Integral performance evaluation of the fresh-produce cold chain:

a case study for ambient loading of citrus in refrigerated containers

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Abstract

More integrated evaluation of cold chain performance is key for developing a more resource-efficient, energy-smart food supply chain. The present study applies this rationale to evaluate the ambient loading protocol for overseas export of citrus fruit in refrigerated containers. Ambient loading implies that fruit, packed into ventilated boxes, are directly precooled in the container. This technique provides several economic and logistical advantages but is particularly challenging for phytosanitary cold disinfestation treatments. For such an integral approach, multiple relevant product and process parameters were monitored throughout the cold chain, such as fruit cooling rate, quality parameters, shelf life, pest disinfestation efficacy, and their spatial uniformity throughout the cargo load. Also energy consumption of the refrigeration unit was measured. The performance of the standard ambient loading practice was compared to two novel airflow strategies: the channelling configuration, which reduced airflow bypass between pallets, and the horizontal configuration, which forced air horizontally through the pallets. Standard ambient loading was able to cool the produce within about 3 d to the seven-eighths cooling time. The channelling configuration exhibited similar cooling behaviour but the fruit lost less moisture, lasted longer in shelf life conditions and had a better quality. The horizontal configuration performed worse on all aspects. The cooling performance of the container clearly depended on the way in which it was stowed and convectively cooled. This more holistic evaluation of the cooling strategy unveiled several trade-offs and allowed a multi-parameter evaluation of technological improvements to cold chain practices.

Keywords: refrigerated container, cold chain protocol, oranges, airflow short-circuits, fruit quality, precooling, seven-eighths cooling time

1. Introduction

An efficient postharvest cold chain is essential to preserve the quality of fresh produce and to extend its shelf life in order to reduce food losses. Postharvest losses in the fruit and vegetable supply chain are currently as high as 13 % to 38 % before reaching the consumer (Gustavsson et al., 2011).

Around 20 % of all perishable foods are lost due to lack of adequate refrigeration infrastructure or access to energy sources (IIR, 2009). Refrigeration also consumes about 8 % of all electrical energy used in the food industry (Zilio, 2014) and a large share of this energy is lost indirectly as it is embodied in food losses (FAO, 2011; Gustavsson et al., 2011).

The cold chain for fresh produce typically involves fast precooling after packaging, transport via air, road or sea, and subsequent storage at wholesalers, retailers and finally consumers. Although past research efforts on precooling and storage are vast (Ambaw et al., 2013; Dehghannya et al., 2010; Norton et al., 2013; Smale et al., 2006), transport operations have received less attention, despite being a critical link in the cold chain (Gac, 2002; James et al., 2006). Fresh produce is often subjected to long-haul refrigerated transport (Fitzgerald et al., 2011). As an example, the majority of all banana fruit and about 50 % of the citrus fruit are transported internationally via maritime transport, mainly in refrigerated containers (GDV, 2014). Refrigerated containers have almost fully replaced bulk reefer vessels here (Arduino et al., 2013; Fitzgerald et al., 2011). More than 400,000 refrigerated containers and 1 million refrigerated vehicles were in use globally in 2002 (Gac, 2002).

For refrigerated vehicles, interesting experimental and numerical (computational fluid dynamics) studies have been performed (Estrada-Flores and Eddy, 2006; Hoang et al., 2012; Moureh and Flick, 2005, 2004; Moureh et al., 2009, 2002a, 2002b; Nunes et al., 2014; Rodríguez-Bermejo et al., 2007; Tapsoba et al., 2006, 2007). In addition to the product temperature history, the main focus has been on the analysis and optimisation of ventilation efficiency or distribution of airflow and temperature within the refrigerated space. Studies on refrigerated containers focussed on monitoring or simulating fruit and air temperatures and cooling behaviour during long-haul transport (Defraeye et

al., 2015b; Jedermann et al., 2014b, 2013; Jiménez-Ariza et al., 2014; Jolly et al., 2000). A novel practice here is real-time monitoring of the temperature of the produce and its geographical position during transport. This allows to control the delivery air temperature online and to improve product logistics in order to reduce transport losses and increase shelf life (Lütjen et al., 2012). The use of wireless sensor technology is also gaining popularity, including radio frequency identification (RFID) tags (Hoang et al., 2012; Jedermann et al., 2014a; Jiménez-Ariza et al., 2014; Laniel and Émond, 2010; Laniel et al., 2011; Zou et al., 2014). However, the focus seems to be more on monitoring fresh produce and controlling environmental conditions rather than R&D of new cold chain practices and protocols. More industry level, but confidential, research is performed as well, driven by manufacturers of containers (e.g., Maersk) and refrigeration units (e.g., Carrier, Thermoking). Given the growing impact of transport in the cold chain, the increased trend to containerization and an unexplored potential for future improvements and new protocols, intensified research efforts on this specific unit operation are required.

In this field, a recent challenge is related to the ambient loading protocol (Defraeye et al., 2015a, 2015b). This alternative to forced-air precooling (Figure 1) implies that fruit are loaded “warm” into refrigerated containers for cooling during long-haul transport. With this practice, the (pre)cooling, i.e., the removal of field heat from the fruit, actually occurs inside the container. In principle, a container has sufficient cooling power to cool the cargo within 2-6 d (Defraeye et al., 2015b; Heap, 2006). Ambient loading can thereby provide several logistical and economical savings. It is currently used for Valencia oranges and grapefruit (Defraeye et al., 2015b) and also for banana fruit (Jedermann et al., 2014b, 2013). Although this practice is successfully used for resilient citrus cultivars, it is unknown how it will perform for mandarins and Navel oranges, as they are more sensitive to decay and physiological disorders.

