Manuscript ID: 54
DOI: 10.18462/iir.icr.2019.0054

An airflow enhancing floor cover to improve temperature uniformity in maritime refrigerated containers

Leo J.S. LUKASSE, Marcel G. STAAL, Edo B. WISSINK
Wageningen UR Food & Biobased Research
6700 AA Wageningen, The Netherlands, leo.lukasse@wur.nl

ABSTRACT

In maritime refrigerated containers air is drawn from just below the ceiling into the refrigeration unit, where it is cooled to the desired temperature and then supplied into 60 mm high longitudinal T-bars, which make up the container floor. Cargo temperatures at the door-end are usually 2 °C higher than the supply air temperature. A better air flow distribution could improve the temperature uniformity. In earlier work four different air flow enhancing floor cover shapes were tested in a climate chamber.
The aim of this study is to assess the effectiveness of the best of those four air flow enhancing floor covers in a field experiment with commercial container shipments from South Africa to The Netherlands. Three test containers contained that air flow enhancing floor cover, three reference containers did not. All other parameters were, to the extent possible, the same for all containers.
Based on the test results it is concluded that the tested air flow enhancing floor cover reduces the difference between the warmest and the coldest cargo temperature in shipments of precooled grapes by approximately 30%.
Keywords: air distribution, air flow, duct, refrigerated container, temperature difference.

1. INTRODUCTION

In maritime refrigerated containers air is drawn from just below the ceiling into the refrigeration unit, where it is cooled to the desired temperature and then supplied into 60 mm high longitudinal T-bars, which make up the container floor. Door-end temperatures are usually up to 2 °C higher than supply air temperature.
In earlier work Lukasse & Staal (2018) found that air flow enhancing T-bar floor covers (hereinafter referred to as 'air flow enhancers') can help to guide more air towards the door-end and hence create more uniform temperatures. The subject of this study is a large scale field experiment to assess the effectiveness of the best air flow enhancer found by Lukasse & Staal (2018).
The aim is to experimentally assess the effect of that air flow enhancer on temperature gradients during real reefer container transport of grapes.

2. THEORY

2.1 Air flow distribution in reefer containers

As already explained in Lukasse & Staal (2018) for climate control in contained spaces conditioned air needs to be guided to the place where it is needed. This is typically done by air ducts. For example virtually every office building has these air ducts, usually hidden behind the ceilings. In the design of air ducts the diameter of the ducts is tuned to air flow rates: wide ducts close to the air conditioning unit, and small ducts delivering the air to the most distant office space. The relatively high air flow resistance of the air duct outlets, as compared to the resistance inside the ducts, helps to achieve a relatively even air distribution throughout the office building.

Reefer containers have a T-floor. The T-floor exists of 35 longitudinal T-bars extending over the complete length of the container's cargo space (see Fig. 1). T-bars are the air ducts of reefer containers, but their design is rudimentary: the cross section is the same over the complete length, and the air flow resistance of the air outlet at the top of the T-bars is very low. Hence most air escapes from the ducts before reaching the container door-end if no further measures are taken. Therefore dedicated air flow enhancers or cargo stowage patterns, closing off the right areas of the T-bar top openings, are a means to guide air to where it is needed and thus improve temperature management. That's why the use of fillers, also known as dunnage is recommended (see e.g. anonymous, no year; de Haan, no year; Montsma et al., 2011). Also covering parts of the floor has been reported (Cronje et al., 2015; Defraeye et al., 2016; Elíasson et al., 2013). Lawton (1995; 1999) presents an L-shaped board placed against / on top of the door-end pallets with the aim to exploit the fact that air in side T-bars warms more than in centre T-bars. The test results reported in Lawton (1999) concern a hand-stowed cargo, while there is no mentioning of palletized cargo. The system is especially meant for tight stows. For loads of trays, specifically facilitating horizontal air flow, even more complex air guidance systems have been proposed (Dodd & Worthington-Smith, 2006).
Lukasse & Staal (2018) were the first to propose a trapezoid shape air flow enhancer, covering the major part of the floor. They report a nearly 50% reduction of cargo temperature differences, measured in climate chamber tests. The subject of this study is to assess the effectiveness of that air flow enhancer in real transports.

