CFD MODELLING OF DEVIATING AIRFLOW AND COOLING CONDITIONS IN BANANA CONTAINERS

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Abstract

Temperature variations in reefer containers with fruits regularly occur due to deviating airflow and cooling conditions (DACCs). There is little knowledge about whether DACCs affect only a small area or the complete container load. In seven tests in containers from Costa Rica to Europe since 2009, we observed a high level of spatial temperature variations. Banana pallets are neither in a perfect rectangular shape nor do they completely fit the inward container dimension, resulting in large variations of gap widths. The effect is enhanced by the biological variance of respiration activity.

We set up a computational fluid dynamics simulation for the airflow and temperature in a container loaded with bananas to provide a better understanding of DACC effects because detailed experimental evaluation was not feasible in a commercial cold chain. The complex geometrics of a container with 960 boxes had to be reduced to a 2-dimensional model.

Almost all DACCs had a predominant local effect. For the following DACCs cooling was slower only in some affected boxes: (a) blocking of a horizontal channel in one pallet and (b) narrow vertical gaps. Double heat generation by higher respiration activity in part of one pallet had also a predominant local effect.

The temperature was between 1.7°C and 4.7°C higher than for the reference case with normal airflow conditions at 48 hours after the start of cooling. Only circulation bypasses by packing mistakes and a reduction of inlet air speed had a significant effect on the average container temperature of +0.6°C maximum. Quality problems and losses of full container loads, as regularly reported in ocean transport, cannot be explained by a single DACC according to our simulation results. A combination of at least two DACCs is necessary to cause severe quality problems.

Keywords: Temperature mapping, air flow simulation, cold chain, hot spot, reefer container

INTRODUCTION AND PREVIOUS EXPERIMENTS

Bananas are one of the most challenging fruits for reefer transportation. Even in the ‘green’ unripe state, they release high amounts of thermal energy by biological activity in a range between 16 and 50 $W \cdot t^{-1}$ (Jedermann et al., 2014) at 15°C, depending on atmospheric conditions, with increasing values for higher temperatures and for more mature bananas. Furthermore, they are sensitive to chilling injuries. Supply air temperature should never be below 13°C, meaning that the cooling capacity of a unit is not fully used.

Bananas for the European market are mostly imported from Central America. An increasing share of the bananas is transported in reefer containers. In our tests, twenty pallets were stowed per 40-foot container. Each pallet contained 48 boxes in six stacks of eight boxes height. Inside the box, the bananas were packed with a polyethylene film bag to prevent moisture and weight loss. The airflow inside the bags was limited to buoyancy forces without direct influence from the outside airflow.

During the two weeks of ocean transport, the pallets were cooled down from about 25°C to about 14°C. During seven tests in containers from Costa Rica to Europe since 2009 with button-cell type data loggers, we observed a high level of spatial temperature variation inside the container (Jedermann et al., 2013). The DS1922L iButton (Maxim 2015) contains

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temperature sensor, battery and memory in housing with diameter of 17.35 mm. Up to 62 iButtons per container were placed in the centre of selected boxes between the bananas. The sampling interval was programmed to 10 minutes. For additional tests ashore, the sampling interval was reduced to 2.5 minutes. Temperature tolerances were measured per logger in a climatic chamber after the field tests. By subtracting these offsets from the field test measurements, the accuracy of the data loggers was improved to $\sigma<0.1°C$.

For simplicity we use the following definitions in the remainder of this paper: '**Tier**' stands for the vertical position of a box in a stack, starting with 1 for the bottom position to 8 for the top position. '**Gap**' refers the vertical airspace between pallets. The term '**horizontal**' refers to airflow or position of a box or sensor along the axis from cooling unit to the door.

The temperature difference between banana boxes with fast cooling and those with slower cooling arrived at a maximum about 48 hours after the start of cooling. Only part of the temperature variation can be explained by a spatial trend. In the vertical direction, the hottest box was found in tier 5 or 6, with a temperature of 3.4°C higher than in the lowest tier 1 (Figure 1a,b). In the horizontal direction, the temperature increased from the cooling unit side to the door side by about 2.4°C (Figure 1c).

