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# Optimizing shipment of lily bulbs in 40ft reefer containers

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Report 1246

# Colophon

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# 1 Introduction

## 1.1 Context

Lily bulbs is an extremely temperature sensitive and precious commodity. Every now and then it happens that upon delivery the condition of the bulbs is disappointing.
Several measures can be taken to reduce the quality loss during transport, both in terms of reefer unit settings and in terms of stowage in the container. It is unclear what exactly is the consequence of which measure. Challenges and questions mentioned by the participants of this project are:

1. Most difficult are shipments starting early after harvest (half Jan. – end of Febr.). Then the peat is incompletely frozen when it leaves the storage room. Freezing it in the container is difficult due to much poorer air circulation as compared to the store.
2. Are there serious differences amongst containers and what are important settings?
3. Exporters have different interpretations of what is the right defrost termination temperature (and relative humidity setting for other species of bulbs). Simple and clear manuals would help.
4. How to stow the cargo inside the container:
   a. effect of chimneys
   b. effect of stowage height
   c. use 20 pallets with 5 chimneys or 21 pallets with only 2 chimneys in the door-end half of the container.

Based on the mentioned challenges this project is executed with the aims described in paragraph 1.2.

## 1.2 Aims

Aim of this project is to assess what lily bulb shippers can do to improve temperature homogeneity in reefer containers loaded with lily bulbs.

## 2 Factors affecting temperature homogeneity in lily bulb containers

Temperature inhomogeneity in any contained space occurs when the location of heat sources is not equal to the location of heat sinks, while the resistance to heat transfer from source to sink is larger than zero. The three mechanisms for heat transfers are heat conduction, heat convection and heat radiation. Heat convection occurs when an air flow carries heat along with the flow of air.

Reefer containers loaded with lily bulbs contain two heat sources and one heat sink:

1. Source 1, autonomous heat production of the lily bulbs ($Q_{resp}$),
2. Source 2, ambient heat ingressing through the insulated container walls ($Q_{ext}$),
3. Sink, the evaporator (or cooler coil) inside the reefer unit of the reefer container ($Q_{cool}$).

A reefer container (Figure 1) consists of a 20 ft or 40 ft HC box with a T-bar floor and a reefer unit. The box is loaded with palletized crates. The refrigeration unit is equipped with evaporator fans that draw warm return air from the headspace above the palletized crates, which is then cooled at the evaporator and finally delivered into the T-bar floor in the box. Typically the temperature of the evaporator is regulated such that the delivery or supply air temperature equals setpoint temperature.