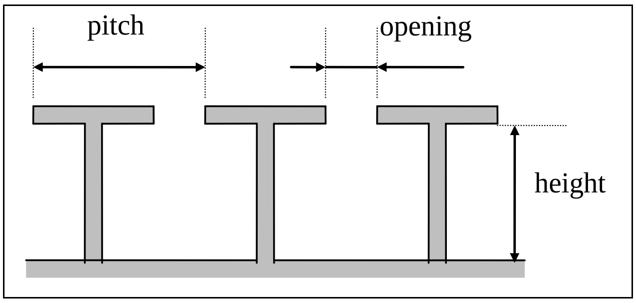

Fig. 1, schematic cross section of a T-bar floor section. Standard dimensions in 40ft HC reefers: height = 60 mm, pitch = 63.5 mm, opening = 35 mm.

2.2 Key performance indicators

In an experimental study on temperature distribution in reefer containers lots of temperature measurements need to be evaluated, and somehow condensed to one or a few simple measures. In climate chamber tests one would typically create a pure steady state. That is not possible in field experiments. Therefore a practical approach needs to be taken.
Table 1 lists the key performance indicators used to evaluate the data collected by the experiment's 31 loggers per container, which are more or less evenly distributed throughout the container load. The KPIs will be explained in the following paragraphs.

Table 1, key performance indicators (KPIs) used to evaluate the results

Name	Description
$\overline{T}$	average over all loggers and all sampling instants
std(*T*)	standard deviation over all loggers and all sampling instants
$(warmest\text{-}coldest)_{all\_trip}$	Warmest time-averaged sensor minus coldest time-averaged sensor in a container. The time-average is taken over the whole trip.
$(warmest\text{-}coldest)_{hot\_ambient}$	Warmest time-averaged sensor minus coldest time-averaged sensor in a container. The time-average is taken over the 48 hours period where ambient temperature was highest.
$(coldest\ sensor\ ID)_{hot\_ambient}$	Location of the sensor which recorded the coldest time-averaged temperature during the 48 hours period where ambient temperature was lowest.
$(warmest\ sensor\ ID)_{hot\_ambient}$	Location of the sensor which recorded the warmest time-averaged temperature during the 48 hours period where ambient temperature was highest.

$\overline{T}$ is just one number, being the average over the temperatures recorded by all loggers over all sampling instants from stuffing till unstuffing:

$$\overline{T} = \frac{\sum_{ti=1}^{Ni}\sum_{s=1}^{Si} T(s,ti)}{Ni*Si} \qquad [°C] \qquad (1)$$

with

$T(s,ti)$ = the temperature recorded by logger s on time instant ti.

Si = total number of loggers per container (= 31).

Ni = total number of sampling instants from stuffing till unstuffing.

Reefer containers set at -0.5 °C control the supply air temperature measured by the unit's supply air temperature sensor to set point. A low mean temperature is therefore indicative of more uniform temperatures. However the unit's supply air temperature sensor is not perfect. A sensor offset of e.g. +0.1 °C reduces the temperature at all locations in the container by 0.1 °C, thus reducing the mean temperature, without affecting temperature uniformity. Hence solely analysing mean temperature is not good enough.

Standard deviation does not suffer the above described weakness. The standard deviation $std(T)$ of the temperature readings recorded by all loggers over all sampling instants from stuffing till unstuffing:

$$std(T) = \sqrt{\frac{1}{Ni*Si-1}\sum_{ti=1}^{Ni}\sum_{s=1}^{Si}(T(s,ti) - mean\ temp.)^2} \quad [°C] \quad (2)$$

In general, a low standard deviation indicates that the data points tend to be close to the mean value of the data set. Assuming normally distributed temperature readings, 68% of the readings are within the range $\overline{T} \pm std(T)$. Hence, the lower $std(T)$ the more uniform the temperatures within the container.

