Full-scale experiments in forced-air precoolers for citrus fruit: impact of packaging design and fruit size on cooling rate and heterogeneity

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Abstract

Forced-air cooling (FAC) is a widely applied postharvest technology to rapidly remove the field heat of packed fresh fruit. The cooling uniformity of the fruit in different pallets and cartons during FAC is critical but often remains unknown in commercial operations. This study investigated the cooling rate and heterogeneity of packed citrus fruit in a full-scale, forced-air precooler, which can hold 40 pallets. The influence of package design (package type and wrapping) and fruit size on the precooling performance was quantified in several experiments with different citrus fruit types ('Navel' orange fruit, 'Nova' mandarin fruit and 'Eureka' lemon fruit). Results showed that the cooling heterogeneity mainly occurred

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along the flow direction. The cooling was uniform in height at the same side of the pallets and between pallets located in different locations in the precooler. High resolution measurements with 25-30 sensors in a single pallet gave an even better insight in this heterogeneity. Fruit wrapping induced a much slower cooling rate and larger cooling heterogeneity, especially in the cartons at the outflow side of pallet. The 'Nova' mandarin fruit in Opentop cartons cooled 24% (at the inflow side of pallet) and 42% (at the outflow side of pallet faster) than the 'Eureka' lemon fruit with similar fruit size in the Supervent cartons, showing the impact of packaging design. These experiments quantified the cooling heterogeneity of the commercial precoolers.

Keywords: precooling; citrus fruit; package; wrapping; forced-air cooling

Highlight

- Cooling heterogeneity along the flow direction in pallets was quantified.
- Fruit wrapping induced slower cooling rate and larger cooling heterogeneity.
- Differences in cooling rates were found up to 42% between different packages.

1. Introduction

Physiological deterioration and a resulting loss in quality of fresh fruit after harvest occur due to respiration and transpiration during postharvest handling (Kader, 1987). The rates of these processes are primarily influenced by fruit temperature (Thompson et al., 2008). An increase in temperature of 10 °C typically induces a 2-3 times higher deterioration rate (Robertson, 2012), which highlights the importance to cool fruit rapidly after harvest (Brosnan and Sun, 2001). The fruit pulp temperature should be reduced as soon as possible after packing in order to maintain quality.

Precooling is a postharvest technology to rapidly remove the field heat prior to refrigerated transport or cold storage. Among the various types of precooling techniques, forced-air cooling (FAC) is usually applied for a wide range of commodities (Kader, 2002, Dehghannya et al, 2010). During FAC, cold air is drawn through pallets via the ventilation holes on the stacked/palletized cartons. A particular problem with FAC in commercial facilities can be the occurrence of cooling heterogeneity between different fruit in a carton, different cartons in a pallet or different pallets in the specific precooler (Alvarez and Flick, 1999a, b, Delele et al., 2008, Ferrua and Singh, 2009a, b, c, 2011, Defraeye et al., 2013, O'Sullivan et al., 2016). The cooling heterogeneity is influenced by the ventilation efficiency of the package design (Berry et al., 2017, de Castro et al, 2004, Émond et al., 1996), the fruit size and the use of additional wrapping such as paper. The stacking pattern of the cartons on the wooden pallet base and the specific design of the FAC system also play a role.

Both numerical simulations using computational fluid dynamics (CFD) (Zhao et al., 2016, O'Sullivan et al, 2016, Wu et al., 2017, Wu and Defraeye, 2017, Han et al., 2015, Ambaw et al., 2013, Defraeye et al., 2013, Delele et al., 2013a, b, 2008, Dehghannya et al., 2010, Verboven et al., 2006) and laboratory experiments (Alvarez and Flick, 1999a, b, Ferrua et al., 2009b, c, Han et al., 2015, Defraeye et al., 2013, Ngcobo et al., 2012, de Castro et al., 2004) have been conducted to gain insights into the cooling rate and uniformity of packed products during FAC. Most of the aforementioned research focused on studying the cooling heterogeneity during forced convection cooling of a single carton or a small ensemble of cartons (a part of an entire pallet). Few experimental studies have been carried out to understand the performance of commercial FAC facilities (Kumar et al., 2008, Verboven et al., 2004). Full-scale experiments on FAC of fruit are rarely reported in literature. One of the reasons is that large quantities of fruit are required to fully fill commercial facilities, which results in a high cost and a high risk when something goes wrong. Furthermore, when performing experiments on commercial shipments, the process of placing and retrieving of the sensors has to be done very fast in order not to impede or break the commercial cold chain. However, such full-scale and on-site experiments are often the only way to assess the actual cooling performance of FAC facilities and the associated cooling heterogeneity between different fruit in different pallets or within a pallet. Such trials can also identify the impact factors such as package design or fruit size on the cooling rate and heterogeneity. The outcome of full-scale experiments on commercial faciliteis are also better accepted by the industry than small-scale laboratory studies.

To shed some light on these aspects, this study evaluates the cooling behavior of packed citrus fruit in a full-scale, forced-air precooler during several commercial precooling runs. This study focuses on the cooling heterogeneity within different cartons in a pallet and between different pallets in a 40-pallet, forced-air precooler for three different citrus fruits ('Navel' orange fruit, 'Nova' mandarin fruit and 'Eureka' lemon fruit). The impact of fruit packaging (ventilated carton and fruit wrapping) and fruit size is also investigated. This study provides a unique experimental insight in the FAC process as performed in practice.

2. Materials and methods

2.1. Forced-air precooler

The full-scale precooling experiments were carried out during April and May 2016 in the Addo cold store owned by Sundays River Citrus Company (SRCC) located in the Sundays River Valley (Eastern Cape, South Africa). SRCC exported 9 million cartons of citrus fruit in 2016. There are 10 forced-air precooler that are used to precool the fruit in the Addo cold store facility. The dimensions of each precooler are 13.0 m × 5.2 m ×4.6 m. Each forced-air precooler is divided into four functional zones: a central air corridor of 1.2 m wide, 4 pallet racks, a lateral supply air zone (the distance between the pallet side and the side wall is 0.7 m) and a return air plenum (Fig. 1). The four zones are separated by the room walls, sealing tarps and pallets. In this design, forty pallets, which is equivalent to the content of two reefer containers, are stacked on the pallet racks and can be precooled simultaneously. Two pallet racks on top of each other are located on each side of the central air corridor. The cold air is forced through the pallets from the lateral supply air zone to the central air corridor, due to the pressure difference created by three exhaust fans (model TF1000/250/7 Q 30, ebm-papst®). These three fans are located along the center line of the ceiling and draw the air, which is warmed-up by the field heat extracted from the fruit, from the central air corridor and blow it into the return air plenum. The warmed-up air is then cooled by two ammonia evaporator coils (47 kW per coil, Baltimore Aircoil Company®) installed in the return air plenum and the cooled air is then circulated back to the lateral supply air zone where it enters the pallets again.