Several effects led to further temperature variations. For example, measurements in the same tier and the same distance to the cooling unit were scattered with a standard deviation of ± 1.07°C around the trend line in Figure 1c. We summarize these effects under the term deviating airflow and cooling conditions (**DACC**s).

DACCs are often caused by an irregular width of gaps. Banana pallets are neither in a perfect rectangular shape nor do they completely fit the inward container dimension, resulting in gaps with a range from being almost completely closed to about 6 cm. In a test ashore, boxes beside a gap of 4 cm were on average 0.36°C cooler than boxes beside a gap of 2 cm (Figure 2a) after a set point change from 16°C to 13°C.

The effect is enhanced by the biological variance of respiration activity. In a further test, some pallets were stowed in a container, which had been stored close to a ripening room overnight. During the night, they were exposed to low concentrations of ethylene by mistake. In some of these pallets, the respiration activity was so high that is was not possible to decrease the temperature under the cooling conditions inside the container (Figure 2b). Strictly speaking, increased respiration activity is not a problem of the cooling system. But for simplicity we also summarized it under the term DACCs.

Blocking of ventilation holes at the side of the boxes and of air channels between the boxes inside the pallet is assumed to be a further contributor to DACCs.

The need for simulation

Losses in containerized banana transportation are regularly reported (e.g. Federal Office for Agriculture and Food, 2015). Occasionally, a full container load is lost due to an uncontrolled start of the ripening process in most pallets. So far, there is only little knowledge regarding whether these losses can be attributed to a single DACC or rather require a combination of several disadvantageous influences. Neither do we know whether DACCs affect only a small area or the complete container load.

Due to the restrictions in a commercial cold chain, we had only very little freedom to design arbitrary experimental setups. After arrival in Europe, we were only allowed to modify the set point over two days by a maximum of +3°C. Conditions with a possible harmful effect could also only be applied during short tests ashore. The installation for ocean transport tests turned out to be very laborious, including customs formalities for technical equipment, high travelling costs, non-English speaking staff and missing technical infrastructure at rural production farms. Because of these limited experimental facilities, airflow simulations provide the method of choice to test the effect of different DACCs in isolation. The goal of this study is to simulate different DACCs and compare their relative magnitude and their effect on neighbouring boxes and pallets.

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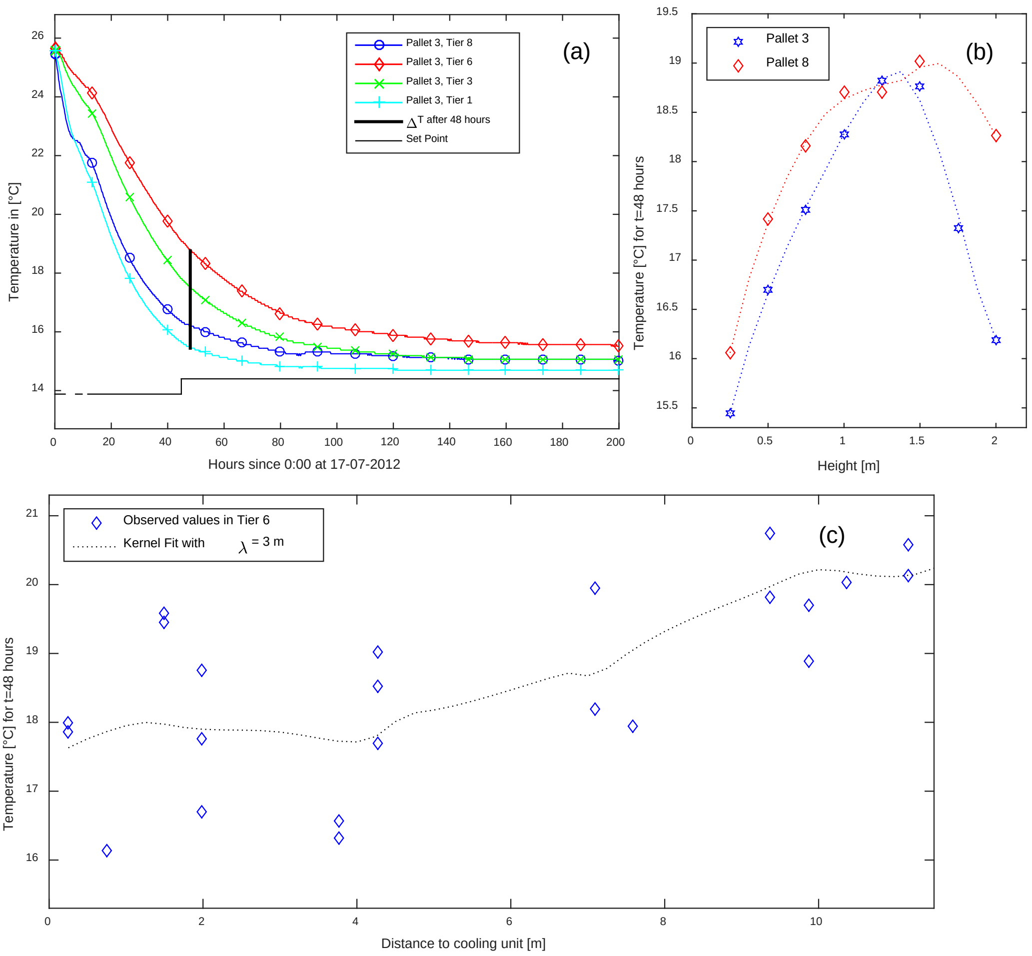