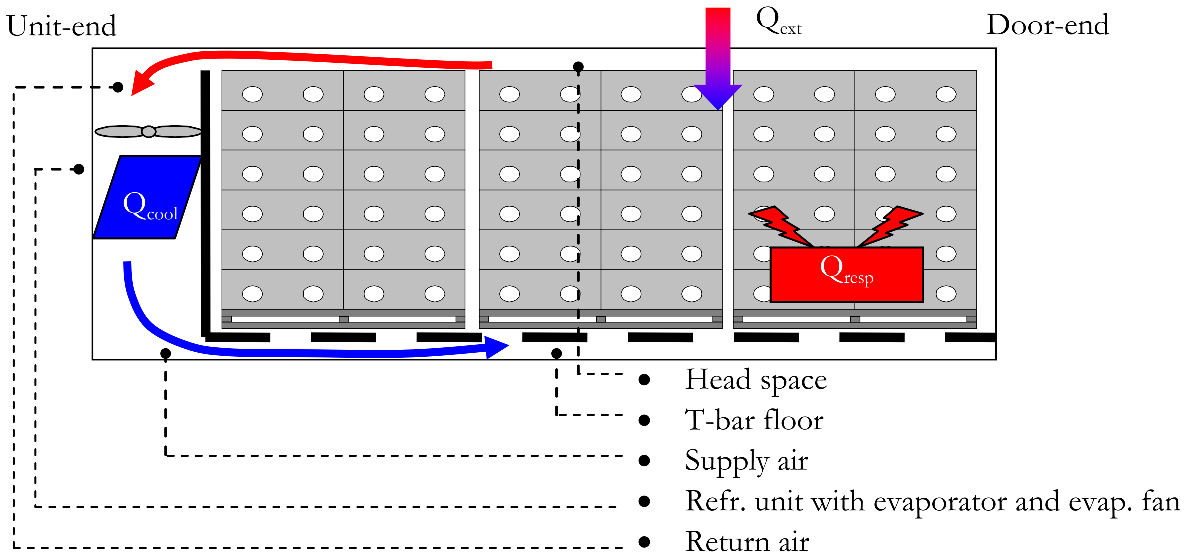

**Figure 1: Schematic overview of a reefer container.**

The dominant mechanism for heat transfer in stowed reefer containers is heat convection: warm air flows from the heat source(s) to the heat sink and ejects its heat there. The air flow is maintained by the evaporator fans. Crucial in improving temperature homogeneity is that air circulates at sufficiently high velocities between the two heat sources ($Q_{ext}$ and $Q_{resp}$) and the heat sink ($Q_{cool}$).

As the evaporator has a temperature below dew point and below 0 °C frost forms on the evaporator. If no measures are taken then that frost will continue to accumulate and finally block the airflow through the reefer unit with devastating effect. Therefore periodic defrosting is required. Defrosting is done by heating the interior of the reefer unit. It interrupts the cooling process and has the potential to raise the lily bulb temperatures near the return air grid due to natural convection of air heated inside the reefer unit. Defrost control involves two decisions: when to start a defrost and when to stop a defrost. Starting of defrost is governed by the specified defrost interval. Nowadays the specification 'AUTO' seems most appropriate, but that is beyond the scope of this project. A defrost stops when a temperature measured at the outside of the evaporator with a defrost termination sensor exceeds a preset Defrost Termination Temperature (DTT). By default DTT is +18 °C. For lily bulbs shipped with closed vents this is probably far higher than necessary.
When optimizing temperature control in reefer containers with lily bulbs one needs to know:

1. How is the current air flow distribution in loaded reefer containers? What is the ideal air flow distribution? Which measures are possible to bring the air flow distribution closer to the ideal situation?
2. What can be done to minimize the adverse effects of defrosting?
3. Could one reduce heat ingress $Q_{ext}$ by just selecting reefers with good insulation value?
4. Where is the major heat source? Is it heat ingress through walls ($Q_{ext}$ in Figure 1) or is it respiratory heat production ($Q_{resp}$ in Figure 1)?

The following sections address these individual questions. First, in relation to question 1, section 3 describes the work related to assessing air flow distribution in different stowage patterns. Then, to answer question 2, section 4 addresses the effect of defrost settings. After which question 3 is addressed in section 5. Finally $Q_{resp}$ is assessed in section 6 and compared with $Q_{ext}$ (question 3). Subsequently the discussion section (section 7) discusses the overall results and how they mutually connect. Finally the 'conclusion' section, section 8, lists the main conclusions in relation to the aim described in section 1.2.

# 3 Air flow distribution

For different stowage floor plans air flow velocities are measured in a 40 ft HC container loaded with lily bulbs. The different stowage floor plans are created in a 40ft HC reefer container made available for this project by Maersk. The reefer container (see Figure 1 in chapter 2) consists of a 40 ft HC box with T-bar floor and a refrigeration unit. The box is loaded with palletized crates. The internal dimensions of a 40ft HC reefer container are: 11.59 x 2.29 x 2.60 m (LxWxH). The lily bulbs are provided by De Jong Lelies and Onings Holland in covered crates at wooden pallets. Each pallet contained 10 layers of crates, in total fifty crates per pallet. The flower bulbs were harvested in 2008 and the air flow distribution measurements are carried out in September 2010.