2.2. Citrus fruit

As the experiments were carried out during normal commercial operations, neither the fruit species nor the fruit size can be chosen, and these were dependent on the batches of fruit that were harvested in the region. However, a constant effort was made to keep variability to a minimum and to use similar conditions. An overview of the citrus fruit (species, cultivar and size) used in the different experiments is given in Table 1. In this study 'Eureka' lemon fruit, 'Navel' orange fruit and 'Nova' mandarin fruit were used. 'Eureka' lemon fruit with a weight range of 96-208 g and a diameter range of 51-72 mm were used for the first three experiments. Thereafter 'Navel' orange fruit and 'Nova' mandarin fruit were used for the last three experiments. The 'Navel' orange fruit had a weight range of 177-325 g and a diameter range of 65-90 mm, while the 'Nova' mandarin fruit had a weight range of 100-118 g and a diameter range of 58-68 mm.

All the fruit used in this study were first degreened after harvest by means of exposure to 3 ppm ethylene for 3 d at 23 °C and 90-95% relative humidity (USDA, 2016). The fruit were then washed in water, waxed with a polyethylene citrus wax (Citrushine, Johannesburg, South Africa) and sorted according to size, color, shape and appearance. For some experiments, either all the individual fruit in a carton or only the fruit in each alternating layer in the carton was wrapped in paper. This is to improve visual appearance, before being packed into cartons and palletized, as it is requested by consumers in some markets, i.e. Middle and Far East. After palletisation of the cartons, the fruit were sent to the Addo cold store for precooling before overseas shipment in refrigerated containers.

2.3. Carton types

Two types of corrugated fiberboard carton were used in SRCC, namely, Supervent (0.4 m ×0.3 m ×0.27 m, Fig. 2a) and Opentop (0.6 m ×0.4 m ×0.17 m, Fig. 2b). The carton type used for the different experiments can be found in Table 1. The Supervent cartons were used for ‘Navel’ orange fruit and ‘Eureka’ lemon fruit, whereas Opentop cartons were used for ‘Nova’ mandarin fruit. The Supervent carton has 4 semicircular vent holes on each lateral side, which enable horizontal ventilation during precooling (Fig. 3a). The Supervent carton is packed with 15.5 ~16.5 kg citrus fruit. Ten Supervent cartons are arranged as a layer of a high-cube pallet (1.2 m×1.0 m×2.16 m), which comprises eight layers and holds 80 Supervent cartons in total (Fig. 3a).

The Opentop carton, with its top side fully open, has one rectangular vent on each long lateral side and two rectangular vents on each short lateral side, which enable a horizontal ventilation pathway during precooling (Fig. 3b). The Opentop carton is generally packed with about 17 kg ‘Nova’ mandarin fruit fruit. Five Opentop cartons are stacked as a layer on a pallet and each pallet has thirteen layers (1.2 m ×1.0 m ×2.21 m) and holds 65 cartons in total (Fig. 3b).

2.4. Placement of temperature sensors

The fruit pulp temperature was measured with the iButton® temperature sensors (Thermocron®DS1922L Maxim, CA, USA), which have an accuracy of 0.5 °C and were programmed to collect data every 2 min. Before the fruit pallets were loaded into the precooler, temperature sensors were inserted into the center of fruit in different cartons of the pallets. These cartons with sensors were all located at the inflow or outflow side of the pallet, i.e. where air enters or exits the pallet. The number and the location of the sensors varied with different experiments. Six full-scale experiments (Table 1) were carried out over the two-month period. Due to the nature of the experiments, which were commercial runs, no repetitions could be performed as the fruit were directly exported after precooling. Different types of experiments were performed in order to elucidate different aspects of the precooling process. Hence, differences in the placement of the sensors were present.

In a first type of experiments, sensors were placed to identify the spatial variation of the cooling rate between different pallets in the forced-air precooler. Exp. 1 is one of these and Fig. 4 illustrates the placement of the temperature sensors. There were two rows of pallets on each side of the central air corridor (Fig. 4a) and each row had 20 pallets with 10 on the top rack and 10 on the bottom rack (Fig. 4b). The inflow side was facing the lateral supply zone, while the outflow side was facing the central air corridor. The black crosses show the positions where air speeds were measured with a hot wire anemometer. The grey dots illustrate the positions of SRCC temperature probes. The fruit pulp temperatures from these probes were used, according to commercial practice, as a reference parameter to control the precooling process. The orange dots denote the positions of iButtons in Exp.1. Six pallets on the bottom rack (B01, B03, B05, B06, B08 and B10) and six pallets on the top rack (T01, T03, T05, T06, T08 and T10) were instrumented with temperature sensors (Fig. 4b). For pallets B01, B10, T01 and T10 near the two ends of the precooler, temperature sensors were placed in the three layers h3, h5 and h7. For the rest of the pallets (B03, B05, B06, B08, T03, T05, T06, T08) temperature sensors were placed in the two layers h3 and h7. For each layer, one iButton was inserted in a fruit in the middle carton at the inflow side (Fig. 4a), while a second iButton was inserted in a fruit in the middle carton at the outflow side (Fig. 4a). The monitored fruit were inserted via the lateral surface of the carton. In Exp.1, 12 pallets were equipped with 56 temperature sensors. The placement of temperature sensors in Exp. 3, 4 and 5 was similar and the number of the sensors is given in Table 1.

In a second type of experiments, sensors were placed to identify the spatial variation of the cooling rate within a single pallet. The setup of Exp. 2, for example, enables the evaluation of the cooling heterogeneity within a single Supervent pallet. The temperature sensors were placed in 3 layers h3, h5 and h7 of two pallets B05 and T05. For each layer, 7 iButtons were inserted into 7 different fruits in 7 different cartons (Fig. 6a). Five more iButtons were inserted in the fruit in other pallets for reference. In total, 49 temperature sensors were used in Exp.2. The setup of Exp.6 enables the analysis of the cooling heterogeneity within an Opentop pallet. The temperature sensors were placed in 6 layers of two pallets B05 and T05. For each layer, 5 iButtons were inserted into 5 different fruits in 5 different cartons (Fig. 6b). At the end of the experiment, one iButton malfunctioned. Therefore, a total number of 59 temperature sensors were used in Exp.6.