The practice of ambient loading could also be advantageous for cold disinfestation treatments of citrus fruit. Such a treatment, as may be required by an importing country, aims at destroying target

pests in the fruit during the export voyage, such as false codling moth larvae. As an example, all citrus fruit exported by South Africa to the USA are required to be precooled to -0.6°C prior to export. Subsequently, they should be kept below -0.6°C for 22 d during transport as a probit 9 disinfestation treatment for false codling moth larvae (FCM) (*Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) and fruit flies (*Ceratitis capitata* and *C. rosa*). Export to countries which do not require disinfestation treatments is normally done by precooling the fruit to about $4^{\circ}\text{C} - 7^{\circ}\text{C}$ prior to loading and shipping at the same temperature. However, cold disinfestation is requested more and more by export markets, including several of those of the South-African citrus industry, which is third largest exporter of fresh citrus fruit worldwide (CGA, 2013). Such an increase in volumes of fruit to be precooled to lower temperatures and the associated longer precooling time is outpacing the current capacity of the available precooling facilities. Ambient loading could relieve the pressure on these facilities. However, this practice has not been proven successful in cooling fruit fast enough to the low temperatures required to comply with cold disinfestation protocols, nor in sufficiently preserving fruit quality. A recent advance that could help mitigate these problems is the use of a partial cold treatment. One such treatment under consideration for false codling moth is cooling to 2°C for 18 d (Moore et al., 2014). Note that the fruit become very susceptible to chilling injury at the low temperatures that are used for cold disinfestation treatments. In this context, it is advised to have the air temperature, which is supplied to each of the pallets via the T-bar floor, as close as possible to the target fruit temperature. Near the refrigeration unit, this air temperature is equal to the supply air temperature (Figure 2), but it usually increases towards the door-end. As such, pallets near the refrigeration unit will receive slightly lower temperatures, which increases the risk of chilling injury.

Another general characteristic of previous cold chain research is that the focus was mainly on one specific unit operation (e.g., precooling, transport) and on optimising a single aspect thereof, such as the product cooling rate and uniformity throughout the box or pallet, or the air speed and temperature distribution in the refrigerated space. The product quality and shelf life, system energy

consumption and the impact of environmental conditions received less attention. Other aspects remain virtually unexplored, such as food losses or the amount of fruit infested with pests. However, to evaluate the overall efficacy of a cold chain, all these aspects need to be monitored throughout all unit operations, especially since each operation has completely different cooling characteristics. Nevertheless, efforts towards more integrated supply chain evaluation are rather scarce (Dabbene et al., 2008a, 2008b; Jedermann et al., 2014b; Rediers et al., 2009; van der Vorst et al., 2009).

As a step beyond current practice, the present study aims to show the added value of a more holistic cold-chain evaluation, as illustrated for the case of the ambient loading protocol for a partial cold disinfestation treatment. To this end, multiple relevant product and process parameters are monitored throughout the entire cold chain for overseas citrus export in refrigerated containers. This postharvest cold chain includes precooling in the container after loading, long-haul transport in the container, followed by a shelf-life period. The efficacy of this holistic approach is demonstrated further by evaluating two novel airflow strategies for refrigerated containers, in addition to the standard vertical cooling. Such multi-parameter analysis throughout the export cold chain is shown to unveil new insights in the trade-offs at play, which is key to devise and optimise future cooling strategies.

Figure 1. Illustration of airflow for forced-air precooling (horizontal flow) and ambient loading in a refrigerated container (vertical airflow) for an 8-layer, high-cube citrus pallet (10 Supervent cartons per layer).

2. Materials and methods

2.1 Refrigerated container, boxes and citrus fruit

Three state-of-the-art refrigerated containers were used, namely Maersk 40 feet containers (outer dimensions L x W x H = 12.2 x 2.4 x 2.9 m), equipped with Starcool refrigeration units (see (“Maersk,” 2014) for more info). The containers were filled with 20 pallets on which 8 layers of boxes were stacked (Figure 1 and Figure 2). Each layer held 10 “Supervent” telescopic corrugated fibreboard boxes (0.4 x 0.3 x 0.27 m), which were filled with ‘Washington Navel’ orange (*Citrus senensis* L. Osb). Each box held 72 fruit of a calibre 5 (diameter 62-65 mm) and was packed to an average weight of 16.5 kg. This ventilated carton box has two semi-circular vent holes, located at the top and bottom of each side. Similar boxes were evaluated previously for forced-air precooling (Defraeye et al., 2014, 2013), but with three semi-circular vent holes on the long side of the box. The ‘Supervent’ package was designed to form horizontal ventilation pathways via the vent holes after palletisation. This box design also enables vertical pathways in principle, which is however less evident in practice due to the staggered stacking of consecutive layers (Figure 1). Although this stacking pattern ensures stability of the pallet during handling and transport, it results in the obstruction of several vent holes. In addition, the slats of the wooden pallet base can fully or partially cover some of the vent holes of the bottom carton boxes.

Figure 2. Side and top cross-sectional views of a refrigerated container with an indication of the stacking pattern of the pallets and of the box layers. The pallets in which sample boxes were provided are numbered. The inner dimensions of the container are shown.

2.2 Airflow strategies

2.2.1 Standard configuration

After harvest (26-27 June 2014), the oranges went through a standard commercial pack house treatment (29 June 2014), which included fungicide treatments (thiabendazole, 500 mg L⁻¹; imazalil, 500 mg L⁻¹; 2,4-dichlorophenoxyacetic acid, 125 mg L⁻¹ as per registered concentration) and a morpholine-free coating (Endura-fresh®, John Bean Technologies, Foodtech, Brackenfell, South Africa). Afterwards, the oranges were packed in boxes. A number of boxes, called sample boxes (see also section 2.3), were used to monitor fruit temperature and fruit quality: 3 boxes per pallet (in layers 1, 4 and 8, Figure 2) for pallets 1, 5, 9, 14, 17 and 20. As such, a total of 18 sample boxes per container were used. To determine the efficacy of the cold disinfestation treatment for FCM, 2 boxes per layer (called FCM boxes, in layers 1, 4 and 8) were placed in 3 of the pallets (1, 5, 9), next to the sample box. These boxes were packed with Lane Late Navel oranges. Only fruit that showed symptoms typical of FCM infestation were used. Per container, 18 FCM boxes were installed.

