Is there a systematic hidden 'hot spot' in refrigerated containers filled with fresh food in ventilated packaging?

Thijs Defraeye [1] *, Leo Lukasse [2], Chandrima Shrivastava [1,3], Celine Verreydt [1,4], Jörg Schemminger [1], Paul Cronjé [5,6], Tarl Berry [5,6]

[1] *Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland*

[2] *Wageningen University and Research, Bornse Weilanden 9, 6708 WG, Wageningen, The Netherlands*

[3] *University of Bern, Hochshulstrasse 6, CH-3012 Bern, Switzerland*

[4] *Wageningen University and Research, Food Quality and Design, Department of Agrotechnology and Food Sciences Bornse Weilanden 9, 6708 WG, Wageningen, The Netherlands*

[5] *Citrus Research International, Nelspruit, South Africa*

[6] *Department of Horticultural Science, Stellenbosch University, Stellenbosch, South Africa*

* *Corresponding author: thijs.defraeye@empa.ch (T. Defraeye) Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Biomimetic Membranes and Textiles, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland*

ABSTRACT

Background. Thousands of refrigerated containers transport fresh fruit and vegetables to feed the world yearly. These containers should preserve fresh-food quality as uniformly as possible throughout the cargo.

Scope and Approach. Several simulation studies have suggested the presence of a systematic hot spot in these containers near the supply-air inlet when warm cargo is cooled down in the container. Induced by airflow recirculation inside the ventilated packaging, the hot spot is located at the bottom of the pallets near the refrigeration unit. The fruit at the bottom of these pallets is well known to be exposed to cold air. However, the existence and impact of this hot spot were not acknowledged explicitly. Interestingly, full-scale experiments and computational fluid dynamics (CFD) simulations contradict the existence of this recirculation-zone-induced hot spot.

Key Findings and Conclusions. We analyzed the literature and the physical phenomena at play to identify if and why this recirculation-driven hot spot occurs. We found that the airflow recirculation can be partially hidden in full-scale experiments and that we are often not looking for it at that location. Physically, the presence of the recirculation zone is plausible. The CFD simulations that predict this zone include all relevant physical processes. However, we still need proof by detailed full-scale experiments to confirm its existence. It is likely that the recirculation only occurs in some ventilated shipments, but then we need to identify for which shipments this happens. If this recirculation zone is present in a ventilated cargo of perishables, we need to solve this problem urgently. We suggest a roadmap with steps to do so. Otherwise, we would be systematically losing food quality in many shipped containers. Besides slowing down fruit cooling, such a recirculation vortex can trap respiration heat, moisture, and metabolic gases. Mitigating this hot spot thus can considerably impact the quality of the fruit and vegetables shipped worldwide.

Keywords

refrigeration; transportation; airflow; fruit; vegetables; computational fluid dynamics

1 Introduction

The number and use of shipping containers worldwide are rapidly growing. Drivers are, among others, the larger amounts of food transported to feed the increasing population, expanding e-commerce, and the rising amount of trade routes (P&S, 2021). We expect the number of containers to double in the next ten years, reaching 7.0 million twenty-foot equivalent units (TEU) by 2030 (P&S, 2021). A significant share of these containers is refrigerated. This global refrigerated container market was valued at 15.1 billion USD in 2019 (Markets&Markets, 2019). An essential share of these refrigerated containers transports fresh fruit and vegetables. For example, the South-African citrus industry – the world's second-largest exporter of citrus – ships 90,000 refrigerated containers overseas yearly (CGA, 2021). Refrigerated containers thus play an essential role in preserving food to feed the world.

During refrigerated transport, the quality of fresh produce in the cargo must be preserved as uniform as possible. The occurrence of pallets with lower fruit quality in consignments leads to food losses and can even result in the rejection of an entire cargo. The exporter may be forced to find an alternative receiver in these cases. This step results in an extension of the supply chain, a shorter postharvest life, and more food loss. Uniform cooling is also important to avoid variations in fruit quality, as this can complicate sales and logistics further down the supply chain.

Many researchers quantified the cooling and fruit-quality heterogeneity in refrigerated containers (Berry et al., 2021; T. Defraeye et al., 2016; Jedermann et al., 2014). One recurring and important issue has not been addressed, namely the possible presence of a systematic hot spot near the supply-air inlet, at the bottom of the pallets. Some simulation studies have identified a systematic hot spot when cooling the cargo. An unwanted airflow recirculation zone in these pallets seems to cause this hot spot. This recirculation zone traps air inside the ventilated packaging, negatively impacting temperature uniformity and fruit quality. The hot spot manifests when cooling down the fresh food in the container. Fresh produce such as citrus or banana is typically loaded warm and cooled down in a container (Thijs Defraeye et al., 2015; Jedermann et al., 2013).