2.5. Full-scale precooling experiments

Before the precooling experiment, plastic tarpaulin sheets (tarps in Fig. 1) were used to close the airflow shortcuts at the wooden pallet base as well as between adjacent pallets. This ensured that the supplied air in the lateral supply air zone was forced to pass predominantly through the vent holes of cartons towards the central air corridor. For all the experiments, the target temperature that the fruit need to attain was 10 °C for 'Eureka' lemon fruit and 3.5 °C for 'Navel' orange fruit and 'Nova' mandarin fruit (Table 1). Fruit were not cooled directly to the target temperature due to a stepdown protocol, in order to minimize the risk of chilling injury. The stepdown cooling was a standard industrial practice in Addo cold store. This implies that fruit is gradually cooled to the target temperatures in several discrete steps, as demonstrated by Fig. 5. The set-point temperature for each step was measured in the cold supply air. In addition to the iButton data loggers, five temperature point probes (Platinum resistance thermometers, PT-100) were inserted in the centre of fruit at specific pallet locations in the forced-air precooler to monitor the cooling process of each step, which is common practice at SRCC in their commercial runs. In addition to temperature, the pressure difference across the pallets was recorded by a differential pressure sensor (SDP1000 / SDP2000, Sensirion AG, Staefa, Switzerland) with an accuracy of 1.0-1.5% of the measured value.

2.6. Half cooling time

The cooling rate of each fruit is assessed by the temperature profile monitored in the center of the fruit pulp. From these temperature profiles (T [K]) the fractional unaccomplished temperature change (Y) can be determined (Defraeye et al., 2015)

$$Y = \frac{T - T_a}{T_i - T_a} \tag{1}$$

where T is the fruit pulp temperature over time, T_i is the fruit temperature at the beginning of each step-down process and T_a is the set-point temperature of the supply air in each step-down process. The half cooling time (HCT) was determined being the time required to reduce the temperature difference between the fruit and the set-point temperature in each step down process by half (Y=0.5). The HCTs reported below were averaged for each fruit over all steps in the step-down processes experiment.

2.7. Statistical analysis

Analysis of variance (ANOVA) was used to determine if the HCT differed between various treatments, with a significance level of 5% ($p \leq 0.05$). All statistical analyses were performed using open source software R3.2.3.

3. Results and discussion

3.1. Cooling heterogeneity between different pallets in the precooler

The temperature profiles of all the monitored fruit in Exp.1 illustrate the cooling heterogeneity in the forced-air precooler. The major highlight was that fruit at the inflow side cooled faster than those at the outflow side (Fig. 5). The mean HCT was 0.61 and 3.78 h for fruit at the inflow and outflow side, respectively. The cooling heterogeneity along the flow direction (from the lateral supply air zone to the central air corridor) was caused by the fact that the fruit at the inflow side added heat to the supplied cold air. This resulted in heating up of the air, by which the fruit at the outflow side cooled slower. To evaluate the cooling heterogeneity between different pallets, the mean HCTs at the outflow side were used as here the differences between different pallets were larger than at the inflow side. The mean HCTs ranged from 4.0±1.1 to 5.0±1.2 h. Therefore, the cooling time was identical between different pallets (horizontal direction, pallet B01-B10 and T01-T10) from one end to the other end of the central air corridor. The mean HCTs between different heights in the precooler ranged from 4.2±0.9 to 5.8±1.8 h. The difference was not statistically significant ($p>0.05$). There was no preferred airflow pathway through the top pallets, compared to the bottom ones in the rack. In summary, the pallets in the different positions of the precooler were uniformed cooled.

3.2. *Cooling heterogeneity in a single pallet*

Fig. 6a shows the temperature history of individual 'Eureka' lemon fruit in Supervent pallet B05 and T05 in Exp.2. Fig. 6b shows the temperature history of individual 'Nova' mandarin fruit in Opentop pallet B05 and T05 in Exp.6. For the 'Eureka' lemon fruit packed in Supervent cartons, there was no significant difference between positions in the same column (e.g., C1 in Fig.6a) of a pallet. However, the cooling rate was different between different columns in a pallet (Fig. 6a). Therefore, the HCTs for 'Eureka' lemon fruit in the cartons at the same column (e.g., C1) throughout the pallet were averaged vertically and are shown in Fig. 7a. The difference in cooling rates for Supervent cartons at column C1 and C2 was statistically insignificant ($p>0.05$). The lemon fruit in carton C3 cooled about half an hour slower compared to those in C1 and C2, which demonstrated the influence of the Supervent carton orientation on the cooling rate. Although the total vent area for both orientations was the same, the total open area was smaller for the C3 orientation, which induced a lower cooling rate. The 'Eureka' lemon fruit in the carton C4, which was in the center of the pallet, cooled 1 h slower than those in the cartons at the inflow side (C1-3). The cooling rate did not differ between the cartons C5 and C6 at the outflow side. However, the 'Eureka' lemon fruit in the downstream carton C7 cooled the slowest and differed significantly from all the other positions in the pallet. Furthermore, the standard deviation in HCT for C7 was also the largest, which indicated a large cooling heterogeneity in C7. For the Supervent pallet, the slowest cooling rate and largest cooling heterogeneity occurred in the cartons at the outflow side when their long lateral sides were perpendicular to the flow direction.

For the 'Nova' mandarin fruit packed in Opentop cartons, the fruit at the same column (e.g., C1 in Fig. 6b) cooled similarly except for fruit in the carton C5. A large spread in the temperature profiles was found in the carton C5, especially during the first step down. Similar to the Supervent pallets, the main differences in the cooling rates were found between different columns, e.g. those located near the inflow or outflow side. Hence, HCTs for 'Nova' mandarin fruit in the cartons at the same column were averaged vertically and are shown in Fig. 7b. For the two cartons at column C1 and C2, the cooling rate did not differ significantly and the orientation of Opentop cartons did not influence the cooling rate at the inflow side. The carton C3 in the center of the pallet cooled slightly slower but not significantly compared to the cartons C1 and C2. The fruit in the carton C4 cooled on average 1 h slower than those in the cartons C1-C3. Carton C5 was the slowest to cool in the pallet and approximately 3.5 h slower compared to the cartons at the inflow side. In C5, the standard deviation between the five cartons (vertical direction) was also the largest, indicating a larger cooling heterogeneity. For Opentop pallets the slowest cooling rate and largest cooling heterogeneity was measured in the cartons at the outflow side (C5) when their short lateral sides were perpendicular to the flow direction.