Another criterion, insensitive to possible unit sensor faults, is the difference between the warmest and the coldest logger. $(warmest\text{-}coldest)_{all\_trip}$ is the warmest time-averaged logger minus coldest time-averaged logger in a container, where the time-average is taken over the whole trip:

$$(warmest - coldest)_{all\_trip} = \max_{s}\left(\frac{\sum_{ti=1}^{Ni} T(s,ti)}{Ni}\right) - \min_{s}\left(\frac{\sum_{ti=1}^{Ni} T(s,ti)}{Ni}\right) \quad [°C] \quad (3)$$

When ambient temperature is highest the temperature gradients inside the container tend to be biggest. Therefore it is informative to analyse the difference between the warmest and the coldest logger specifically during the period where ambient temperature was highest, this is done in $(warmest\text{-}coldest)_{hot\_ambient}$:

$$(warmest - coldest)_{hot\_ambient} = \max_{s}\left(\frac{\sum_{ti=ths}^{the} T(s,ti)}{the-ths+1}\right) - \min_{s}\left(\frac{\sum_{ti=ths}^{the} T(s,ti)}{the-ths+1}\right) \quad [°C] \quad (4)$$

where

ths = time instant defining the start of the period of hot ambient.

the = time instant defining the end of the period of hot ambient.

Finally, it is informative to know the locations of the coldest and the warmest spots. These are given in $(coldest\ sensor\ ID)_{hot\_ambient}$ and $(warmest\ sensor\ ID)_{hot\_ambient}$:

$$(coldest\ sensor\ ID)_{hot\_ambient} = \operatorname*{argmin}_{s}\left(\frac{\sum_{ti=ths}^{the} T(s,ti)}{the-ths+1}\right) \quad [-] \quad (5)$$

$$(warmest\ sensor\ ID)_{hot\_ambient} = \operatorname*{argmax}_{s}\left(\frac{\sum_{ti=ths}^{the} T(s,ti)}{the-ths+1}\right) \quad [-] \quad (6)$$

Apart from the KPIs described in Table 1 temperature contour plots for cross sections of the containers will be made to visualize temperature gradients throughout the containers at some moments during the trip.

3. MATERIALS AND METHODS

A field experiment was done in a commercial shipment of six standard 40 ft. HC reefer containers travelling at the same time in the same corridor. The three test containers contained an air flow enhancer, the three reference containers did not contain the air flow enhancer. All other parameters were as much as possible identical: all containers are 40 ft. HC reefers with Carrier PrimeLine refrigeration units, set point -0.5 °C, fresh air exchange closed. Manufacturing date is 2015 for five containers, and 2009 for one container. All containers are positioned on deck on tier 1, none of them at the outer bay. Hence all of them are shaded from direct sunlight and experience approx. the same ambient temperature. See Table 2 for detailed specifications of the journey. Just before unstuffing the data recordings from the refrigeration units' controllers were retrieved.

Table 2, trip details.

Characteristic	Value
date of stuffing	21-01-2017
place of stuffing	Gouda, South Africa
date of loading on vessel	26-01-2017
date of unloading from vessel	13-02-2017
date of unstuffing	14-02-2017
place of unstuffing	Barendrecht, The Netherlands
port of loading	Cape Town, South Africa
port of unloading	Rotterdam, The Netherlands