In literature, this phenomenon has been shown by fluid dynamics simulations when cooling down the cargo (Figure 1). Most experiments, however, seem to contradict this finding. It is well known that (too) low temperatures are often found at the bottom of the first pallets, which can damage the fruit by chilling injury. The presence of the recirculation zone above is, however, not acknowledged. The recirculation zone can cause other problems even if cargo is already cool. Respiration-driven 'hot spots' are critical for highly respiring shipments such as bananas or mangoes (Issa & Lang, 2016). In the recirculation zone, the removal of metabolic gases or water vapor is slowed down. The resulting higher temperatures and gas concentrations are detrimental to the quality of the fresh food. If such a systematic hot spot is present in containers filled with ventilated packaging, it could affect many refrigerated containers that exporters ship with fruit and vegetables each year.

In this study, we aim to understand better if this recirculation-driven hot spot occurs in reality or not. We list and analyze the contradictory findings from physics-based simulations and full-scale experiments. We explain the physical phenomena at play. We provide arguments pro and contra regarding the possible existence of this recirculation zone and the associated hot spot. We suggest future steps to help identify and solve this hot spot if it exists in reality.

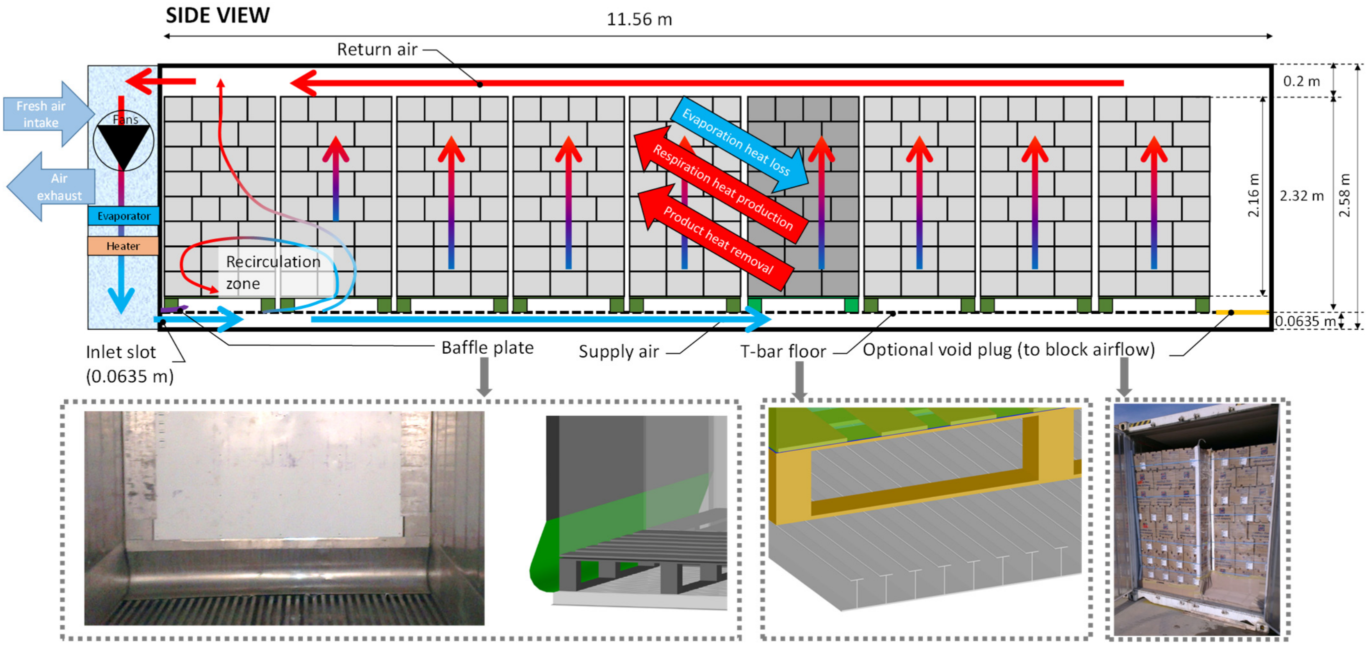

Figure 1. Schematic of a refrigerated container (side view) with airflow and recirculation zone. Several details are highlighted, including the baffle plate, the T-bar floor and the void plug.

2 State of the art

2.1 Physics-based simulations indicate a recirculation zone and hot spot

Several simulation-based studies showed the presence of a recirculation zone. Their findings are summarized in Figure 2 and discussed below.