Figure 1. Recorded temperature data inside a banana container during transportation from Costa Rica to Europe. (a) Temperature over time curves in one vertical stack, (b) Temperature at 48 hours after the start of cooling as a function of height in the stack, (c) Temperature as a function of the horizontal position of sensors in tier 6.

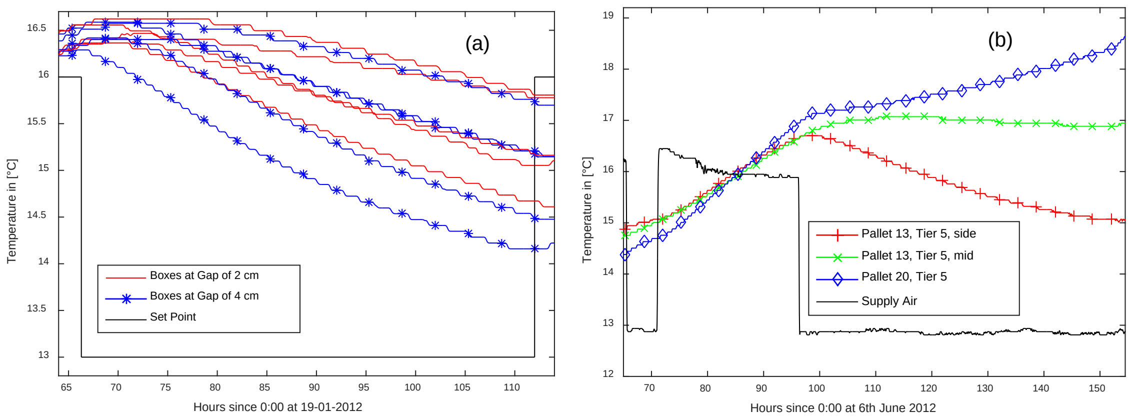

Figure 2. Temperature curves recorded in two different tests ashore. (a) Influence of gap width, (b) development of a hot spot in pallet 20 by increased biological activity.

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Outline

In the next section, we describe the setup for the computational fluid dynamics (CFD) simulation software. Simulation results are presented and discussed in section 3, including a comparison of the importance of different DACCs and of the limitation of the simulation experiments. Final conclusions are summarized in section 4.

METHOD FOR SIMULATION AND MODEL SETUP

The CFD simulations were carried out by Comsol Multiphysics in version 5.0 (Comsol 2014a). The conjugate heat transfer model (Comsol 2014b) combines turbulent airflow (k-ε model) and mechanisms of heat transfer in fluids and solids.