After packing and palletisation, the boxes were loaded into the refrigerated container (1 July 2014), thus within 4-5 d after harvest and within commercial guidelines. The gap at the end of the container, where the T-bar floor was not covered by a pallet, was closed to avoid airflow short circuiting here (indicated in orange in Figure 2), as recommended (GDV, 2014). On July 2nd, the container was turned on and cooling was initiated, after which long-haul transport overseas was simulated by keeping the fruit inside for 21 d (until 23 July). It should be noted that the other container experiments (section 2.2.2) were started at the same time, by which they all were subjected to the same external conditions. Note that the initial fruit temperatures were rather mild and do not reflect extreme conditions, i.e. during a very hot harvest period.

The duration of the cooling period (21 d) was chosen in order to mimic a 3-d forced air precooling period followed by a transport period of 18 d. The air temperature set point of 1 °C was chosen to evaluate the efficacy of a new system approach to control FCM during export to Europe, for which an envisaged 2 °C pulp temperature was put forth (Moore et al., 2014). The set air temperature was 1 °C from the start of the experiment to use the cooling capacity of the refrigeration unit at its maximum, in order to cool the fruit down as fast as possible. The set temperature was taken lower than the envisaged final fruit temperature (2 °C) to attain the latter faster and to offset the heat produced by additional heat sources (e.g., heat transmission losses) and fruit respiration. Another reason is to be able to achieve sufficient cooling near the door end, as the air temperature supplied to the pallets via the T-bar floor can be a few degrees above the set point there. The container was operated at 380V and 50Hz. The evaporator fans operated continuously, forcing air vertically through the pallets. They had a maximal rotational speed of 29.2 s^{-1} (RPM = 1750) but the rotational speed was controlled by the refrigeration unit's software. During a defrosting cycle, which was scheduled automatically depending on the amount of ice on the evaporator, the fans were switched off by the Starcool temperature control system. Ventilation with fresh air was induced at 4.2 L s^{-1} ($15 \text{ m}^3 \text{ h}^{-1}$), as currently required for citrus exported from South Africa (PPECB, 2013). This air exchange rate was only a fraction of the air circulation rate of the fans ($\sim 280 \text{ L s}^{-1}$ [$1,000 \text{ m}^3 \text{ h}^{-1}$]).

After the 21-d cooling period, mimicking 3 d “precooling” followed by 18 d “transport”, both performed within the container, refrigeration was stopped, pallets were removed from the container and all the sample boxes were removed from the pallets. Each carton was weighed and all fruit were evaluated for chilling injury or decay incidence. The fruit with the temperature data loggers in the sample boxes were removed and the data logger was retrieved. For each sample box, 10 fruit were removed and stored at ambient conditions (20-25 °C and 80 % RH) for an additional 14 d to simulate a shelf life period. Thereafter the fruit were weighed and the incidence of chilling injury and decay was determined. The cartons containing the FCM fruit were evaluated destructively to verify the efficacy of the partial cold disinfestation treatment.

2.2.2 Novel airflow strategies

In addition to the standard loading of the pallets for container cooling, two new airflow strategies were evaluated, namely the “channelling” and the “horizontal” airflow configurations. Unless stated otherwise, the experiments were performed in the same way as for the standard configuration (section 2.2.1).

The channelling configuration protocol aimed to improve produce cooling rates by reducing airflow bypasses between the pallets as much as possible, and by reducing blockage of box vent holes by the pallet base. Assuming 1.2 x 1 m pallets, the available space between pallets is 9 cm over the width of the container (2.29 m), which enables significant airflow bypass. In the longitudinal container direction, there will also be an amount of airflow bypass in practice, even when pallets are very closely spaced and if the gap at the end of the container floor is closed (Figure 2). It is advised that such bypasses should be avoided (GDV, 2014) as they negatively affect the cooling rate, which was recently demonstrated using computational fluid dynamics (CFD) (Defraeye et al., 2015a). To reduce such bypass, each pallet was wrapped with plastic (polyethylene) foil prior to loading, down to the pallet base (Figure 3). The perforations that were made by the forklift truck while loading the pallet into the container were sealed again afterwards. On the T-bar floor of the container, a grid was

made with cardboard on which the pallets were placed. In this way, airflow bypass via the gaps between pallets was minimised as all air was forced to flow via the pallets now, through the ventilated boxes (Figure 3). These measures will however change the airflow resistance of the cargo, thus also the working point and the airflow rate of the system, as discussed later on. In addition, porous plastic pallets were used (FTE INSIGHT, South Africa) to reduce the blockage of the box vent holes, compared to a wooden pallet base. After the pallets were unloaded from the container, the plastic foil was removed.

Figure 3. Cross-sectional views of a pallet and a refrigerated container for the channelling airflow configuration.

The horizontal airflow configuration is a newly developed commercial technique (Swift Horizontal Airflow system, Cordstrap, Durban, South Africa, Patent SA2006/03644 (Provisional PCT) and PCT/IB/001811, (Dodd, 2012)). It aims at improving produce cooling rates in a container by forcing

the air via a horizontal pathway through the pallets (Figure 4). Its rationale suggests to mimic the horizontal precooling situation, where most citrus boxes are designed to cool that way. The airflow pathway differs from the conventional configuration as it is longer (9-11 pallets) than for normal precooling (1 pallet) or vertical container cooling (8 layers). This longer pathway could have an impact on the cooling behaviour (Figure 4). The efficacy of this counterintuitive, but interesting, concept was therefore explored in a semi-commercial situation in the present study. To enforce horizontal flow, the majority of the T-bar floor was covered with a plastic sheet, except the last 3 m before the end of the container (Figure 4). Furthermore, three long inflatable dunnage bags were placed at different locations on top of the pallets, spanning the entire width of the container. These bags promoted horizontal airflow and inhibited air-flow short circuiting via the top enclosure.