3.1 Packaging and stowage

Each container was stowed with 21 pallets according to the floorplan sketched in Fig. 3. Pallet 19 is a europallet (80 x 120 cm), all other pallets are standard pallets (100 x 120 cm). All grapes are cultivar Thompson Seedless, class 1, of regular berry size.
A standard pallet carries 5 stacks of 25 trays. The height of the pallets stacked with trays is 2.40m. Trays are made of corrugated cardboard, and measure L x W x H = 60 x 40 x 9 cm. The bottom of the trays contains four vent openings of ø25mm. The trays have an open top. In the upper end of the long sides the trays have an opening of 33 x 220 mm, allowing for some horizontal air flow.
When filling a tray first one LDPE liner is placed. 11 Punnets with grapes are placed inside the liner. One SO_2 pad is placed on top of the punnets, then the liner is folded over the punnets and SO_2 pad, and non-hermetically closed with three small adhesive tapes. The liners contain 52 vent openings of ø6mm, evenly distributed over the sides, and the outer areas of top and bottom area folded around the 11 punnets.
The space for vertical air flow through a pallet load is very limited, because vent openings in the bottom of trays are limited in size and number and effectively blocked by the liner inside the tray. The space for horizontal air flow through a pallet load is also limited. The short sides of trays have no vent openings. The long sides of trays have a vent opening, but most of this area is obstructed by punnets folded in the liner. Moreover, the bottom of the next tray ± rests on top of the punnets in a tray. Possibly only the three stacks next to each other, with connected vent openings in the long tray sides, allow for some horizontal air flow through the pallet load. See Getahun et al. (2017) for possible consequences on temperature gradients.

3.2 Air flow enhancing T-bar floor cover

The field trial's airflow enhancers were provided by www.otflow.com. The company manufactures air flow enhancers based on the shape of the best air flow enhancer found by Lukasse & Staal (2018). For ease of manufacturing the dimensions deviate a little from those of the best floor cover reported in Lukasse & Staal (2018). See Fig. 2 for a sketch of the air flow enhancer used in this trial, including its dimensions.
Thanks to the trapezoid shape first the wall-side T-bars open up. The further from the unit-end the more side T-bars open up. This favourably stimulates air, leaving the T-bars before the door-end, to flow between the cargo and the wall, where heat enters the container. The air in the centre T-bars can only leave the T-bars near the door-end, and is used for removing heat from the door-end.

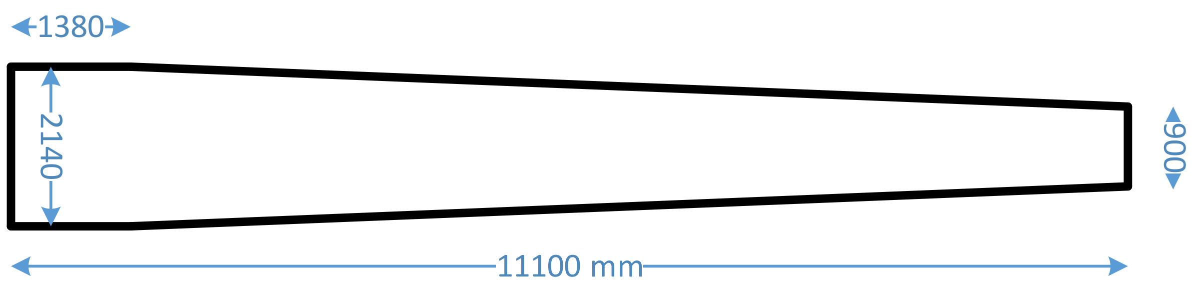

Fig. 2, sketch of air flow enhancer used in the experiment (dimensions in mm). The narrow end is placed at the door-end 580 mm from the end of the T-bar. As a result the 2140 mm wide section at the unit-end covers 1050 mm of T-bar and approx. 330 mm of baffle plate.

3.3 Measurements and instrumentation

In each container the temperatures were recorded with LogTag trix8 temperature loggers in 31 locations. All loggers are placed inside grape cartons. See Fig. 3 for the exact positions. The loggers have a 0.1 °C resolution. Temperatures were logged at 10 min. intervals. Loggers were pre- and post-calibrated at 0 °C and 30 °C. The maximum observed deviation from reference is 0.3 °C @ 30 °C, and only 0.1 °C @ 0 °C.