Model geometry

Turbulent airflow is one of the most laborious simulations in CFD. Therefore, we had to abandon the approach to simulate a full 3-dimensional geometry with 960 boxes and narrow gaps. Instead, we restricted the simulation to a 2-dimensional (2D) model consisting of a row of ten pallets with eight tiers in two stacks each. In total, 160 boxes of 25 cm height and 50 cm length were simulated (width of 40 cm ignored).

The geometrical setup of the simulation included a foam block on top of the last pallet at the door side (Figure 3a), which was placed there to avoid a circulation bypass in the airflow. A baffle plate of 6 cm length below the first pallet prevented a short-cut along the side of the cooling unit.

In our 2D model, the pallets had only two vertical sides in direct contact with the air stream, instead of four in the real 3D scenario. Therefore, the gap width between the pallets was increased to 4 cm, which was slightly higher than the average gap width observed in the experiments. The horizontal distance of boxes within a pallet was set to 0.4 cm.

Air inlet

Cooling air with a temperature of 13°C flowed from the Thermoking Magnum Plus unit (Ingersoll Rand, 2008) into the container over an inlet of 8 cm height. The inlet speed was set to 8 $m \cdot s^{-1}$, equivalent to 5276 $m^3 \cdot h^{-1}$ for a width of 2.29 m. For a supply voltage of 460 Volt / 60 Hz and a counter pressure between 1 and 2 mBar, this was well in accordance with the manufacturer data sheet.

Model for banana boxes

Parameters for the cardboard outside wall of the boxes were taken from Praeger et al. (2015) with thickness d_C=0.8 cm, thermal capacity C_C=1070 $J \cdot kg^{-1} \cdot K^{-1}$, specific density ρ_C=150 $kg \cdot m^{-3}$ and thermal conductivity κ_C=0.05 $W \cdot m^{-1} \cdot K^{-1}$.

The content of the boxes was simulated as an air-banana mixture with uniform physical properties. Physical properties for bananas are known from the literature with C_B=3350 $J \cdot kg^{-1} \cdot K^{-1}$ (Wild, Scharnow and Rühmann, 2015), ρ_B=1100 $kg \cdot m^{-3}$ and κ_B=0.249 to 0.458 $W \cdot m^{-1} \cdot K^{-1}$ (Bart-Plange et al., 2012). The value of the first two properties for the mixture could be directly obtained by multiplication with the volume content of 0.4. The thermal conductivity of the mixture κ_{Mix} was caused by conduction through the bananas and convection in the free airspace inside the closed film bag. The value for κ_{Mix} could not be directly calculated; different values were tested, and, finally, κ_{Mix}=0.1 $W \cdot m^{-1} \cdot K^{-1}$ was selected for giving the best fit between the simulated and experimental temperature over time curves.

The banana boxes contained a small free airspace in the corners and between the top of the film bag and the cardboard. Because of the complex 3D geometry, the cooling effect by horizontal airflow through the boxes was hard to obtain. For the 2D simulation, we simplified the horizontal flow to an air channel of 1 cm height, the height, which gave the best fit with the experimental data.

The heat generation by respiration activity was set to 24.3 W·t[-1] at 13°C according to an average value of our experiments. For a temperature change of 10°C, the respiration activity increased by a factor of Q_{10}=3. This Q_{10} value gave a good fit between the experimental data and an empirical time-variant single-box model in previous simulations (Jedermann et al., 2013).

Model convergence

The generated mesh with a normal size consisted of 920,000 domain elements. A direct simulation of the conjugated model was only feasible for a maximum of five pallets. For a higher number of pallets, we encountered severe convergence problems. As a remedy for this problem, we had to split turbulent airflow and heat transfer simulation. The first stationary model simulated airflow for a fixed temperature of 13°C. The surfaces of the boxes cooled down within a few hours, and only the centre of the boxes, which were not in direct contact with the air stream, remained for a longer period of time at the initial temperature of 25°C. The influence of temperature differences on the airflow was, therefore, considered as a minor effect and neglected. In the second step, a time-variant heat-transfer model was calculated based on fixed airflow according to the first model.