Figure 4. Cross-sectional view of a refrigerated container for the horizontal airflow configuration.

Possible airflow bypass pathways along the pallet bases are depicted with dotted lines.

In all three configurations the first two pallets, closest to the refrigeration unit wall, were placed on the container's "kick plate" to inhibit cold air delivered at the base of these two pallets to flow directly to the return air duct. In addition, the T-bar floor near the door, on which no pallets could be placed, was sealed with void plugs (sheets of carton fixed to the floor). This is a general practice in shipments of citrus fruit from South Africa.

After packing, the three containers were placed next to the Sundays River Citrus Company (SRCC) pack-house in Addo (Eastern Cape, South Africa) in order for them to be exposed to similar outdoor

environmental conditions during the experiment. After loading the pallets, doors were sealed and three containers were started at the same time. No repetitions of this experiment were performed due to the large cost associated with filling three entire containers with citrus fruit for a 3-week time span.

2.3 Measurements

2.3.1 Fruit cooling

Prior to pallet loading, a temperature sensor was inserted in the pulp core of one orange per “sample box” via an incision (i-button®, Maxim, CA, USA, accuracy of ± 0.5 °C, data logging every 20 minutes). This orange was placed in the centre of the box. Three such sample boxes were mounted per pallet (layers 1, 4 and 8, Figure 2) for six pallets per container (pallets 1, 5, 9, 14, 17 and 20). The sample boxes were positioned in the middle of each pallet layer. As such, the spatial variation of the fruit cooling rate with respect to the location of the pallet in the container and the height of the box on the pallet could be determined.

Each refrigerated container was also equipped with 3 USDA-approved temperature sensors which are commercially used to measure fruit pulp temperature at predetermined positions in the container. These sensors are placed in positions known in the fruit transport industry to be the warmest places and are required to measure compliance with a specific cold chain protocol during refrigerated transport. The first probe (USDA1) was placed in a box at the top of pallet 1, nearest to the air return intake (Figure 2). The second sensor (USDA2) was placed in a box in the middle of pallet 5, close to the centre line of the container. The last sensor (USDA3) was placed in the middle box of pallet 10, in the second last row before the door of the container (USDA-APHIS, 2014).

From these fruit core temperature profiles (T_c), the fractional unaccomplished temperature change (Y) was determined:

$$Y = \frac{T_c - T_a}{T_{c,i} - T_a} \quad (1)$$

where subscripts i and a represent the initial (core) temperature of the fruit (around 16-19 °C) and the set cooling air temperature of the container (1 °C), respectively. From this Y value, the seven-eighths cooling time (SECT, $t_{7/8}$) was determined, which is the time required to reduce the temperature difference between the fruit and the cooling air by seven eighths ($Y = 0.125$). The SECT is frequently used in commercial (pre)cooling operations because the fruit temperature at that value is acceptably close to the required storage temperature (Brosnan and Sun, 2001). It also enables a straightforward comparison of cooling rates of fruit that were at a different initial temperature. The temperature T_c at the SECT will differ for each fruit as it depends on this initial temperature. On average, $T_c(t_{7/8})$ was around 2.9 °C in all containers, which is very close to the envisaged fruit temperature (2 °C). Note that for a cold treatment to officially start, the regulatory fruit temperature needs to be exactly attained.

2.3.2 Fruit quality, shelf life and mortality of FCM larvae

The following quality and shelf life attributes were measured for the fruit in the monitored boxes: (1) mass loss, chilling injury and decay incidence in the sample boxes; (2) mortality of false codling moth (FCM) larvae in the infested fruit placed in the FCM boxes. Mass loss was measured by weighing the sample boxes before the experiment and after the transport period. The mass loss over the shelf life period was measured for 10 oranges per sample box before and after the 14-d period. Chilling injury, i.e., scalding or pitting of the fruit rind (Cronje, 2007), and decay incidence were evaluated after the transport period for all fruit in the sample boxes and after the shelf life period for the 10 selected fruit of each sample box. To this end, the number of oranges that showed incidence of chilling injury or decay were counted. Decay incidence involved evaluating for green mold (*Penicillium digitatum*) and blue mold (*P. italicum*).

Mortality of FCM larvae in the fruit was measured destructively by cutting all the fruit after a one day storage period at 27°C, which was required for the larvae that were not killed by the treatment to recover. The larvae were removed from the fruit and if any movement was observed, the larvae was recorded as alive. The instar of each larvae was also recorded, according to head capsule width (Daiber, 1979). In addition to the fruit in disinfestation treatment, 97 control fruit were dissected and the numbers of alive and dead FCM larvae were recorded as well as their instar.

2.3.3 Environmental conditions inside container

The speed of the air at the return air grille of the container (1.83 x 0.4 m², outlet 0.3 x 0.1 m) was continuously measured by means of two small vane anemometers (Votcraft DL-151AN, range 1-20 m s⁻¹, accuracy 3 %), as indicated in Figure 2. Such measurements will allow estimating the difference in airflow rate (i.e. working points) between the three airflow strategies.

The temperature of the supply air (inlet), as well as the temperature and relative humidity (RH) of the return air (outlet) of the containers were also measured with data loggers (i-buttons®, Maxim, CA, USA, accuracy of ± 0.5 °C, data logging every 20 min). Measuring the return air conditions allows evaluating any temperature rise due to the extraction of the field (and respiration) heat from the fruit. The supply air conditions show to what extent the refrigeration unit was removing this heat load to regain the set temperature, which is especially challenging at the start of cooling. In addition, the Starcool refrigeration units also logged supply and return air temperature as well as return air relative humidity. Data from these built-in sensors corresponded well with measurements from sensors positioned in the containers for the experiment. The outside ambient temperature and relative humidity were also measured in order to monitor the ambient conditions to which the containers were exposed. These data are not reported here as they were very similar for all containers, so they will not induce differences between the airflow strategies.