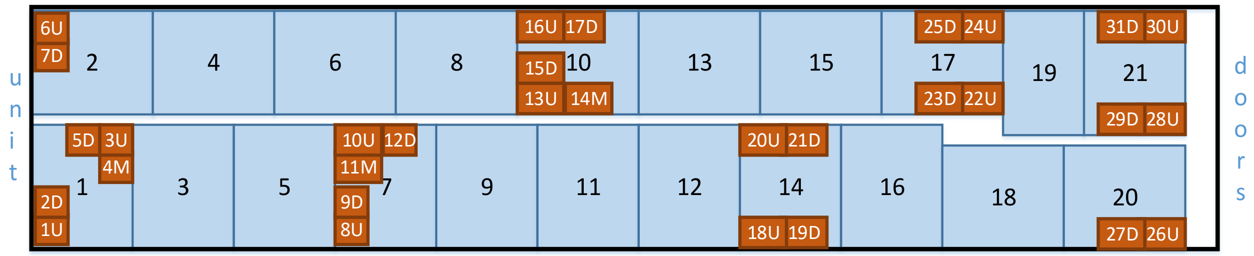

Fig. 3, placement of temperature recorders in all trial containers (top view). Red squares indicate positions of temperature logger numbers, U = Up (top layer), D = Down (bottom layer), M = Middle (layer 12). All Upper loggers are drawn in the right position. D- and M- loggers are positioned right underneath the U-loggers. It's just for ease of drawing in the 2D plane that they're drawn beside each other.

4. RESULTS

The data recordings retrieved from the refrigeration units' controllers (not shown) confirm that all units operated normally. The unit datalogs also recorded ambient temperature. The warmest ambient temperatures are recorded between 31-01-2017 and 02-02-2017, day 10 till 12 of the trial. In that period all six units record very similar ambient temperatures, fluctuating between 26 and 35 °C.

4.1 Temperatures recorded by experiment's loggers

Two of the 186 loggers went missing, all others recorded flawlessly. Table 3 lists the values for the KPIs defined in section 2.2. Columns 2 till 7 present the values for the six trial containers.

Table 3, key performance indicators per container (A till C are containers with air flow enhancer, and D till F without).

KPI	A	B	C	D	E	F
T	0.1	0.2	0.2	0.4	0.1	0.4
$std(T)$	0.6	0.6	0.5	0.8	0.7	0.7
$(warmest\text{-}coldest)_{all\_trip}$	1.6	2.0	1.6	2.4	2.3	2.9
$(warmest\text{-}coldest)_{hot\_ambient}$	2.2	2.6	1.9	2.9	3.2	3.6
$(coldest\ sensor\ ID)_{hot\_ambient}$	7	4	7	4	7	4
$(warmest\ sensor\ ID)_{hot\_ambient}$	30	18	27	18	26	28

In Table 3 the mean temperature in container E is distinctly lower than in containers D and F. The cause is unclear, but may *e.g.* be due to an offset of the unit's supply air temperature sensor. The other criteria are less ambiguous.

The three lowest standard deviations $std(T)$ are observed in the three containers with air flow enhancer, showing that the air flow enhancer helps to reduce temperature gradients. The criteria $(warmest\text{-}coldest)_{all\_trip}$ and $(warmest\text{-}coldest)_{hot\_ambient}$ show the same: the smallest temperature differences are found in the containers with air flow enhancer.

Compare $(warmest\text{-}coldest)_{all\_trip}$ for container (A, B, C) to container (D, E, F) to see that the air flow enhancer reduces the average difference between warmest and coldest temperature by approx. 30%. The same holds during the hottest part of the trip (see '(warmest-coldest), hot ambient' in Table 3).

The air flow enhancer has no clear effect on the location of the coldest spot: $(coldest\ sensor\ ID)_{hot\_ambient}$ is 4 in container B, D and F, and 7 in container A, C, and E. As illustrated in Fig. 3 both are located in the lower half of the two unit-end pallets.