## 3.1 Stowage floor plans

The different stowage floor plans are as follows. Internal dimensions of reefers (width x length) are 2.29 x approx. 11.6 m, while pallets are 1.00 x 1.20 m. As a consequence maximum 20 pallets fit in in two different ways, A and B, as shown in Figure 2. Option C in Figure 2 shows a floor plan with 21 pallets. In floor plan B and C the pallets are stowed in such a way that between the pallets 'chimneys' are formed. Floor plan B contains 5 chimneys and floor plan C contains 2 chimneys. Floor plan B is not common in lily transport.

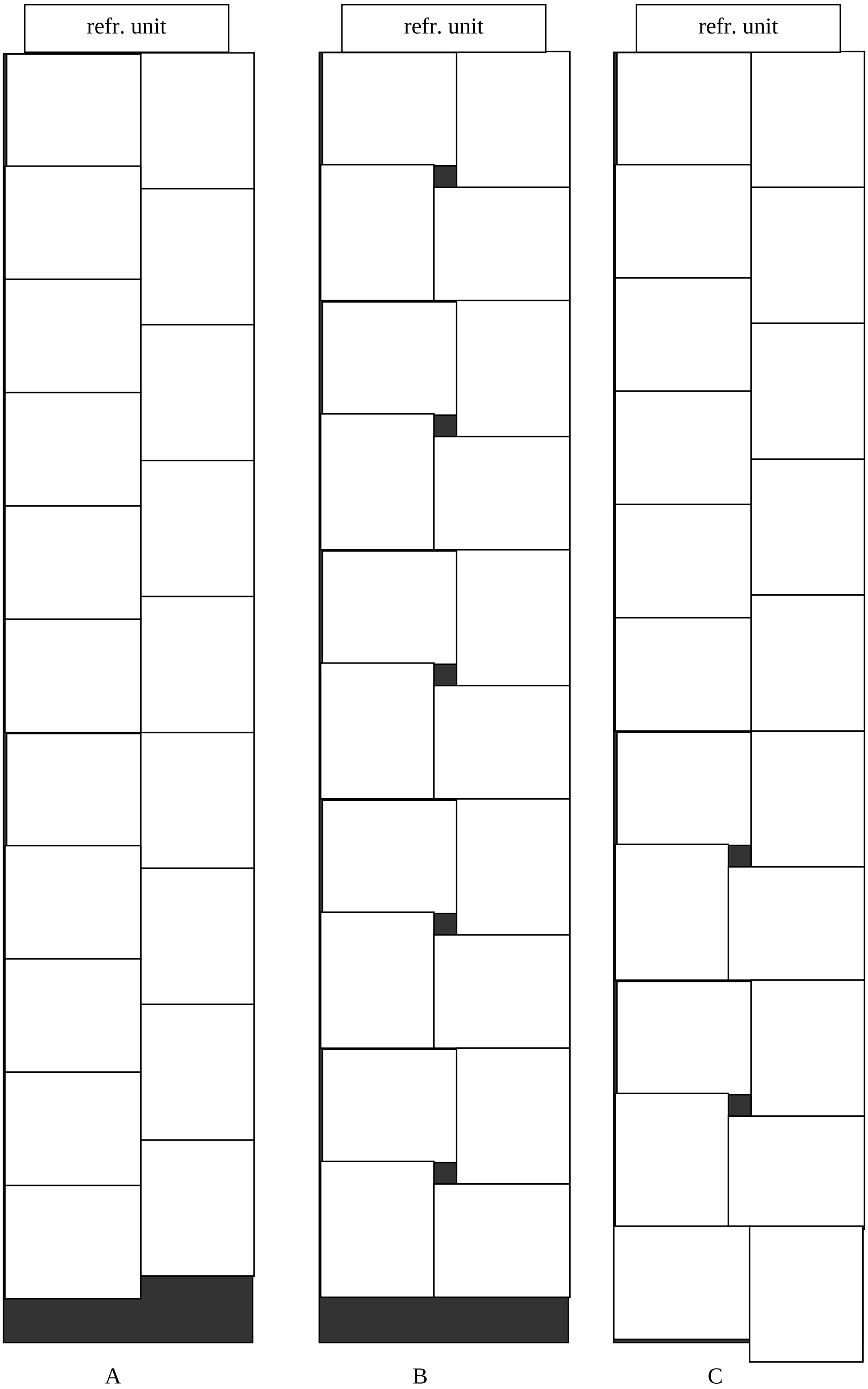

**Figure 2: Different floor plans for pallet stowage (A, B = 20 pallets, C = 21 pallets). Black areas are T-bar areas not covered by palletized cargo.**