2.3.4 Container energy consumption

The energy consumption (kWh) of the refrigeration unit of each container was measured during the transport period using a standard energy meter (accuracy 1 kWh). The measured value includes the energy required for the compressor, evaporator fans and microcontroller, amongst others. These data were used to identify whether containers with different airflow strategies have a different energy use, and to correlate energy use to the fruit cooling rate.

3. Results

3.1 Supply and return air

The supply and return air conditions measured by the container's recording equipment were similar to those of the sensors installed for this experiment. Therefore only the built-in sensor data are presented in Figure 5. Initially there was a slight difference in the supply air temperature between the containers, even though the set air temperature (1 °C) was the same. The reason is the different amounts of heat extracted from the fruit, combined with the mutual difference in automatic climate control by the unit's software (Maersk Quest I). Nevertheless, all supply temperatures were reduced quite rapidly to the set temperature, roughly within a day. The multiple temperature drops below the set point (1 °C) for the standard and horizontal configurations, as also recorded by the installed sensors, are linked to the automated temperature management of the Starcool system.

The temperature difference between supply and return air is the highest at the start of the cooling process (< day 5). The differences in supply and return temperatures between the three cases are already a first indication that the rate at which heat was extracted from the fruit was not the same. The channelling configuration shows the largest temperature difference (Figure 5b). The amount of heat that is advected with the return air to the refrigeration unit and that has to be cooled away, is however also dependent on the flow rate of this warm air. The measured air speed serves as a first indication of this airflow rate (Table 1). So despite the larger temperature difference for the

channelling configuration (Figure 5b), one has to take into account that it seems to have a slightly lower airflow rate than the others. It is clear from Figure 5 and Table 1 that much less heat was extracted by the horizontal configuration. Furthermore, the RH rises over the first days to an almost steady, high value, which is higher for the horizontal configuration. This rise is not only due to increased air humidity but is also associated with the temperature decrease. Note that the air speed varied over time to some extent as it was regulated by the control unit software (Maersk Quest I).

Table 1. Air speeds ($m s^{-1}$) at the return air grille for three airflow strategies, measured by two anemometers per container.

Configuration	Sensor 1	Sensor 2	Average
Standard	2.4	2.9	2.6
Channelling	1.8	1.7	1.8
Horizontal	2.3	1.9	2.1

Figure 5. Environmental conditions in the containers, as logged by the container's sensors for all airflow strategies: (a) temperature of supply and return air; (b) temperature difference between supply and return air; (c) relative humidity of return air.

3.2 Fruit cooling

The SECT is used to evaluate the fruit cooling rate as well as the cooling uniformity between different boxes on a pallet and between pallets in the container. The SECT is a direct measure of the time needed to cool down the fruit and thereby allows us to assess the feasibility of the ambient loading protocol. This quantity also provides straightforward means to compare with typical SECT obtained from precooling.

3.2.1 Magnitude of SECT

The SECT for the three airflow strategies is reported in Figure 6 for the sample boxes (18 per container) and in Figure 7 for the USDA sensors (3 per container). The top sensor in pallet 20 of the standard container malfunctioned and no data were retrieved. For the top sensor in pallet 9 of the horizontal configuration, the SECT was not attained within the duration of the experiment and the data are therefore not shown. In section 4.1, these SECTs will be compared to those of previous precooling and container cooling studies.

In general, a vertical cooling behaviour is evident in all three configurations, meaning that the bottom positions reach the SECT before the middle and top positions. The achieved SECT values are the lowest for the standard configuration, namely below or equal to 3 d. For the channelling configuration, the SECT improved at some locations but the average SECT is slightly higher than the standard one (2.1 vs. 2 d). Its trend points towards slower cooling of the bottom layer and faster cooling of the middle layer, although this does not hold for all pallets. Note that the small differences in supply air temperature could also induce some differences in cooling behaviour

between different airflow strategies, but this effect is expected to be quite limited. Also note that often a slower cooling rate is found for pallets near the door end, but this was not explicitly found in this study. Particularly for the standard configuration, the cooling near the door end was very similar to that at locations closer to the refrigeration unit.

The horizontal configuration provides much worse cooling rates for almost all pallets, except for pallet 1 (its SECT scale differs in Figure 6). This inferior performance is attributed to the longer (horizontal) pathway for air to follow, resulting in extensive warming up of the air. In addition, the airflow bypasses via the pallet base below the first box layer. Flow of cold air is preferentially directed towards the pallet base region (see Figure 4) as this horizontal channel exhibits a lower airflow resistance than via the middle and top regions on the pallets, which are densely packed with boxes.

The USDA sensors show a different trend: all airflow strategies produce similar results, except for the last sensor (USDA3) in the channelling and horizontal configuration, which was positioned in the second last row from the door (pallet 10). The reason for these higher values is probably that the sensors were positioned in fruit located at the side of an outer box of a pallet, whereas the sensors in the sample boxes were inserted in the middle box of the pallet and in the centre of each of these boxes. The “USDA sensor” fruit could have been less exposed for the channelling configuration, as no cooling airflow can access it via the gaps between the pallets due to the plastic foil which was wrapped around. It has to be noted that, in the context of cold treatments, the decisive criterion to assess the efficacy of a treatment is actually the highest cooling time that is found. Of course, one has to bear in mind that these extreme values need to be picked up by the sensors. From Figure 6, the standard treatment seems better than the channelling configuration, as the latter has the highest cooling time at a specific location. From Figure 7 however, which relies on the official USDA sensors, the channelling configuration comes out better.

Figure 6. Seven-eighths cooling time (SECT) for three airflow strategies for different pallets (P) at three heights in the pallets. The average value of the SECT over all boxes in the container (AVG) and the standard deviation (STD) are also given. The SECT scale differs for the horizontal configuration.

Figure 7. Seven-eighths cooling time (days) for three airflow strategies for the three USDA temperature sensors in the container.