3.3. The influence of fruit size on HCT

In order to analyze the influence of the fruit size on the cooling rate, the HCT values for non-wrapped fruit of 'Eureka' lemon fruit, 'Navel' orange fruit and 'Nova' mandarin fruit were used (Fig.8a, b, c). The HCTs for the lemon fruit ranged from 0.54 to 0.64 h at the inflow side and from 3.58 to 3.92 h at the outflow side. However, the differences in HCTs between different lemon fruit sizes were not statistically significant at both inflow and outflow sides. The size of the 'Navel' orange fruit did not influence the HCT at the inflow side significantly. At the outflow side, the 'Navel' orange fruit with larger diameter of 90-

95 mm cooled 0.8 h faster compared to the smaller 'Navel' orange fruit with diameter of 77-81 mm. Although 'Navel' orange fruit with large diameter cooled a bit faster, the difference in cooling time was consistently smaller than 0.8 h with a standard deviation larger than 0.2 h. At the inflow side, 'Nova' mandarin fruit with diameter of 59-64 mm cooled 0.2 h slower than those with diameter of 55-59 mm, but the difference is not statistically significant ($p > 0.05$). At the outflow side, the influence of 'Nova' mandarin fruit size on the cooling time was statistically insignificant. The maximum difference in fruit diameter in this study was about 10 mm and this might lead to the limited influence of fruit size on cooling rate.

3.4. The influence of fruit wrapping on HCT

In order to analyze the influence of fruit wrapping on the cooling rate, the HCTs for non-wrapped and wrapped 'Eureka' lemon fruit with similar diameters (59-63 mm) were extracted from Exp.1 and Exp.3. Wrapping did not seem to largely influence the cooling time at the inflow side. At the outflow side, however, wrapped 'Eureka' lemon fruit cooled on average 6 h slower than non-wrapped 'Eureka' lemon fruit (Fig. 9a). A larger standard deviation (3 h) was also found for wrapped lemon fruit at the outflow side. Wrapping of lemon fruit therefore resulted in a reduced cooling rate and also increased cooling heterogeneity at the outflow side.

In addition, the influence of wrapped 'Navel' orange fruit on cooling rate was analyzed by comparing HCTs for wrapped, alternatively-wrapped and non-wrapped fruit (Exp.4 and 5). The 'Navel' orange fruit for analysis were chosen from pallets with fruit of a similar diameter range of 77-81 mm. The findings on the 'Navel' orange fruit concurred with those of the lemon fruit. Wrapping did not influence the cooling time at the inflow side (Fig. 9b). At the outflow side the alternatively and fully wrapped 'Navel' orange fruit cooled 0.5 and 3.9 h slower compared to non-wrapped fruit. The alternatively and fully wrapped cartons resulted in an increased cooling heterogeneity, as indicated by the large standard deviations of 1.7 to 2.9 h for these treatments.

The slower cooling rate as a result of fruit wrapping is due to the extra thermal resistance to convective heat removal which is induced by the wrapping paper itself and by the stagnant air layer it creates between the fruit surface and the paper. However, the extra thermal resistance might not be the dominant factor as the wrapping did not influence the cooling time at the inflow side of the pallets. The wrapping paper also causes an obstruction to airflow in the air space between individual fruit in the cartons. This obstruction of the free air space between fruit with the paper is regarded as the primary reason for the reduced cooling rate as a result of a large increase in the airflow resistance in the carton. The high airflow resistance also leads to a larger cooling heterogeneity, specifically at the outflow side of the pallet.

3.5. The influence of package design on HCT

Two carton types, namely Supervent and Opentop (Fig. 2 and 3), were used in these experiments. The market share is 70% and 15% for Supervent and Opentop, respectively, in the export of South African citrus fruit. The Supervent carton was used for the lemon and orange fruit, whereas Opentop was used for mandarin fruit in this study. As mandarins are never packed in a Supervent carton, and lemons and oranges are rarely packed in Opentop cartons, the interaction between fruit type and carton type cannot be evaluated. Therefore, the HCTs of 'Eureka' lemon fruit with a diameter range of 59-63 mm in Supervent cartons (Exp.2) were compared to those of 'Nova' mandarin fruit with a similar diameter range of 59-64 mm packed in Opentop cartons (Exp.6). At the inflow side, the 'Nova' mandarin fruit in the Opentop cartons cooled 24% faster than the 'Eureka' lemon fruit in the Supervent cartons (Fig. 10). At the outflow side, the 'Nova' mandarin fruit in the Opentop cartons cooled 42% faster compared with the 'Eureka' lemon fruit in the Supervent cartons (Fig. 10). There were about 1105 kg fruit in Opentop pallets and about 1280 kg fruit in Supervent pallets. Apart from improved ventilation, the reduced field heat that needs to be removed from the fruit might also cause the fruit in Opentop pallet to cool faster. The cooling heterogeneity was similar for Supervent and Opentop pallets, as indicated by a comparable standard deviation. As fruit type (the shape difference) might have a significant influence on the cooling rate, it is suggested that this aspect should be further quantified in future studies.

4. Conclusion

The influence of package type, fruit size and wrapping on the cooling rate and heterogeneity was investigated by full-scale experiments. These were carried out in a commercial, 40-pallet, forced-air precooler during commercial runs on precooling citrus fruit for export. The main conclusions were:

- The cooling heterogeneity mainly occurred along the flow direction through the pallet, which was identified for all pallets in the precooler, and was also identified at a higher spatial resolution within a single pallet.
- For pallet packed with Supervent cartons, the slowest cooling rate and largest cooling heterogeneity occurred in the cartons at the outflow side, which had the long side

perpendicular to the flow direction.

- For the pallet packed with Opentop cartons, the slowest cooling rate and largest cooling heterogeneity occurred to the cartons at the outflow side, which had the short side perpendicular to the flow direction.
- The fruit size was found to have limited influence on the cooling rate for the range of sizes evaluated for 'Eureka' lemon fruit and 'Nova' mandarin fruit. For 'Navel' orange fruit, a statistically significant difference was found in some instances.
- Paper wrapping reduced the cooling rate significantly and increased the cooling heterogeneity in the pallets.
- The 'Nova' mandarin fruit in Opentop cartons cooled 24% (at the inflow side of pallet) and 42% (at the outflow side of pallet) faster compared to the 'Eureka' lemon fruit of similar size in the Supervent cartons.