### 3.2 Air velocity measurement equipment

In order to get insight in air distribution in the container the air velocity is assessed by measuring dynamic pressure. The dynamic pressure [$P_d$] depends on the air density $\rho$ [kg/m$^3$] and the velocity $v$ [m/s] at a specific measuring point according to equation 1.

$$P_d = \tfrac{1}{2}\rho v^2 \qquad [1]$$

From equation 1 the air velocity can be calculated according to:

$$v = \sqrt{\frac{2P_d}{\rho}} \qquad [2]$$

Pitot tubes are used to measure air pressure and with a pressure transmitter the measured pressure is expressed in Pascale (Pa). In this project a Testo pressure transmitter (type 0638 1347) is used with a range of 0 – 100 Pa which corresponds with an air velocity of 0 – 12.5 m/s. In Table 1 the relation between pressure and air velocity is given.

**Table 1: relation between dynamic pressure and air velocity at air temperature of -1.5°C.**

| $P_d$ [Pa] | 0 | 1 | 2 | 3 | 5 | 8 | 10 | 20 | 30 | 50 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $v$ [m/s] | 0 | 1.2 | 1.8 | 2.2 | 2.8 | 3.5 | 3.9 | 5.6 | 6.8 | 8.8 | 12.5 |

In Figure 3 again the relation between pressure and air velocity is shown. The graph shows a non-linear correlation with a high slope at low pressures.

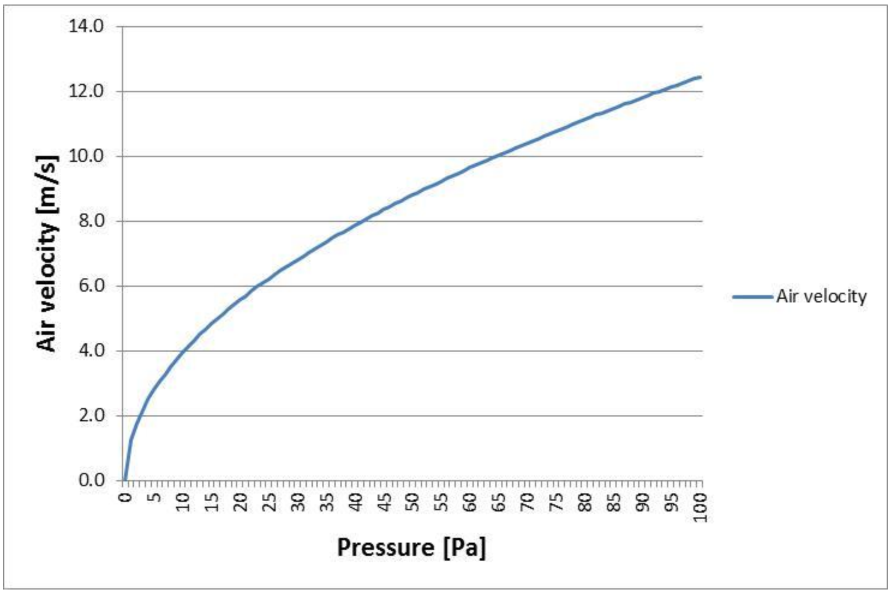

**Figure 3: non-linear correlation between pressure and air velocity.**

The used pressure transmitter gives the pressure in units of whole Pa. For the low pressure (low velocity) this means that measurements below 1 Pa can be shown as 0 Pa. 1 Pa is equivalent to 1.2 m/s. The air velocity in this range varies between 0 and 1.2 m/s. In general the resolution of the measurement device is less for low pressures.