3.2.2 Heterogeneity of SECT

The heterogeneity in the SECT is evaluated by means of its standard deviation, as calculated in following ways (Table 2): (1) within a pallet over its height by evaluating the SECT of each layer (1, 4 and 8); (2) within a layer by evaluating the SECT of each sample box in that layer over the entire

container; (3) within a container by evaluating the average SECT of each individual pallet but also by evaluating the SECT of each individual box. In general, the uniformity is the highest for the standard configuration, and is slightly lower in the channelling configuration. The horizontal configuration shows a very high cooling heterogeneity, resulting from the variation between pallet positions as well as between boxes on a pallet (see Figure 6).

Table 2. Heterogeneity of SECT in a container, evaluated by different standard deviations.

Standard deviation on SECT	Standard	Channelling	Horizontal
Within pallet			
Pallet 1	0.6	0.4	0.9
Pallet 5	1.0	0.7	5.8
Pallet 9	0.7	1.5	2.6
Pallet 14	0.8	0.5	1.8
Pallet 17	1.0	1.1	4.3
Pallet 20	0.9	1.1	1.5
<i>Average</i>	<i>0.8</i>	<i>0.9</i>	<i>2.8</i>
Within layer			
Top	0.3	1.2	4.5
Middle	0.3	0.6	2.4
Bottom	0.3	0.2	0.6
Within container			
For individual pallets	0.3	0.6	2.2
For individual boxes	0.7	1.1	3.6

3.3 Fruit quality, shelf life and FCM mortality

3.3.1 After the transport period

The fruit quality parameters after the simulated transport period of 21 d are given in Figure 8. They are expressed as the percentage of mass loss of all fruit in a sample box as well as the incidence of chilling injury and decay. The efficacy of false codling moth disinfestation is summarised in Table 3. Dissection of the 97 control fruit (not placed in the containers) revealed 32 larvae: 12 second instar, 10 third instar, 5 fourth instar and 5 fifth instar. All control larvae were alive.

The mass loss is less than 1 % on average for all containers, which is better than the 3-5 % that is usually found in the South African citrus industry. The channelling configuration shows the least mass loss, which indicates that wrapping the pallets with the plastic foil reduced the moisture loss in some way, even though vertical airflow was still maintained through the pallet. A possible reason is that moisture removal via the air-gap bypass between different pallets was avoided, leading to an overall higher humidity level inside the wrapped pallet, thereby inducing less moisture loss. Another general trend is that the top boxes loose more moisture compared to the middle and bottom ones. This high moisture loss is directly related to the higher temperature of the fruit in the top boxes. As a result, the vapour pressure deficit between the fruit and the surrounding air will be larger and will also be maintained for a longer duration (Thompson et al., 2008). The amount of chilling injury per box was relatively low for all configurations, namely 1.1 % to 2.7 % on average. The highest incidence and variability were found for the horizontal configuration, with a few very high values. In general the bottom positions had the highest chilling injury for all configurations, as they were exposed to the lowest air temperatures. The decay incidence ranges from 1.7 % to 3 % on average, and was higher than the 1 % to 1.5 % standard for the South African citrus industry.

Only for the horizontal configuration, FCM larvae survived, namely 10 % and 52 % in pallet 5 (middle and top layer), and 7 % and 19 % in pallet 9 (middle and top layer). The lack of mortality in these

positions nicely correlates with the higher temperatures found here (Figure 6): pallet 5 (top position) had a SECT > 13 d and for pallet 9 (top position) the SECT was even not reached.

In the standard and channelling configurations, 100 % mortality of all larval instars, including fourth and fifth, was recorded at all levels and in all pallets. Fourth and fifth instar larvae are recognised as the most cold-resistant larval instars (Boardman et al., 2012; Myburgh, 1965, 1963). If one pools the fourth and fifth instar larvae from the standard and channelling configuration treatments, this provides a total of 214 larvae. However, as the fruit were naturally infested at the time of harvest, one can consider the relative distribution of FCM instars to be a fair representation of what one might expect in reality, thus providing a total of 442 larvae in the standard and channelling treatments. As total mortality was achieved, this is equivalent to a demonstration of around 97.7 % mortality at the 95 % confidence level or probit-7 mortality (Schortemeyer et al., 2011). Note that the correlation of FCM mortality to the temperature history of the fruit can be evaluated most accurately by controlled laboratory experiments. However, full-scale trials as performed in the present study are essential to convince the industry by explicitly demonstrating the efficacy of the cold disinfestation treatment.

Figure 8. Percentages of mass loss, the amount of fruit with chilling injury and the amount of fruit which showed decay incidence for each box in a pallet (P) for three airflow strategies after the transport period. The mass loss of the middle layer of pallet 5 for the standard configuration amounts to 3.3 %.

Table 3. Number and mortality of all five instars of FCM larvae (L1 to L5) after 21 d cold treatment for three container configurations and at three different layers in the pallet.

		L1	L2	L3	L4	L5	Total
Number of larvae							
Standard	Top	2	8	13	12	16	51
	Middle	1	16	34	17	22	90
	Bottom	1	10	16	11	21	59
	Total	4	34	63	40	59	200
Channelling	Top	1	20	27	13	37	98
	Middle	0	10	23	14	21	68
	Bottom	3	22	21	12	18	76
	Total	4	52	71	39	76	242
Horizontal	Top	2	6	26	9	24	67
	Middle	0	13	34	26	21	94
	Bottom	0	9	29	13	25	76
	Total	2	28	89	48	70	237
Mortality							
Standard	Top	100 %	100 %	100 %	100 %	100 %	
	Middle	100 %	100 %	100 %	100 %	100 %	
	Bottom	100 %	100 %	100 %	100 %	100 %	
Channelling	Top	100 %	100 %	100 %	100 %	100 %	
	Middle	100 %	100 %	100 %	100 %	100 %	
	Bottom	100 %	100 %	100 %	100 %	100 %	
Horizontal	Top	100 %	83 %	81 %	89 %	50 %	

Middle	100 %	85 %	94 %	100 %	95 %
Bottom	100 %	100 %	100 %	100 %	100 %

3.3.2 After shelf life

The same fruit quality parameters are given in Figure 9 after the shelf life period (14 d at ambient conditions), but now only measured on a limited amount of fruit (see section 2). The channelling configuration also shows the least mass loss. The mass loss does not correlate to the vertical position in the pallet (layer 1, 4, 8), which is not surprising as all fruit were subjected to similar environmental conditions. For the same reason, the spatial heterogeneity of chilling injury incidence and fruit decay between the boxes is much less. None or only one fruit out of 10 showed chilling injury and decay in most boxes. Future experiments could consider evaluating more fruit to have better statistics. After the shelf life period, the channelling configuration clearly outperformed the other two with respect to fruit quality.