This study was carried out in parallel with commercial precooling and the results underlined the value of such detailed measurements and data analysis. Results from small-scale experiments often cannot provide adequate answers to the questions asked by the fruit industries in order to optimize forced-air precoolers and to troubleshoot problematic situations.

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Fig.1 Forced-air cooling (FAC) room used to precool citrus fruit (Red and blue solid lines denote warm return and cold supply air, respectively).

Fig. 2 Geometry and dimensions (in mm) of the two cartons: (a) Supervent and (b) Opentop.

Fig. 3 Geometry and dimensions (in mm) of the two pallets: (a) Supervent and (b) Opentop. Blue and red arrow lines show the airflow direction.

Fig. 4 (a) Top view of the forced-air precooler, which has two rows of pallets. The fans are located in the ceiling along the centerline of the corridor. The inflow side is facing to the lateral supply air zone while the outflow side is facing to the central air corridor. The blue and red arrows depict the airflow direction. Orange dots denote the positions of temperature sensors in Exp.1, grey dots indicate SRCC temperature probes and black crosses show the position to manually check airflow speeds with a hot wire anemometer. (b) Side view of the precooler. Each row has 20 pallets with 10 on top rack and 10 on bottom rack. For each pallet, h3, h5 and h7 denote the third, fifth and seventh layer of the pallet.

Fig.5 Pulp temperature profiles in the center of individual fruits in different pallets during precooling experiment Exp.1. Inflow side and outflow side are marked in Fig. 4. The black dotted line denotes the temperature at half cooling time when fruit cools from 14 °C to 12 °C. The red dotted line denotes the temperature at half cooling time when fruit cools from 12 °C to 10 °C.

Fig.6 Pulp temperature profiles in the center (core) of individual fruit at different positions in a pallet during precooling experiment: (a) Supervent cartons with 'Eureka' lemon fruit (diameter of 59-63 mm) in Exp. 2 and (b) Opentop cartons with 'Nova' mandarin fruit (diameter of 90-95 mm) in Exp.6. Blue arrows denotes the inflow side and red arrows denotes the outflow side.

Fig.7 Column averaged half-cooling time (HCT) for (a) ‘Eureka’ lemon fruit with diameter range of 59-63 mm in Supervent cartons and (b) ‘Nova’ mandarin fruit of diameter range of 90-95 mm in Opentop cartons. The colors of the bars correspond to different carton locations (columns) in a pallet. Blue arrows denotes the inflow side and red arrows denotes the outflow side.

Fig.8 The influence of fruit size (mm) on half cooling time (HCT) of the three citrus fruit types. The numbers at horizontal axis (e.g., 56-59) are the diameter range (in mm) of fruits. ‘Inflow’ and ‘Outflow’ side at the horizontal axis are marked in Fig. 4.

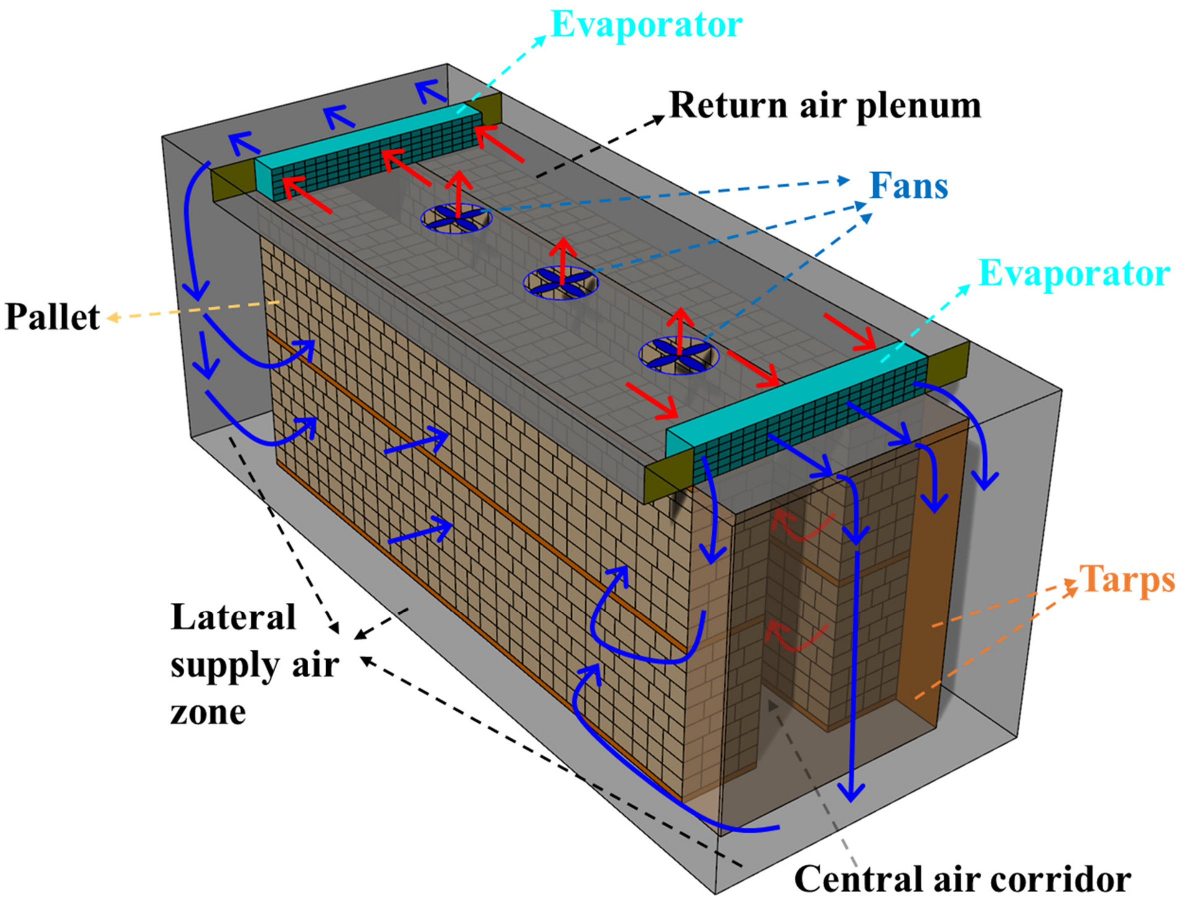
Fig.9 The influence of fruit wrapping on HCT of (a) ‘Eureka’ lemon fruit of size 59-63 mm from Exp.1, 2 and 3; (b) ‘Navel’ orange fruit of size 77-81 mm from Exp.4 and 5. The numbers at horizontal axis represent wrapping type: 0 - non-wrapped; 0.5 - fruit in each alternating layer were wrapped; 1 - each individual fruit was wrapped. ‘Inflow’ and ‘Outflow’ side at the horizontal axis are marked in Fig. 4.