The air flow enhancer has no clear effect on the location of the warmest spot: $(warmest\ sensor\ ID)_{hot\_ambient}$ is different in nearly every container, but all locations are in the door-end half of the container, mostly near the doors and against the ceiling. See Fig. 3 for illustration of sensor locations.

Another informative, though more qualitative, way of analysing temperatures is by looking at contour plots. Fig. 4 present the contour plots of temperatures for a side view of the containers at moment of the trip where ambient temperature was highest. The position of sensors in the 3D container is defined by (length, width, height). Fig. 4 plots in the 2D surface spanned by (length, height), using all 31 sensors per container. When at a specific (length, height)-combination multiple sensors are present, the figures present the average of those sensors. For example the temperature at (length, height) = (0, 0) is the average of the readings from sensors 2 and 7, while the temperature at (length, height) = (1.0 m., 0) is the reading of sensor 5 (see Fig. 3).

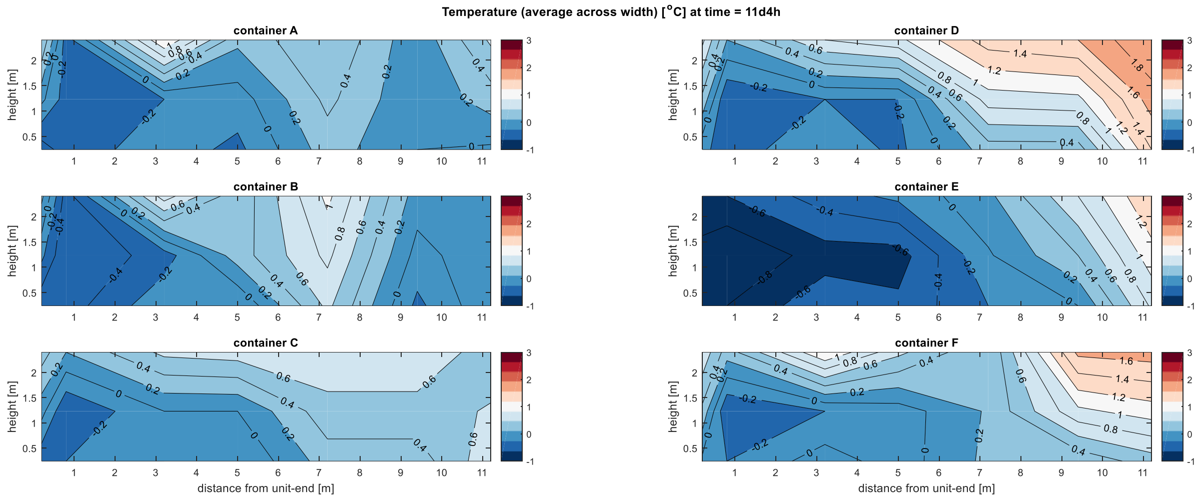

Fig. 4, contour plot of temperatures (side view) when ambient temperature is highest (30 ~ 35 °C).

Fig. 4 nicely visualizes the effectiveness of the air flow enhancer in suppressing high door-end temperatures during hot ambient conditions.

5. DISCUSSION

A priori a concern was whether the air flow enhancer would limit the air flow in the lower parts of pallets 1 till approx. 7 too much, resulting in hot spots due to autonomous heat production in that zone. None of that was observed. Apparently, in this low respiring fruit, the air flow enhancer allows for sufficient airflow in the lower regions of the pallets at the unit-end.

The trial containers were carried on deck. Many reefer containers are carried in holds below deck. In the holds ambient temperatures are usually higher than on deck. Hence it is to be expected that in many shipments air flow enhancers will have a bigger effect than observed in this trial.