### 3.3 Pressure measurements on different stowage floor plan

The different stowage patterns are tested in a 40ft HC reefer container running at 60Hz power supply at a temperature setting of -1.5 °C. With pitot tubes the dynamic pressure is measured in the T-bars, in the headspace above the crates and in the chimneys at different positions over the length of the container. Figure 4 gives a photo impression of the measurements in the container.

**Figure 4: clockwise starting upper left: pitot tube in T-bar; pitot tubes in T-bar at 3 positions; 3 pitot tubes at sledge above the crates; pitot tube fixed in chimney.**

The pitot tubes are positioned in the T-bars and headspace at the unit-end. After doors are closed and a period of some minutes, in order to establish the air flow, the measurement take place. Then doors are opened and each pitot tube is moved 1 meter to the door-end of the container. This continues until the door-end of the container is reached. The pitot tubes in the chimneys are fixed at a height of 1.25m. In Figure 5 the different pitot tubes are schematically shown with numbers.

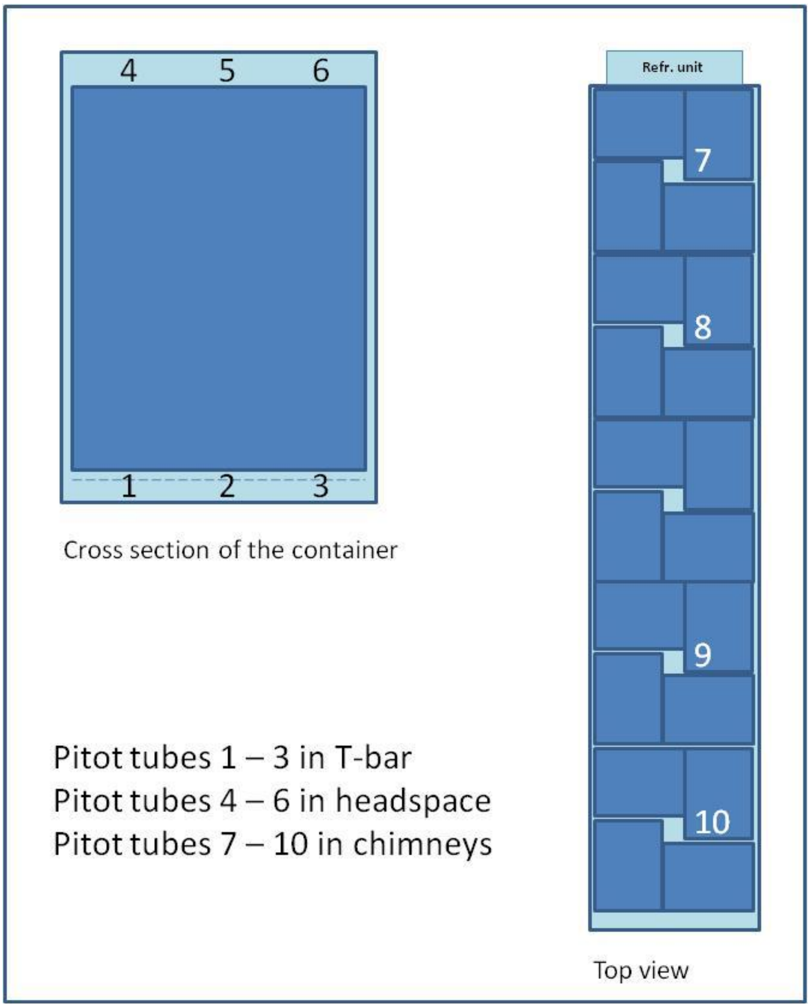

**Figure 5: Schematic overview of pitot tubes in the container.**

### *3.3.1 Test programme of pressure measurements*

Measurements are done with six different configurations. The configurations differ in floor plan, stacking height of 8 or 10 layers, top of the T-bars at the door-end covered or uncovered, and whether or not a cover is placed on top of the part of the T-bars that is not covered by the cargo in the first 6 meters from the unit-end. Before each test a manual defrost is carried out in order to create the same starting conditions. Table 2 shows the test programme. The code in column 2 of Table 2 (<letter 1><number><letter 2><letter 3>) identifies the measured configuration, it is used again in the legends of Figure 7 - Figure 14. Explanation of te code Table 2 (column2): <letter 1> refers to stacking pattern (column 3), <number> is the stacking height (column 4), <letter 2> is the first letter of the description in column 5 (Covered/Uncovered) and <letter 3> is the first letter of the description in column 6 (Covered/Uncovered). For example code B10CU identifies a measurement configuration with floor plan B, a stacking height of 10 crates, top of T-bars at the door-end Covered, and the part of the T-bars that is not covered by the cargo in the first 6 meters from the unit-end remains Uncovered.