Fig. 10 The influence of packaging on HCTs. Data for Supervent is from Exp.2 using ‘Eureka’ lemon fruit with size of 59-63 mm. Data for Opentop is from Exp.6 using ‘Nova’ mandarin fruit with size of 59-64 mm. ‘Inflow’ and ‘Outflow’ side at the horizontal axis are marked in Fig. 4.

Table 1. A summary of the six different experiments

Highlights

- Cooling heterogeneity along the flow direction in pallets was quantified.
- Fruit wrapping induced slower cooling rate and larger cooling heterogeneity.
- Differences in cooling rates were found up to 42% between different packages.



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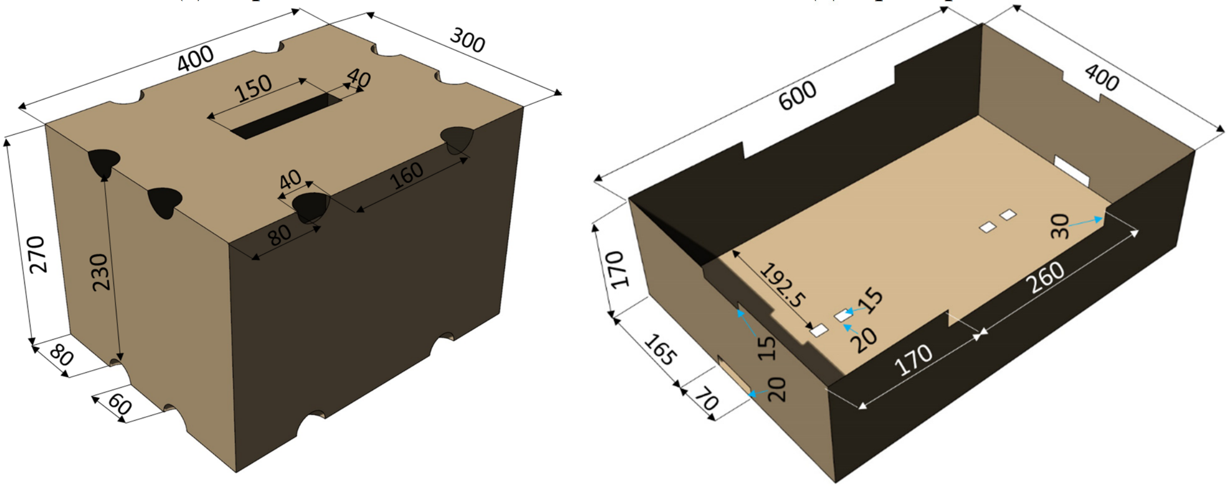
(a) Supervent carton

(b) Opentop carton



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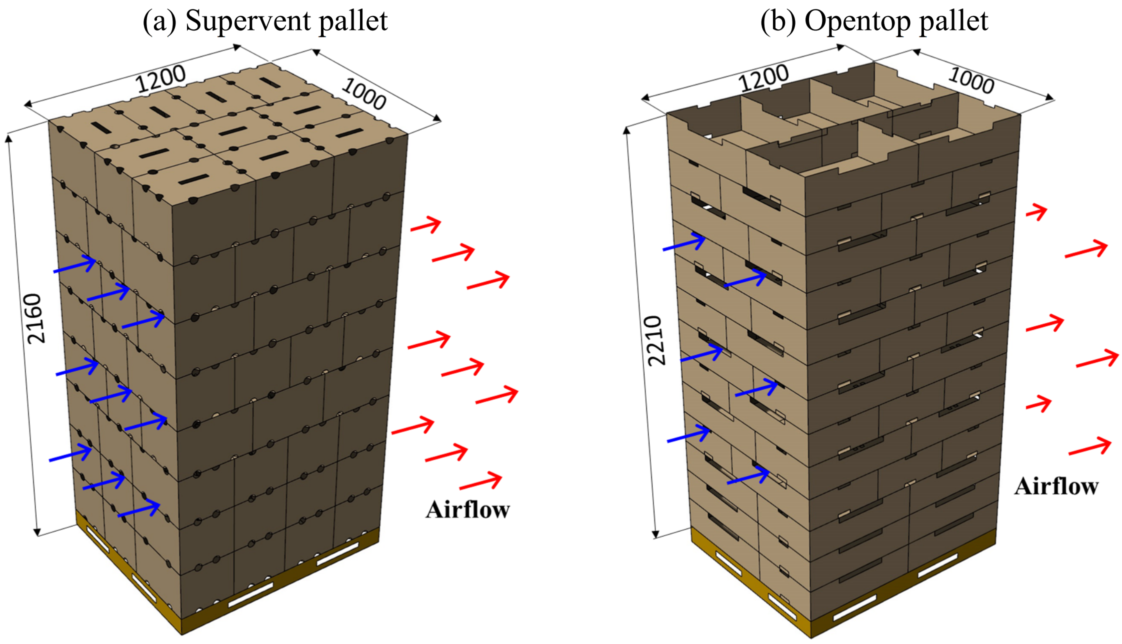
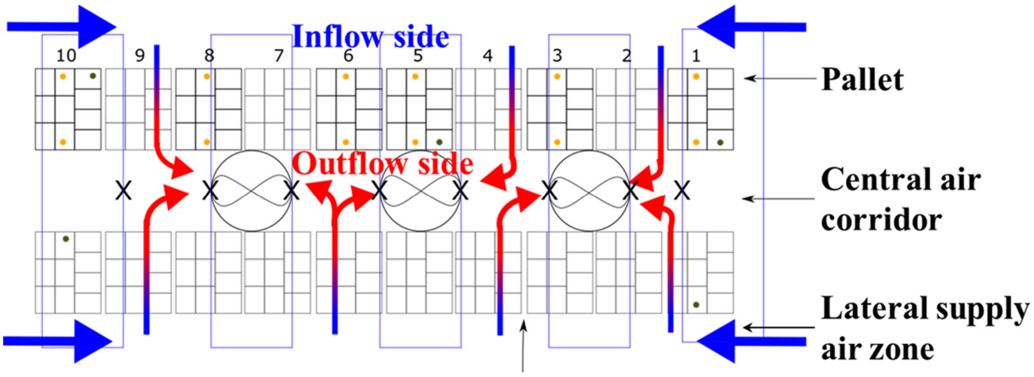
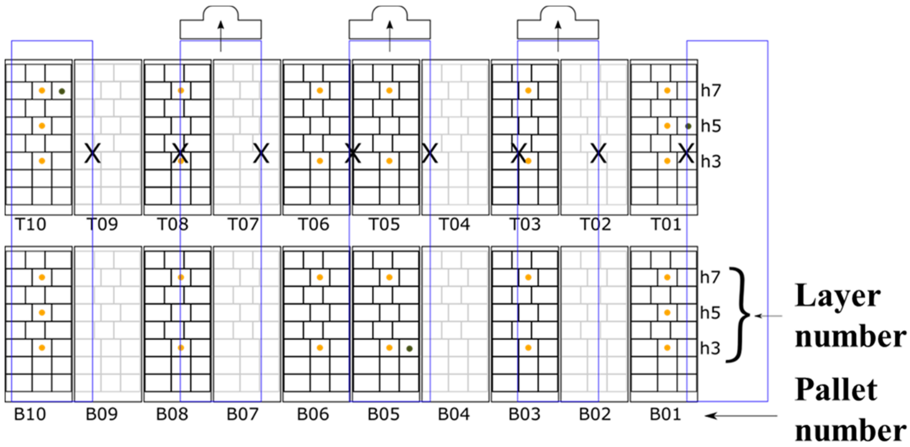