- (Getahun et al., 2017a) identified the recirculation zone near the bottom of the inlet from their simulated flow fields. This recirculation zone appeared in the vertical gap between the two rows of pallets and inside the pallets. The authors also found much slower cooling in the pallets close to the refrigeration unit from the simulations. This slower cooling for the first two pallets was not observed experimentally (see section 2.2).
- (Getahun et al., 2017b) identified a high-temperature zone at the vertical wall where the refrigeration unit is placed, as caused by the recirculation zone. For more permeable packaging, this higher temperature zone became much smaller.
- (Senguttuvan et al., 2021) found a low-speed zone in the pallets near the refrigeration units. Since the study did not show the streamlines of velocity vectors, the occurrence of a recirculation zone is not confirmed, but it is likely occurring in this low-speed zone. Corresponding higher temperatures in these pallets associated with such a recirculation zone are also reported.
- (Tiamiyu, 2020) found a recirculation zone within the pallets. They evaluated several pressure resistances of the cargo that represent permeable to less permeable ventilated packaging. They evaluated several packaging designs. In all cases, a recirculation vortex was found. For very air-permeable packaging, the recirculation zone was small. For each packaging design, airflow recirculation near the inlet was found. The impact of the flow recirculation on the fruit temperature for these configurations was not reported or analyzed.
- (Jiang et al., 2020) did not report a distinct recirculation zone for their refrigerated container. However, the pallet closest to the refrigerated container heated up slightly faster due to respiratory heat than the second pallet. The wooden pallet base was modeled as a porous medium, whereas other studies have neglected to model the pallet base.
- (Issa & Lang, 2016) found a recirculation zone in the vertical gap between pallets in a refrigerated container. However, the pallets in their computational model were not ventilated, so they were modeled as impermeable packaging. Nevertheless, they detected a hot spot in this region in their thermal measurements of ventilated packaging.

In summary, multiple simulations for different types of ventilated cargo identify a recirculation zone in or in-between the first pallets close to the refrigeration unit. Some simulations also predict a higher temperature in these zones when cooling down the cargo. However, the existence of this warmer region, caused by the airflow field, has not been explicitly discussed in these works.