Figure 9. Percentages of mass loss, the amount of fruit with chilling injury and the amount of fruit which decayed for the control fruit of each box in a pallet (P) for three airflow strategies during the shelf life period.

3.4 Container energy consumption

The refrigeration unit's energy consumption was recorded from the energy meter after the first day (19 h) and after the transport period (21 d), and is given in Table 4. The typical cooling capacity of a refrigeration unit for a 40 feet container lies around 7-10 kW for the considered set air temperature (Defraeye et al., 2015b; GDV, 2014; Jolly et al., 2000). The data after the first day confirm that the refrigeration unit's capacity is fully utilised to cool away the field heat. The energy consumption after the 21-d period however shows much lower values, which are in line with previously measured data for such prolonged periods (Lukasse et al., 2011). The reason is that once the fruit has been (pre)cooled to a certain extent, the cooling unit requires much less energy. It only needs to offset the heat transmission losses through the container walls, the fruit's respiration heat, the latent heat due to moisture evaporation, the heat loss due to infiltration and the heat produced by the equipment. In addition, energy for fans and microcontroller operation is required. It should be noted that since all containers were exposed to similar exterior conditions, the transmission losses will be rather similar.

Table 4. Energy consumption and power use of refrigeration unit for different airflow strategies at two points in time.

	Energy consumption (kWh)	Power (kW)	Difference from standard (%)
Day 1			
Standard	166	8.9	
Channelling	178	9.5	+ 7 %
Horizontal	149	8.0	-10 %
End (day 21)			
Standard	827	1.7	
Channelling	900	1.8	+ 9 %
Horizontal	516	1.0	- 38 %

In particular, the contribution of the evaporator fans is relevant to address as they are responsible for a significant amount of the container's energy use, i.e., roughly 2 kW at high speed (Defraeye et al., 2015b; GDV, 2014). In the present experiment, they ran continuously throughout the entire experiment. Their energy use is related to the working point at which they operate, i.e., the pressure rise versus the flow rate. A higher airflow rate will normally induce higher energy consumption, given that the fan efficiency does not change. The airflow rate, thus also the fan energy use, differs for the airflow strategies (Table 1) as each cargo has its own airflow resistance due to the different airflow pathways. However, it has to be noted that optimised fan control strategies have been implemented recently in the refrigeration unit's software (Maersk Quest I and II), which reduce energy consumption by controlling fan speed, based on the heat load that is experienced by the refrigeration unit (Lukasse et al., 2011). As such, in addition to the stowing strategy, the container's control software used in the present experiment (Maersk Quest I) also affected the airflow rate, thus energy consumption, in a way that can vary from container to container. During the temperature pulldown period, e.g. the first day(s), the fan is expected to work at full speed.

However, the higher energy use for the channelling configuration during the first day cannot be directly related to differences in fan energy use as the airspeed is lower (Table 1). It could be that a higher cooling load is imposed onto the refrigeration unit in the first days of the experiment as the amount of heat extracted from the fruit is larger and thereby heats up the return air more (Figure 5), by which more heat has to be cooled away. For the horizontal configuration, this initial cooling load is much less, as the field heat was removed over a much longer period.

In any case, the differences between airflow strategies show that the way of stowing and convectively cooling a container has an important impact on its energy consumption. This energy aspect definitely deserves more attention in the future, since large costs are associated with the energy use in the horticultural cold chain.

4. Discussion

4.1 Feasibility of ambient loading

Ambient loading with the standard and channelling configuration was able to cool the citrus fruit in an acceptable time frame to the SECT, i.e., within about 3 d. Theoretical calculations showed that a container should have sufficient cooling power to achieve a SECT of 2-5 d (Defraeye et al., 2015b). These SECT values correspond to the 2 to 6 d which Heap (Heap, 2006) reports to be necessary for cooling of produce during transport. A numerical study on vertical airflow cooling of an idealised pallet of citrus fruit using computational fluid dynamics showed that SECTs around 1-3 d can be obtained, depending on the box height (layer) in the pallet (Defraeye et al., 2015a). This study also showed that the presence of gaps between pallets heavily penalised the SECT. These acceptable SECTs were contrasted by a recent feasibility experiment for ambient loading (Defraeye et al., 2015b), which was quite similar to the present study: an average SECT of about 9 d was obtained, with peak values above 15 d. The fact that a step-down cooling was applied is probably responsible for these differences, whereas using an immediate set point of 1 °C in the present study induced a faster cooling process. Other (unpublished) feasibility tests of ambient loading by the authors also produced longer SECT.

However, based on the present experiments, ambient loading of Navel oranges seems a viable technology, compared to horizontal pre-cooling (SECT typically < one day), due to the rather fast cooling process (about 3 d to reach SECT) as well as the cooling homogeneity that was achieved. Ambient loading also seems feasible for use in the context of (partial) cold sterilisation treatment.