Fig. 3 Geometry and dimensions (in mm) of the two pallets: (a) Supervent and (b) Opentop. Blue and red arrow lines show the airflow direction.

(a) Top view



(b) Side view



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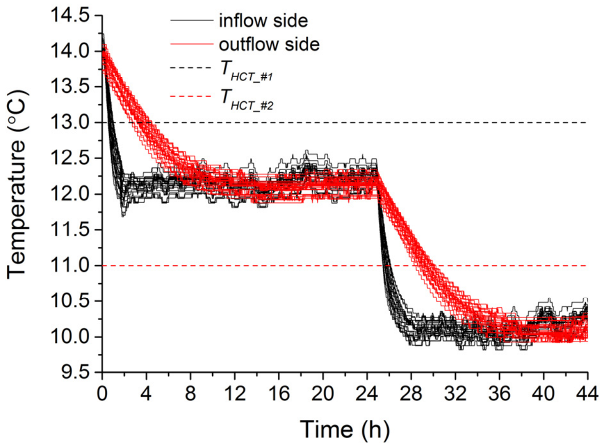

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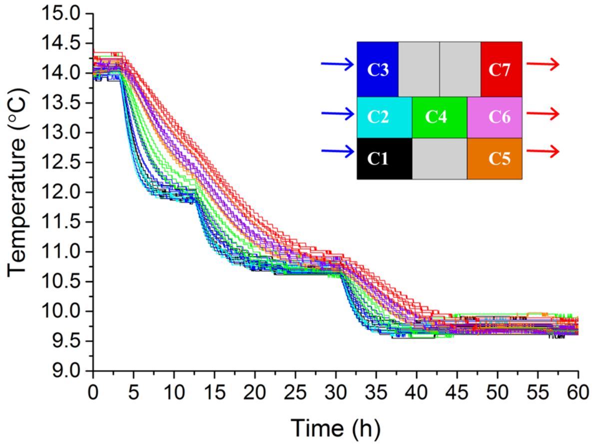
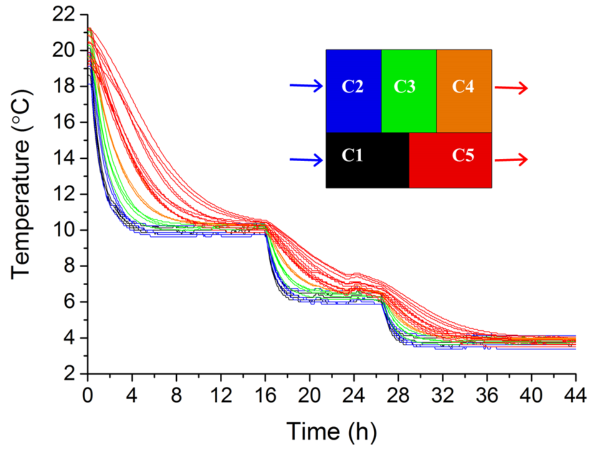
(a) Supervent, 'Eureka' lemons, size 59-63



(b) Opentop, 'Nova' mandarins, size 90-95



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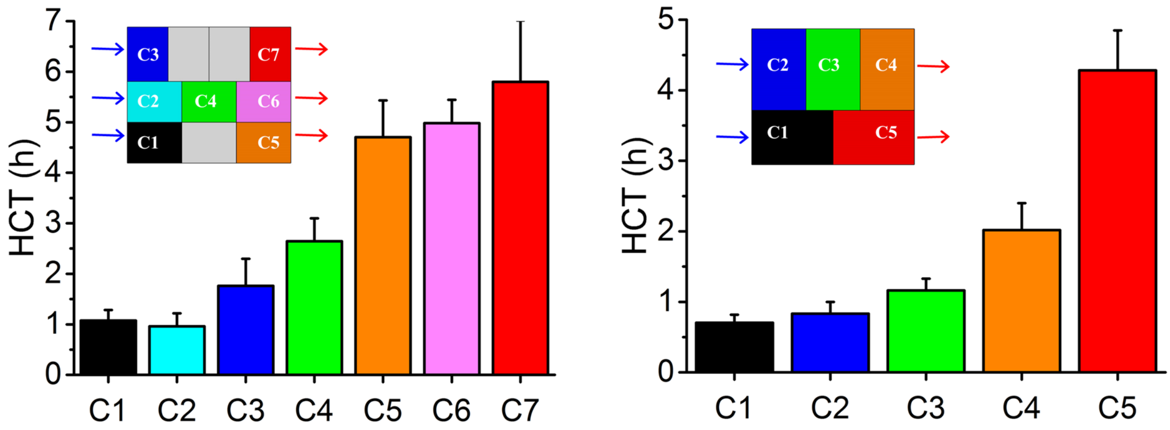
(a) Supervent, ‘Eureka’ lemons, size 59-63 (b) Opentop, ‘Nova’ mandarins, size 90-95