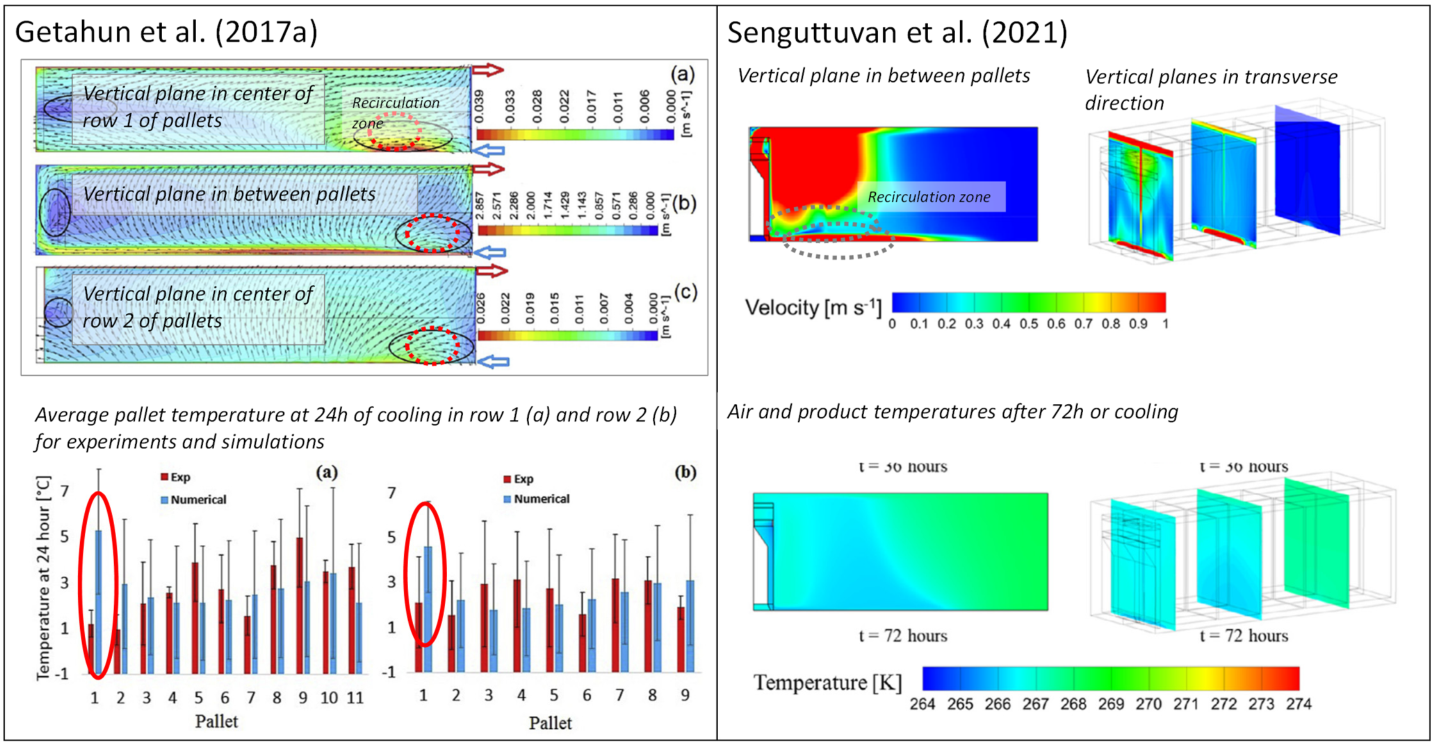

Figure 2. Results of simulation studies identify a recirculation zone near the container inlet and the associated hot spot. The dotted ellipses indicate some of the recirculation zones (in Getahun et al. (2017), and the black ellipses just indicate the high and low-speed zones).

Table 1. Specifications of recent simulation studies on refrigerated containers.

Author(s)	Topic/aim	Internal dimensions	Product in container	2D/3D model	Airflow rate or speed	Cargo unit	Cargo precooled	T-bar floor and or pallets modeled as	Mesh/Grid	Fluid flow (lam. turb.)	Heat transfer in a porous medium	Heat of respiration modeled	Heat exchange with environment	Simulation & Time step	Software used	Monitored quantities/metrics - Main evaluated parameter
Refrigerated container																
(Getahun et al., 2017a, 2017b)	Model validation with full-scale experiments. The impact of ventilated packaging design	40' container (11.59 x 2.29 x 2.54 m)	Apple (cv. Top Red)	3D	5400 m^3/h	20 pallets of 1.2 x 1 x 2.16 m	partially	yes	16 million cells	Turbulent SST k-ω model, anisotropic	One phase	yes	yes	Transient, 180 s	ANSYS Fluent 16	Airspeed + temperature magnitude & distribution
(Jiang et al., 2020)	Improving cooling by reducing airflow bypassing the cargo	40' container (11.59 x 2.29 x 2.54 m)	Cherry tomatoes	3D		20 pallets 1 x 1.2 x 2.115 m	yes	no	10 million cells	Turbulent SST k-ω model, anisotropic	One phase	yes	yes	Transient, 360s	ANSYS Fluent 17	Airspeed + temperature magnitude & distribution
(Senguttuvan et al., 2021)	Improve airflow distribution and cooling uniformity by different refrigeration unit designs	20 ' container (5.79 x 2.31 x 2.30 m)	Apple fruit	3D		10 pallets 1 x 1 x 2.04 m with 50 mm gaps	no	no	1.8 million cells	Turbulent k-ε model, isotropic	One phase for fruit, two phases for evaporator coil.	yes	no	Transient, 180 s	ANSYS Fluent 19.1	Airspeed + temperature magnitude & distribution
(Issa & Lang, 2016)	Airflow analysis to identify hot spots and container loading patterns	20' container	Banana	3D	5480 m^3/h	11-12 pallets of 48 boxes of 0.5 x 0.4 x 0.25 m	-	no	-	Turbulent k-ε model	n.a. (adiabatic pallets)	-	no	Steady, n.a.	COMSOL Multiphysics	Airspeed magnitude & distribution
(Tiamiyu, 2020)	Evaluate packaging designs and cooling/airflow patterns	40' container (11.59 x 2.29 x 2.55 m)	Apple fruit (cv. Golden Delicious)	3D	5500 m^3/h	20 pallet of 1.2 x 1 x 2.15 m	partially	yes	21.4 million cells	Turbulent SST k-ω model, anisotropic	Two-phase	-	no	Transient, 60 s	ANSYS CFX 19.1	Airspeed + temperature magnitude & distribution

2.2 Full-scale experiments on containers rarely indicate a recirculation zone and hot spot

The presence of a recirculation zone near the inlet is typically not identified by experiments. Airspeeds are often measured inside the cargo of ventilated packaging or the gaps between the pallets (Delele et al., 2008; Lloyd, 2013). Even when the airspeed – the magnitude of the velocity vector – is measured, measuring its direction is even more challenging. There are also difficulties with installing the sensors, such as multidirectional hot-wire anemometers. Other techniques measure velocity vectors, namely particle image velocimetry (PIV) and laser Doppler anemometry (LDA). Such measurements are not possible inside non-optically transparent porous media, such as ventilated packaging filled with fresh foods (Ferrua & Singh, 2008). These velocity measurement techniques have been applied to measure in and around ventilated packaging in laboratory setups (Duret et al., 2014; Laguerre et al., 2012; Moureh et al., 2009; Pham et al., 2019) or empty packaging in refrigerated enclosures (Moureh et al., 2009; Tapsoba et al., 2006, 2007). To our knowledge, these techniques have not been applied in fully packed refrigerated containers since there is no optical access. Indirect techniques that estimate the airspeed based on the measured convective heat transfer rate still only give the magnitude (Lloyd, 2013; Moureh et al., 2009). Recently, the most advanced sensor device to measure airspeed inside ventilated palletized fresh fruit and vegetables was presented (Geyer et al., 2018). This sensor measures airspeed. However, to our knowledge, nobody has attempted yet to quantify the airflow field in a refrigerated container at a sufficient resolution to identify the recirculation zone.