RESULTS OF THE SIMULATION

The effect of different DACCs was compared according to the spatial temperature distribution 48 hours after the start of cooling. The values for average ΔT_{AV} and local maximum ΔT_{max} temperature offsets in the following were calculated as differences from a container with completely regular gap widths and heat generation per box as shown in Figure 3a. Even under these ideal conditions, the temperature varied by 3.82°C from 16.54 to 20.36°C.

Three groups of DACCs were simulated, including variations of the gap width between pallets, local triggers inside a single pallet and general disturbances of the airflow by circulation bypasses or reduced ventilation speed. All DACCs had a negative effect on the temperature distribution. Most effects were local with higher temperature in some boxes with ΔT_{max} between 1°C and 8.5°C. Only general airflow disturbances showed a significant effect on the average container temperature with ΔT_{AV} of up to 0.6°C. The detailed results are summarized in Figure 4a.

Variations in the gap width between the pallets can hardly be avoided during stowage in a container. A narrow gap of 2 cm width between P5 (Pallet 5) and P6 led to higher temperatures in P5 with ΔT_{max}=1.69°C and a slight increase in P6 but hardly affected the remainder of the container (Figure 3b). A random shift of all pallets with σ=±1 cm, which is the more realistic case, resulted in ΔT_{max}=0.99°C.

Among the **General airflow disturbances**, a reduction of the inlet air speed by 20% led to the highest increase of the average container temperature by ΔT_{AV}=0.60°C, followed by the missing foam block with ΔT_{AV}=0.51°C. The latter produced a large local peak in the lower tiers of P10 with ΔT_{max}=5.78°C. A circulation bypass of the airflow through a large gap between P1 and P2 of 10 cm width was less severe. The average temperature increased only by ΔT_{AV}=0.25°C. This circulation bypass was the DACC with the longest influence range. The temperature peak was found at a distance of 1.7 m to the gap with ΔT_{max}=3.48°C (Figure 3c).

Local triggers assigned to single boxes created significant local peaks but hardly affected any other boxes. Blocking a horizontal channel in P5 affected only tiers 5 and 6 above and below the obstacle with ΔT_{max}=4.64°C (Figure 3d). Doubling the respiration activity in six boxes in P5 with ΔT_{max}=2.60°C also had only a negligible effect on neighbouring boxes.

Figure 4b shows the time-diagram for the hottest boxes related to these two DACCs. Cooling is slower but still possible. But, for the blocked channel, the temperature is after 180 hours of cooling still above 16°C, with a risk of starting an unwanted ripening process. If both a blocked channel and increased respiration activity coincide in the same box, the box

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develops into a hot spot were lowering the temperature is almost impossible ('x' marker in Figure 4b). ΔT_{max} increased to 8.48°C.

Limitations of the simulation for banana containers

The reduction of the simulation to a 2D model entailed several problems as a comparison with the experimental results shows.

There was a significant horizontal variation inside the pallets between the side towards the cooling unit and the side towards the door. The former was on average 0.99°C warmer. This effect was much larger than in the experimental data and has its cause in the limitations of the 2D model. The 2D model gives a wrong relation between vertical and horizontal surfaces of the box. In order to compensate for two missing vertical surfaces, the horizontal airflow was overestimated. Furthermore, the vertical airflow through the corners inside the boxes could not be modelled in two dimensions.