**Table 2: Measured configurations.**

| Test | Code | Floor plan | Stacking height | T-bar at door-end | T-bar at right side |
|---|---|---|---|---|---|
| 1 | B10CU | B | 10 | Covered | Uncovered |
| 2 | B10UU | B | 10 | Uncovered | Uncovered |
| 3 | A10CU | A | 10 | Covered | Uncovered |
| 4 | C10CU | C | 10 | Covered | Uncovered |
| 5 | A8CU | A | 8 | Covered | Uncovered |
| 6 | C10CC | C | 10 | Covered | Covered (1st 6 m from unit) |

Changing the stacking height from 10 layers to 8 layers the distance from the upper side of the crates to the roof of the container increases with 52 cm, which means more headspace.
In Figure 6 below the covered T-bar in Test 6 is shown. Pallets are stowed tightly against the left wall and each other which leaves an air slit at the right wall of about 10 cm width. In order to avoid short-circuiting of air through the pallet openings, over the first 6 meters the pallet openings at the right side are filled up. The length of 6 meters is an arbitrary choice just to see if there is any effect.

**Figure 6: cover at right side of first 6m of the container (left); filled up pallet opening (right).**

## 3.4 Results

According to the test programme described in Table 2 in this paragraph the results are graphically presented. The legend of the graphs can be explained as follows: for example in Figure 7 'B10CU' means stowage pattern B; stacking height of 10 layers; T-bar at door-end is Covered; T-bar at right side is Uncovered. The measured pressures in the T-bars and in the headspace are presented in the graphs as average air velocity.

### *3.4.1 Covered and uncovered T-bar*

For stowage pattern B two measurements are done, with and without covering the T-bar between door-end and last pallet. This measurement on the covered and uncovered configuration is done at the same time and under the same conditions. In Figure 7 and Figure 8 the air velocity is shown for the T-bar and the headspace above the crates.