Apart from the recirculation zone, the higher temperature zone or 'hot spot' associated with it is not identified conclusively in experiments. Also, the associated lower food quality is not reported in this region. The findings of these studies are summarized in Figure 3 and discussed below.

- (Getahun et al., 2017a) did not find slower cooling for the first pallets near the refrigeration unit. This finding strongly contrasted with their simulation results, where this first pallet cooled much slower. The experimental comparison of average pallet temperatures was made using only three temperature sensors per pallet, placed at different heights. The average temperature of the pallet could therefore differ. The hot spot could still be hidden in the experimental data.
- (T. Defraeye et al., 2016) found in their experiments two pallets with about 30% higher cooling time at the bottom of the pallet, namely the one at the refrigeration unit and one in the middle of the container. The fruit

mass loss at the bottom of these pallets was also the highest. These pallets did not stand out concerning fruit quality and pest mortality.

- (Issa & Lang, 2016) detected by thermal measurements in ventilated packaging as a hot spot in this region. The cause was claimed to be the existence of a recirculation vortex, so confirming its existence.
- (Berry et al., 2021) found no significant slower cooling of the first pallet, and a critical hot spot was found at the door-end of the container. The study also highlighted how vulnerable the airflow and consequent fruit cooling patterns in a container are due to small changes in the geometric layout, such as gaps between the pallet stacks and the container walls.
- (Jedermann et al., 2011) found that pallets near the refrigeration unit take less than half the time to cool down than those at the container's door end, indicating that no hot spot occurs here.
- Our communication with several stakeholders dealing with refrigerated containers (exporters, importers, retailers, etc.) identified that occasionally fruit quality problems occur with the first pallets due to elevated temperatures. Several quality evaluators have reported higher chilling injury at the bottom of the first two pallets against the refrigeration unit wall, so those on the baffle plate. Note that the vertical metal wall near the refrigeration unit becomes quite cold in some containers. The reason is that the cold temperatures of the evaporator are transferred partially by conduction to the refrigeration unit. As such, this conduction can help lower the temperatures of the pallets in contact with the vertical wall.

In summary, several challenges made that researchers did not, or could not, set up an experiment to measure a possible recirculation zone in ventilated pallets in a refrigerated container. Fluid dynamics simulations are still the most viable option for detailed airflow fields in refrigerated containers. In experiments, we need to rely on an indirect method for identifying the presence of the recirculation vortex in full-scale experiments: by measuring a low airspeed zone or slower fruit cooling. However, full-scale experiments did not equivocally show a higher temperature zone at the bottom of the first pallets. We thus need to question the physical presence of a recirculation zone.