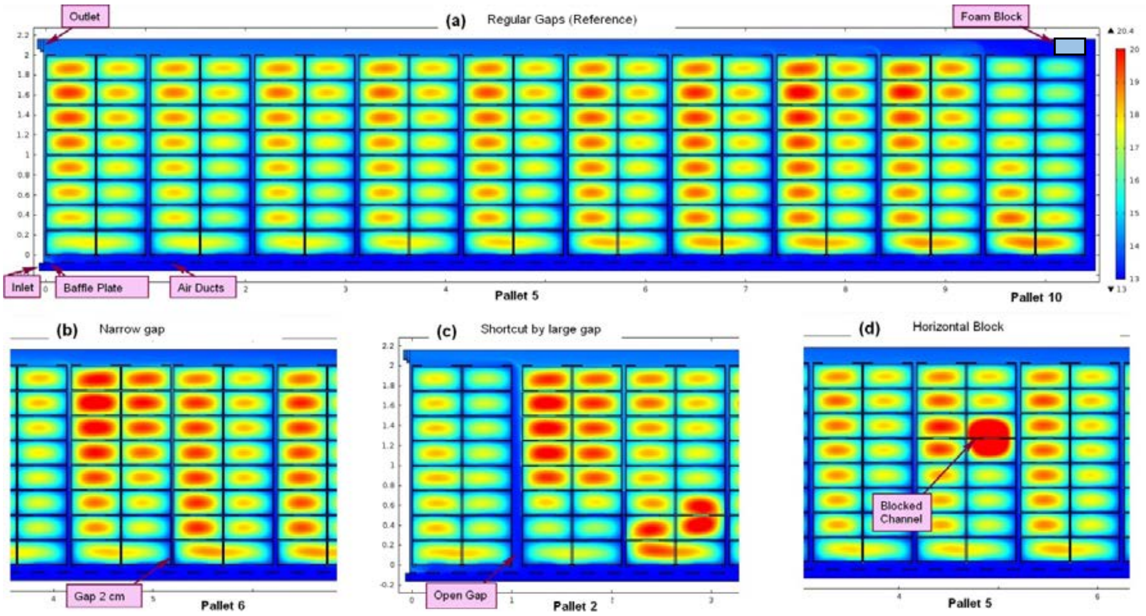

Figure 3: Temperature distribution 48 hours after the start of cooling. (a) Reference setup with regular gaps and detail view for 3 different DACCs: narrow gap of 2 cm width (b), circulation bypass through large gap of 10 cm (c), and blocked horizontal channel between 2 boxes (d).

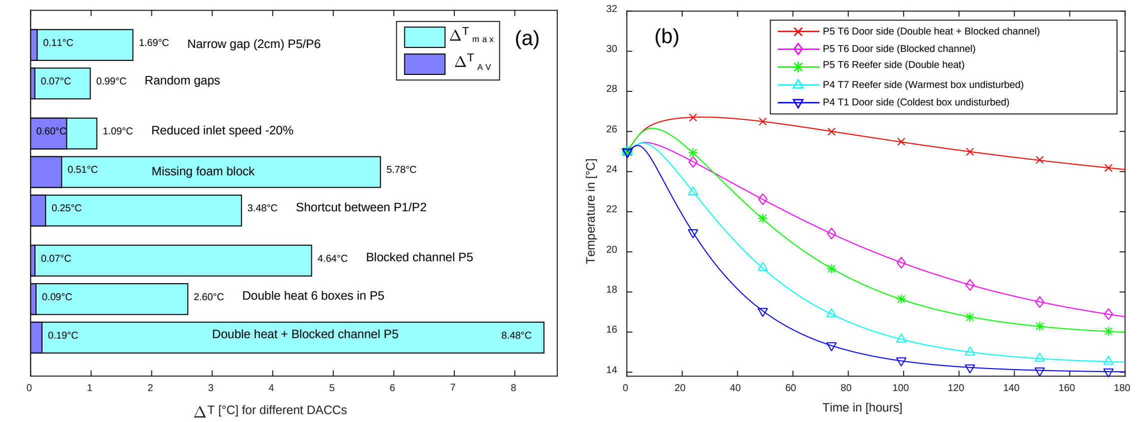

Figure 4. (a) The temperature increase of different DACCs compared to the reference with regular gaps, 48 hours after the start of cooling. (b) Time curves for local disturbances and a comparison with the undisturbed temperature in pallet 4.

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The global temperature trend could not be exactly reproduced by the simulation. The vertical temperature change was less than in the simulation. The hottest box was found in tier 7 instead of tiers 5 or 6.

The first pallet at the reefer unit cooled down slower than did P2 and P3. This is in accordance with cooling problems in the pallets at the air inlet found in earlier experiments with a different container. But such an effect was not observed in the current measurements with a newer cooling unit as shown in Figure 1c. The influence of the baffle plate was overestimated in the simulation.

Pallet 10 at the door side was excluded from further evaluation because it showed much lower temperatures as in the experimental data. The problems at the door side are assumed to also be caused by an overestimation of the horizontal airflow.

