTC		
	Row 1	Row 2	Row 3	Row 1	Row 2	Row 3
Standard	6.5	2.0	0.6	0.98	1.05	1.19
Supervent	14.7	7.6	3.6	0.68	0.66	0.77
Ecopack	18.2	12.9		0.38	0.53	