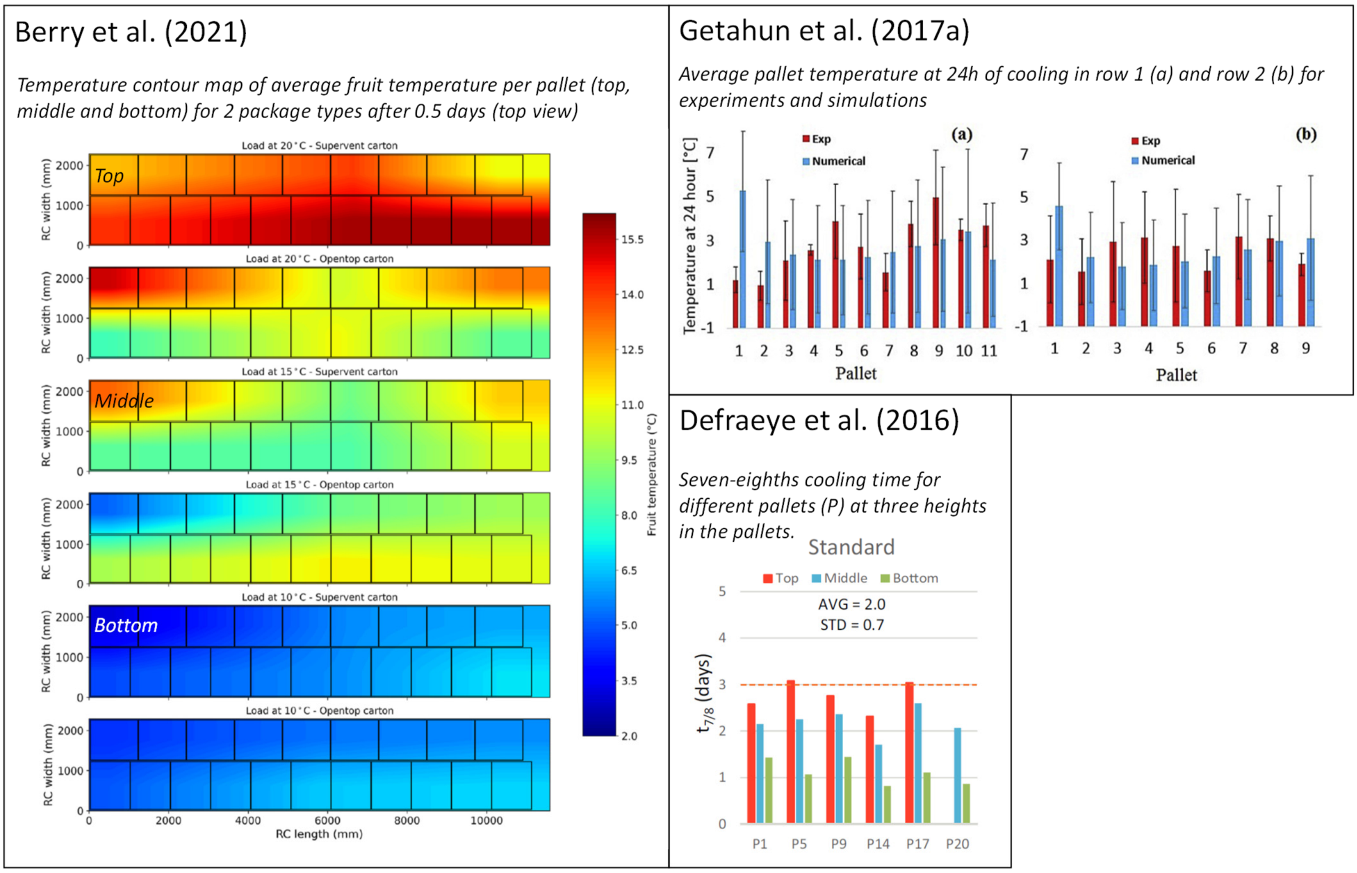

Figure 3. Results of full-scale experimental studies that do not show a recirculation zone near the container inlet or an associated hot spot.

3 Discussion

Fluid dynamics simulations and experiments currently give us contradictory findings. Simulations indicate the presence of a recirculation zone near the refrigeration unit and the resulting possible occurrence of a 'hot spot' while experiments do not. We currently still do not know for sure if this zone exists. We analyze the physical phenomena that could give rise to this recirculation zone (Figure 1). Based on this reasoning, we motivate why this recirculation zone and hidden 'hot spot' could exist or not.

3.1 Physical phenomena that could induce a recirculation zone

First, let us describe the airflow pathway (Figure 1). The evaporator fans induce airflow that leaves the refrigeration unit at a flow rate between 2000 - 5500 $m^3\ h^{-1}$. A narrow inlet slot with a height of around 64 mm leads to local airspeeds of about 3.8 - 10.5 $m\ s^{-1}$. Based on this airspeed and the slot height, the corresponding slot Reynolds numbers are 16,600 – 45,700. At these slot Reynolds numbers, the airflow is turbulent (van Hooff, Blocken, Defraeye, Carmeliet, & van Heijst, 2012; van Hooff, Blocken, Defraeye, Carmeliet, & Van Heijst, 2012). This turbulent flow enters the T-bar floor. Above the T-bar floor, an open space is present. This space is caused by the wooden pallet base, about 160 mm high. A baffle plate is present at the inlet to avoid air bypassing the first pallet (Figure 1).

After entering the enclosure, the Coanda effect makes the airflow remain attached to the bottom surface. The pressure zone generated around the horizontal air-jet stabilizes the high-speed jet, so it remains attached to the bottom of the container. The baffle plate should not contribute significantly to the flow attachment to the bottom wall, as the Coanda effect is the main driver. In addition, the T-bar confines the airflow partially in its half-open channels. The channels have a porosity of about 50% in the vertical direction. The T-bar floor thus further prevents the air from flowing upwards by invoking a resistance. Both the Coanda effect and the horizontal T-bar channels guide the air to reach the door-end of the container. Most of the airflow likely passes by the first pallets as it is still attached to the floor. The airflow cannot make the 90-degree turn, by which it does not directly flow into the first pallet. This effect can give rise to the recirculation zone that simulations identify.