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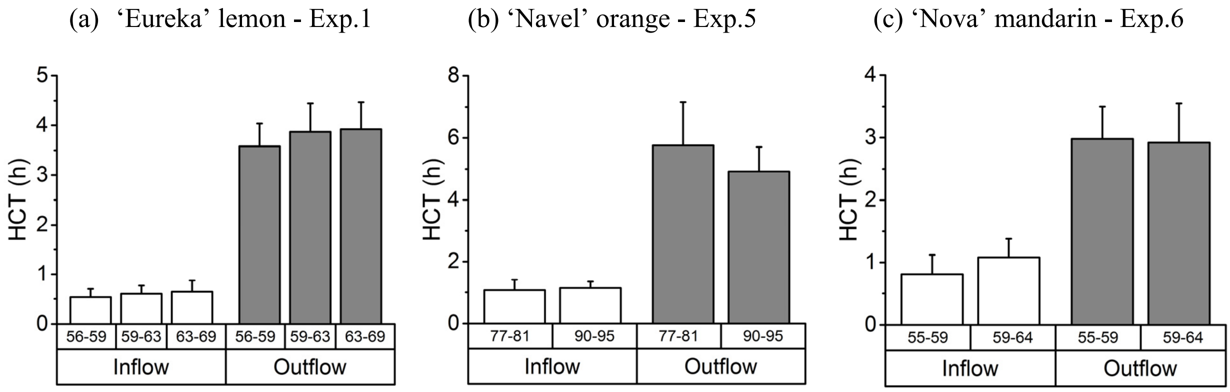

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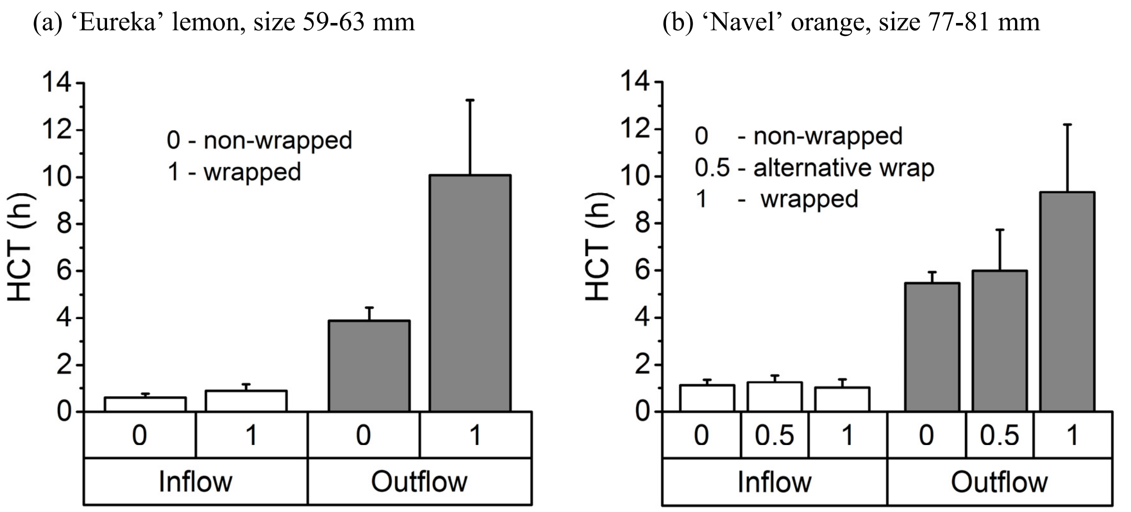

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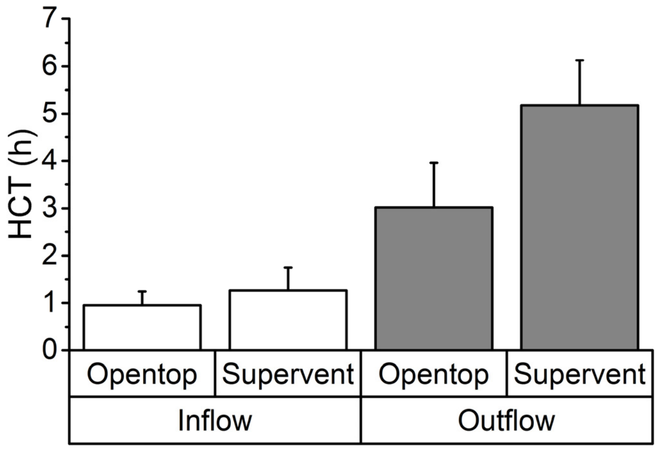

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Table 1. A summary of the six different experiments

	Exp.1	Exp.2	Exp.3	Exp.4	Exp.5	Exp.6
Duration [h]	65.7	93.0	40.3	87.0	92.5	46.5
Average initial fruit temperature [°C]	14.9	22.7	18.5	18.8	19.1	19.8
Number of step downs[(1)]	3	4	2	4	4	3
Target temperature [°C]	10	10	10	3.5	3.5	3.5
Average pressure drop across pallet [Pa]	59	40	56/71[(2)]	63.4/82.9	66/77.1	41/48
Number of temperature sensors	56	42	53	57	60	59
Fruit type (species and cultivars)	'Eureka' lemon	'Eureka' lemon	'Eureka' lemon	'Navel' orange	'Navel' orange	'Nova' mandarin
Fruit diameter [mm]	56 - 69	59 - 63	51 - 72	65 - 77	77-90	58 – 59
Number of monitored pallets	12	2	16	12	20	12
Package type	Supervent	Supervent	Supervent	Supervent	Supervent	Opentop
Wrapping	None	None	Partially[(3)]	Fully	Partially	None

[(1)] Fruit was often not cooled directly to the target temperature. Instead, fruit was firstly cooled to an intermediate temperature and then gradually cooled to target temperature, which is called a step-down cooling.

[(2)] In Exp.3-6, there are two different pressure drops during different step-down cooling processes.

[(3)] 'Partially' means that some of the pallets have wrapped fruit and others have non-wrapped fruit.