4.2 Comparison of airflow strategies

The rationale behind the channelling configuration, namely to avoid airflow bypass alongside the pallets, is opposed to that of (Jedermann et al., 2014b, 2013), who deliberately added gaps (chimneys) between pallets. In their study, they argued that the absence of gaps between pallets

would negatively affect fruit cooling, and they actually found a slight improvement in cooling rates by allowing for space between some of the pallets in the container. Since such gaps were found to negatively affect cooling rate in other studies (Defraeye et al., 2015a) and since guidelines advise against this (GDV, 2014), the channelling configuration was developed and explored in this study. From a purely convective cooling point of view, heat removal from the fruit should be increased when airflow bypass is reduced, given that the mass flow rate of the approaching cold air is the same.

The complexity associated with manipulating airflow and cooling in refrigerated containers was illustrated in the current study. The channelling strategy did not provide the desired improvement in cooling rate compared to the standard practice. This is in part caused by the decrease in airflow rate, due to the higher resistance of the cargo since the airflow short-circuits between pallets were closed. There is thus a clear trade-off between improved flow conditions and airflow rate. However, the mass loss of the fruit, and thus loss of commercial value, was reduced in the channelling configuration during the transport period and during shelf life. After being exposed to shelf life conditions, the fruit also had a markedly better quality and lifetime, which is beneficial for retailers and customers. The temperature history of the fruit subjected to the channelling configuration, which is strongly affecting shelf life, thus seems to be most beneficial. The energy use of the refrigeration unit was not much higher. Although improvements have not been achieved on all fronts, this new airflow strategy is worthwhile exploring further, since it seems there is a positive effect on fruit quality, mass loss and shelf life. Particular improvements in optimising the practical implementation, in tuning the working point of the evaporator fans (pressure rise vs. flow rate) and in control software optimization could be sought. It has to be kept in mind that in the present experiments the container's control software can have affected the performance of the airflow strategy, as it relied on environmental conditions to regulate the cooling unit and the airflow rate.

The horizontal configuration is not a viable alternative to improve fruit cooling in ambiently loaded citrus fruit. The cooling rates were negatively affected as well as the fruit quality, shelf life and FCM mortality. The achieved energy savings should however never compromise produce quality. From the present results, it is thought that the fundamental drawbacks of this configuration are the longer pathway which the air must follow through the fruit and the occurrence of substantial air flow bypass in the region of the pallet base (Figure 4). This is the most preferential pathway for the cold air to follow compared to through the boxes on the pallets. The standard practice in the citrus industry does require cardboard panels (called void plugs) to block this bypass at some locations, but this effect will be limited as air will quickly bypass this blockage via the boxes above it (Figure 4) or via the gaps alongside the pallets and/or the wall. One should also take into account that this cooling strategy adds additional time and effort when loading the container, and requires skilled personnel.

It is interesting to note that there was no survival of FCM larvae in two of the configurations, despite the fact that the fruit only spent fewer than 18 d at 2 °C or below. More importantly, historical data indicate that a temperature of -0.55° for a duration of 21 d is required to achieve probit-9 mortality (Myburgh, 1965), i.e. 99.997 % mortality at the 95 % confidence level (Schortemeyer et al., 2011). To demonstrate probit-9 mortality however, one requires 94587 test individuals, whereas in our case only 214 (considering only fourth and fifth instar larvae) or 442 (all larvae) were available. Nevertheless, this is a strong indication that a partial cold-sterilisation protocol could successfully reduce the risk to a negligible level or even, in practical terms, eliminate it.

Based on the present study, the efficacy of the three USDA sensors to evaluate the cooling behaviour of the cargo can be questioned. The USDA fruit cooling rates did not correspond to the ones of the sample boxes. As such, the inferior performance of the horizontal configuration was not reflected in the USDA sensor data. The reason is probably that the sensor locations, i.e., in a box at the side of the pallet near the air gap between the pallets, are not representative for the average cooling behaviour of the cargo. This finding is striking as these sensors are currently being used as

one of the few inputs to decide on the acceptability of the shipment's compliance with cold sterilisation protocols. Therefore, more robust ways to evaluate and monitor the thermal history of shipments of fresh produce on each commercial shipment should be implemented.

4.3 Towards more integral evaluation

The more holistic evaluation of cooling strategies, as applied in this study, revealed trade-offs between cold chain performance parameters (see section 4.2) but also allowed a multi-parameter comparison of different strategies in a unique way. Although these experiments were time-consuming and labour-intensive to set up and required a multidisciplinary team of horticulturalists, entomologist and engineers, their added value is evident. Nevertheless, restrictions on the amount of sensors to be used and on mounting them in a time-efficient way will remain. Therefore, numerical simulations with CFD (e.g., (Defraeye et al., 2015a)) could complement such experiments to fill some of the data and knowledge gaps which are present, since information on the state of each individual fruit can be obtained. Such *in-silico* evaluation is, however, mostly restricted to evaluating cooling rates and energy use. Models for fruit quality, shelf life and pest disinfestation are not incorporated in such CFD studies yet, to the best of our knowledge.

4. Conclusions

A step towards a more holistic experimental evaluation of cold chain protocols was applied to evaluate the feasibility of ambient loading for overseas export of citrus fruit in refrigerated containers. In this way, the performance of the standard practice was compared to two novel airflow strategies which aimed at improving produce cooling: a channelling configuration which reduced airflow bypass between pallets and a horizontal configuration which forced air via a horizontal pathway through the pallets.

With the standard ambient loading protocol, the produce could be cooled within about 3 d to the seven-eighths cooling time. The channelling configuration exhibited a similar cooling behaviour but the fruit lost less moisture, lasted longer in shelf life conditions and had an overall better quality. The horizontal configuration performed worse on all aspects. This research showed that the way of convectively cooling a container has a clear impact on its cooling rate, fruit quality, shelf life, pest disinfestation efficacy and the associated spatial uniformity but also on the energy consumption of the refrigeration unit. More attention should be given to the interaction of the cargo load with the container operation and control. Such efforts towards integrated assessment are essential for more resource-efficient and energy-smart cold chains for fresh produce throughout all its unit operations. Finally, more extensive trials should be conducted to further test the disinfestation potential of the protocols used for different pests, including false codling moth.

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