Once the airflow has passed the T-bar floor, it enters a space where the pallet bases are located. The air passes upwards through the ventilated packaging, which provides the most significant airflow resistance in the container enclosure compared to the T-bar floor and the pallet base. The airflow resistance of the pallets affects the airflow field in the bottom plenum of the container where the wooden pallet bases are. The high resistance of the ventilated packaging will cancel out non-uniformities in the airflow. The pallet's aerodynamic resistance thus determines what the flow in the container and inside the ventilated cargo looks like. A void plug, placed at the door-end on top of the open T-bars, is sometimes used to reduce airflow bypass at the door-end of the container.

From literature and our experience, the packaging and the stowing strategy have a key impact on the airflow, thus creating a possible recirculation zone (Getahun et al., 2017b, 2018; Tiamiyu, 2020). The packaging resistance to airflow in both vertical and horizontal directions, and their ratio, play a role. (Getahun et al., 2017b) found in simulations that if the vertical resistance to airflow decreased, the horizontal airflow component also decreased, so the air flowed much more vertically through the packaging. More open, well-ventilated packaging reduced the size of the recirculation zone (Tiamiyu, 2020), in addition to gaps or channels created during the stowing.

3.2 To be or not to be: arguments pro and contra

We motivate here why this hidden 'hot spot' and recirculation zone could exist or not.

1. We did not identify the hot spot yet experimentally

The first scenario is that the hot spot is present, especially when cooling down warm cargo inside a container, but this was not yet identified in experiments. Several reasons could be the cause of that. First, only a few sensors that measure pulp temperature are placed per pallet in field experiments, usually three per pallet. The recirculation occurs in the bottom of the ventilated pallet and only in pallets close to the refrigeration unit. Therefore it is likely not always picked up in experiments (**Error! Reference source not found.**). Second, we could be overlooking this region as it is not the usual location where problems are expected as it is so close to the refrigeration unit.

Typically hot spots are expected at the door-end of the container. Thermal damage from too low temperature to chilling-injury-sensitive fruit near the inlet is a more common concern. The problems and hot spots could also be considerably less than at other locations, and they do not get noticed that easily. As such, no additional sensors are placed here. Another reason we could overlook this phenomenon is that there is a lot of variability between the different shipments due to individualized loading practices. This variability can mask the reduced food quality in the recirculation zone in a supply chain. Finally, the recirculation zone may only be present for some ventilated packaging types but not all. As such, it is not systematically manifested in all refrigerated container shipments. In summary, a systematic problem of airflow recirculation could be partially hidden in full-scale experiments, and we were also not looking for it.

2. There is no hot spot. We just simulate it

A second scenario is that the hot spot is not there, despite several fluid dynamics simulations predicting its presence. In essence, this scenario implies that the simulations do not capture one or more critical physical phenomena or do not include sufficient details to make predictions in this area accurately. One example is that the turbulence models do not accurately predict turbulent high-speed jets that expand in an enclosure and the resulting Coanda effect. Studies have reported that some turbulence models, such as the standard k-ε model, overestimate the Coanda effect of the wall jet, failing to predict the jet separation (Moureh et al., 2009). As a result, this can lead to a predicted recirculation zone that is too large. Laminar flow simulations at equivalent airspeeds typically do not predict a recirculation zone.

Another cause could be that the impact of the T-bar floor on the airflow is not accurately captured. However, several CFD simulation studies included the T-bar floor explicitly. Therefore it is unlikely that the modeling of the T-bar floor is the reason. The wooden pallets are often not included in the model. (Jiang et al., 2020), however, modeled pallets as a porous medium and did not notice a recirculation zone, so maybe modeling the pallets play a role, but this needs to be further confirmed by simulations.

Another discrepancy between simulations and reality is that the ventilated packages are modeled as a homogeneous porous medium. In reality, air flows through discretely distributed vent holes, some of which are blocked by imperfect stacking. Several high-speed jets will appear at the vent holes. A well-delineated recirculation zone, as in Figure 2, is not probable. In this case, the airflow pattern will differ from the simulated ones in Figure 2. A recirculation zone can be more easily generated in the simulations in this continuum. However, using the porous medium approach to calculate flow in the pallets of fruit is only valid under certain conditions. The representative elementary volume (REV), i.e., a computational cell or control volume, should be much larger than the pore size or fruit diameter. For large fruit such as citrus fruit, this is rarely the case. Hence, the simulations introduce a modeling discrepancy with reality by using the porous medium approach. The alternative, discretely modeling each of the thousands of fruit and hundreds of ventilated packages with vent holes, is computationally extremely expensive. In reality, it is likely that the flow pattern still contains a zone where flow is not vertical through the first pallets since the Coanda effect will still be present. However, a distinct recirculation vortex might not be present.