A comparison of the shape of the time-curves shows that cooling started much faster in the experimental data. This effect can be best explained by problems of the measurement setup. The simulation predicted banana pulp temperature, but the data loggers measured the air temperature inside the film bag instead. Air reacts faster to cooling from the outside. But a slower initial change of the banana temperature is physically correct; temperature changes take time to penetrate to the centre of the box.

In regard to these problems, a 2D simulation cannot provide an exact temperature prediction. But at least it can give a raw estimation of the magnitude of temperature variations caused by different DACCs and lead to a better understanding of their relation to quality problems.

DACCs as an explanation for quality problems

The question arises whether DACCs provide a sufficient explanation for the quality problems in banana ocean transport that are regularly reported.

The spatial temperature distribution inside a reefer container is anything but uniform. Both experimental and simulation data confirm a trend for higher temperatures in tiers 5 to 7 and towards the door side. The trend is overlaid by local variations caused by varying gap widths and differences in respiration activity. Respiration activity is increased by, for example, scratches and pressure marks due to improper handling and by fungal infections of single boxes.

Wild et al. (2015) describe circulation bypasses by large gaps between pallets as a major problem. But, in our simulation, the effect was rather moderate, with an average temperature increase of ΔT_{AV}=0.25°C. A missing foam block or deficient inlet ventilation speed are more severe with ΔT_{AV} up to 0.6°C, but they neither are sufficient to create a local hot spot nor to explain the spoilage of a whole container load. Other DACCs had only a local effect. Container-wide problems can, therefore not be attributed to a single DACC.

SUMMARY AND CONCLUSIONS

Simulation of the cooling process for food products often entails complex geometries. Some simplifications cannot be avoided for it is almost impossible to model each banana in each box. The reduction to a 2D model had several problems as described above. So, a 3D simulation is highly desirable but very challenging to perform. Even for the simplified 2D model, a computation time of 2½ hours was necessary on an i5-Quad-Core workstation (16 GByte RAM, 3.3 GHz CPU and 1333 MHz Bus). The time variant model required 2.9 GBytes of disk space. For a 3D model, the required resources would increase by some powers of 10.

But the accuracy of the 2D model is still sufficient for a general comparison and evaluation of different DACCs, although no exact quantitative prediction is possible. All DACCs led to a temperature increase. Except for the missing foam block and large gaps, local triggers had only a local temperature effect. Local effects with high temperature peaks were predominant for almost all DACCs. Blocking a horizontal channel inside one pallet created the highest local temperature difference, compared to a setup with regular gaps and channels of ΔT_{max}>4°C.

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The simulations showed that it is not possible to explain critical cooling problems by a single DACC. At least two DACCs have to coincide to create a hot spot as in the example in Figure 4b. Further biological factors have to be taken into consideration for a better understanding of quality problems in banana transportation. Ethylene gas is produced during ripening but also triggers the ripening process. Because ethylene penetrates through the film package, high biological activity in one box can trigger ripening of the whole container by this autocatalytic effect (Jedermann et al, 2014). This risk for container-wide infection is well known, although there are neither measurements for changes of ethylene concentration during transportation nor is an exact model available.

A chain of events that leads to the loss of a full container load can be, for example, caused by the following: (a) a temperature increase in two boxes by blocked ventilation holes and a narrow gap between pallets, (b) higher respiration activity by pressure marks and (c) increased ethylene production and the start of the autocatalytic effect.

A reliable detection of DACCs is only possible with a high number of temperature measurement points. Otherwise, the probability that DACCs are not noticed is very high. The estimation of the container's average temperature also requires a higher number of sensors. Otherwise, merely local deviations can be misinterpreted as global change.

In this article, we evaluated the effect of several DACCs that contribute to the cooling problems of banana containers. Tracing these DACCs by multipoint temperature measurement gives valuable information to predict the risk of quality problems.

ACKNOWLEDGEMENT

This research was supported by the Federal Ministry of Education and Research, Germany under reference number 01IA10001 'The Intelligent Container' and by the German Research Foundation (DFG) for the project 'In-network data analysis of spatially distributed quantities' under grant Je722/1. Further information: *www.intelligentcontainer.com.*

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