The air flow enhancer has a positive effect on temperature uniformity. How to appreciate that? In many cases the temperature effect may be too small to observe an effect on quality. Then the use of the air flow enhancer may be pointless. On the other hand the air flow enhancer has a positive effect on temperature, and therefore mitigates the risk of temperature-related quality issues.

How will the air flow enhancer perform in transport of different products? This trial proves the positive temperature effect of this air flow enhancer for a load of properly precooled grapes. Of course the results apply to a wider range of commodities. The same effect is to be expected in any load of properly precooled low-respiring product.

Where to use the air flow enhancer in practice is a commercial decision: it's a trade-off between extra costs, extra work and extra waste against a reduced risk of temperature-related quality issues. A shipment reaching the receiver with temperature-related quality issues concentrated at the door-end would have benefited from the air flow enhancer. It is probably not useful to apply the air flow enhancer in every grape transport. The use of the air flow enhancer is first of all recommended in transports of weak batches of temperature-sensitive products, travelling in trade lanes with long transit times and hot ambient conditions.

Another potentially interesting application domain of the air flow enhancer is in cold treatment shipments. Cold treatment shipments are shipments during which a cold treatment is applied to the fruit. Cold treatments are treatments meant to control specific pests associated with the shipments of fruit. Many quarantine authorities of fruit importing countries have their own authorized cold treatment schedules. All of them are based on the principle that a given pest insect, *e.g.*

Mediterranean fruit fly, cannot survive a temperature colder than *treatment limit* °C for *duration* days. In cold treatment shipments three temperature recorders have to be inserted in the fruit in prescribed locations. At least one of those locations is in a pallet near the doors. Failing to maintain the three recorded temperatures below the *treatment limit* °C for *duration* days can have large commercial impacts. An air flow enhancer increases temperature uniformity and hence increases the chance of complying with the protocol. For more details on cold treatment see *e.g.* Anonymous (2016).
It remains to be seen how this air flow enhancer performs in commodities which are not properly precooled or have a high autonomous heat production. In the (large volume) banana trade it is standard practice to stuff without precooling the fruit. Moreover bananas have a relatively high autonomous heat production. Therefore a test on a load of palletized bananas would be informative. Most informative would be a long shipment through hot climates, *e.g.* Ecuador to Europe in containers placed below deck.
During stuffing it turned out that the air flow enhancer could not stand the weight of the forklift. The cover tore in many places. In the experiment the tears were repaired with duct tape. This has been reason for Otflow to revisit the design of the air flow enhancer after the experiment. In the new design it is installed in parts such that the forklifts don't need to drive on it during stuffing.

6. CONCLUSIONS

This trial's air flow enhancing floor cover reduces the temperature difference between warmest and coldest measurement location in shipments of precooled grapes by approx. 30%.

ACKNOWLEDGEMENTS

This work is part of the GreenCHAINge Vegetables & Fruits project work package 1, which was jointly commissioned by Bakker Barendrecht, VEZET, Albert Heijn and Maersk Line. The commissioning companies jointly financed the research, with financial support by Foundation TKI Horticulture (the Dutch Ministry of Economic Affairs) (project number 623 909 0301, TKI number 1406-031). We acknowledge all of them for their contribution.
Scientific field experiments like this are only possible if all parties involved, give their full cooperation. That happened. We are therefore very grateful for the excellent support received from the trial partners Maersk Line (represented by Steen Aunstrup and Johann Bosman), Bakker Barendrecht (represented by René Geelhoed), Horizon Fruits (represented by Cobus van der Merwe) and Otflow (represented by Otto de Groot).

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APPENDIX 1, TEST LOG

Date [dd-mm-yyyy]	**Description of activities**
14-12-2016	pre-calibration of temperature loggers
20-01-2017	preparation and labelling of experimental pallets
21-01-2017	stuffing of all six trial containers
13-02-2017	Retrieval of refrigeration units' data records in port of destination
14-02-2017	unstuffing of trial containers
15-02-2017	post-calibration of temperature loggers