3. There is a recirculation zone but not a clear hot spot

A third scenario is that the recirculation zone is there, but the hot spot is not manifested clearly. The reason could be that the cargo being transported is often precooled. Suppose the cargo is also not respiring significantly. In that case, the resulting hot spot does not become apparent. The reason is that the fruit remains cool once the field heat is removed, even if this recirculation zone is present. For non-respiring cargo that is cooled in the container, for example, citrus fruit (T. Defraeye et al., 2016; Thijs Defraeye et al., 2015), the hot spot only appears in the first days of cooling. Therefore its impact on the fruit quality is likely limited and not noticed explicitly in commercial shipments.

4. There is a recirculation zone, and it results in a cold spot

A fourth scenario is that a recirculation zone is present at the bottom region of the pallets near the refrigeration unit, but this zone leads to a cold zone. The recirculation zone, driven by the air exiting the air inlet, is cycled through the pallets and then partially returned to the delivery air, where new cold air is exchanged into the cycle. When the cargo is fully cooled down, the net result is a region where the lowest temperatures are found. This fruit will be exposed to this cold air for several weeks, making these coldest locations vulnerable to chilling injury. This recirculation of cold air can potentially induce chilling injury in sensitive fruit types on the bottom of the first pallets near the refrigeration unit. Such quality problems are reported frequently in this region. The presence of a recirculation zone might thus amplify the chilling injury as a cold vortex is maintained. Prior studies have not reported such a recirculation zone, but it is a viable scenario and should be considered in future research. Therefore, the industry might associate the bottom of the first pallets with a 'cold spot' instead of a 'hot spot'. Actually, both can be present at different times, with a different impact on fruit quality decay: The hot spot can occur during the first days if warm cargo is cooled down, and the cold spot can emerge afterward for the rest of the trip.

4 Outlook

We shed light on the possible presence of a currently hidden hot-spot zone in a refrigerated container filled with ventilated pallets of fresh food. This hot spot would be caused by a recirculation zone near the bottom of the first pallets at the refrigeration unit, particularly when the cargo is cooled down. Apart from slowing down fruit cooling, such a recirculation vortex can hold, to some extent, more respiration heat, moisture, and metabolic gases (oxygen, carbon dioxide, ethylene). This effect can lead to controlled atmosphere storage, ethylene scrubbing, and microbiological growth control problems. This hot spot is only likely to appear and affect fruit quality for respiring or non-precooled cargo cooled down in the container.

If this recirculation zone systematically exists in the ventilated cargo of perishables, research efforts should be structured to solve this problem. The reason is that we systematically lose food quality in each shipped container. The way forward would be to place, for many shipments, multiple temperature sensors in the fruit at the bottom of the first pallets close to the refrigeration unit during the cooling process. Measuring other metabolic gasses in this region could also help identify this critical spot. However, once identified, solutions that adjust airflow in the container might be challenging to implement at a large scale since refurbishing all containers is challenging. One solution could be to install a higher T-bar floor in the container. This floor will lower the jet Reynolds number at the inlet and help suppress the Coanda effect so that the flow does not directly go around the corner. A more straightforward solution would be to opt for improved ventilated packaging that induces less recirculation.

If this flow-driven hot spot does not exist but only appears in fluid-dynamics simulations, we urgently need to find the cause and solve it. We would need high-resolution experiments that monitor airflow and fruit cooling in this zone to compare with the fluid-dynamics simulations. Once the discrepancies are identified, the solution is to include the physical aspects that increase accuracy by suppressing the simulated recirculation zone in the model. However, it is most likely that the recirculation zone occurs in some ventilated cargos but not all since it depends on the packaging systems. Influence parameters include plastic bags in the cartons, vent-hole design, number of cartons per pallet, cartons with or without a lid, and the wooden pallet design. Therefore, we must identify which physical influence parameters invoke the recirculation in simulations and reality. The turbulence modeling could play a key role in accurately predicting the air jet in the T-bar floor and the Coanda effect. We might want to step away from Reynolds-averaged Navier Stokes models, such as the k-ε model.

Furthermore, we can also model the ventilated packages and the fruit discretely instead of via the porous medium approach. This way, we identify the real flow patterns in the pallets and avoid averaging out the presence of discrete air jets with the porous medium approach. The computational cost will be tremendous. One study required 40 million control volumes (Wu et al., 2019) to simulate just a single pallet of citrus fruit.

We need to urgently clarify if this recirculation-driven phenomenon is present or not in the ventilated cargo of perishables, such as fruit. Actual proof would still require detailed full-scale experiments. Thousands of refrigerated containers are shipped yearly with refrigerated perishables, which are continuously rising. Therefore, improving the airflow and reducing hot spots considerably impact the quality of the world's produce.

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AUTHOR CONTRIBUTIONS

T.D. conceptualized the study and acquired funding; T.D. did the project administration; T.D. performed the investigation, developed the methodology, and executed the work with key input of C.S and T.B.; T.D. wrote the original draft of the paper; T.D. and J.S. did the visualization; C.S., J.S., P.C., T.B, C.V. and L.L performed critical review and editing.

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