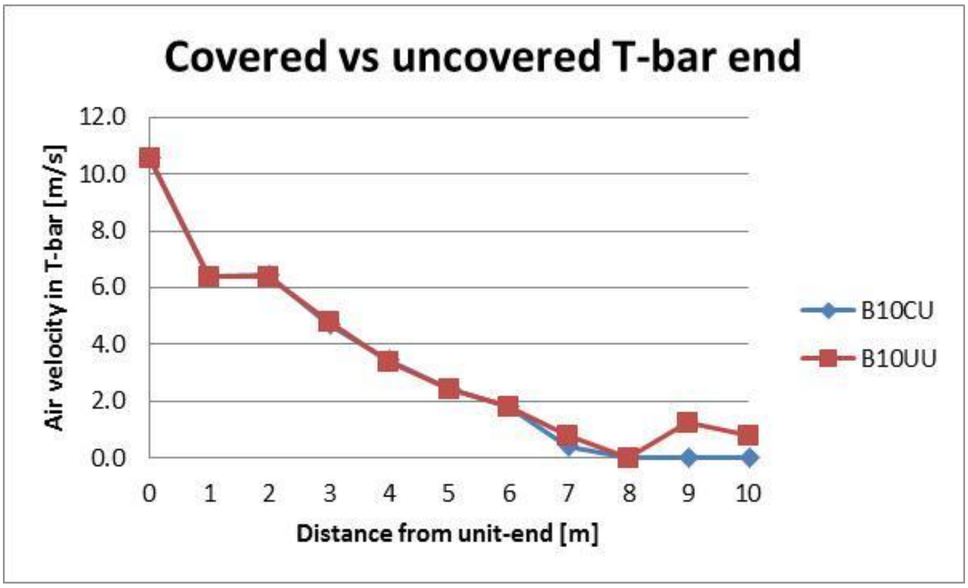

**Figure 7: Stowage pattern B, height 10 layers covered and uncovered T-bar. Measurements in the T-bars.**

The air velocity measured with the tubes in the T-bars is the same over the whole length of the container with covered and uncovered T-bar end. Initially the air velocity is 10.6 m/s. At 8 meter from the unit-end the air velocity is 0 m/s. There are no notable differences in air velocity between covered and uncovered T-bars at the door-end.

The increase in velocity between position 1 and 2 meter is due to a defrost during the measurement. At the door-end of the container also an increase is measured with uncovered T-bars between door-end and the last pallet also due to defrost. Clearly insufficient air reaches the back of the container.

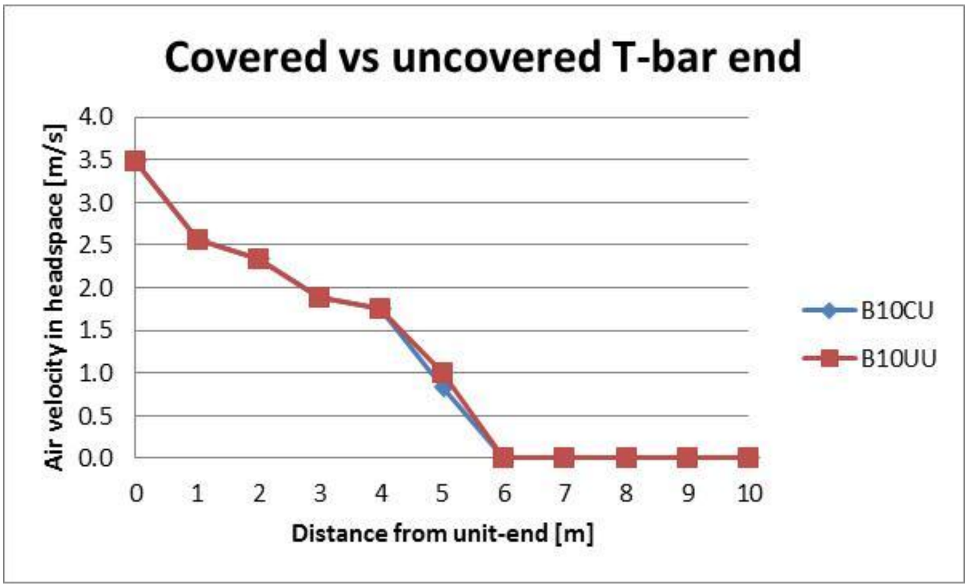

**Figure 8: Stowage pattern B, height 10 layers covered and uncovered T-bar. Measurements in the Headspace.**

In Figure 8 for both covered and uncovered situation the air velocity in the head space is the same. Initially this is 3.5 m/s. After 5 meters air velocity drops to zero. There are no notable differences in air velocity between covered and uncovered T-bars at the door-end.

### *3.4.2 Effect of different stowage patterns.*

Figure 9 and Figure 10 show the air velocities over the total length of the container for stowage pattern A, B and C, all with covered (horizontal cover on top of the last part of the T-bar floor that is not covered by palletized cargo) T-bar end.

*Measurements in the T-bars.*

Figure 9 in general shows that air velocity decreases quickly in the first 2 meters from the unit-end. Then decreases slower and is zero in the back of the container.
The average air velocity at the air inlet of the unit is between 10.6 – 11.5 m/s. After 6 meters the air velocity decreased to 0 m/s with stowage pattern A and C. In the case of stowage pattern B this is after 7 meters. Between the stowage floor plans A, B and C there are no notable differences in air velocity in the T-bars and thus air distribution in the container in these three stowage plans is virtually identical.

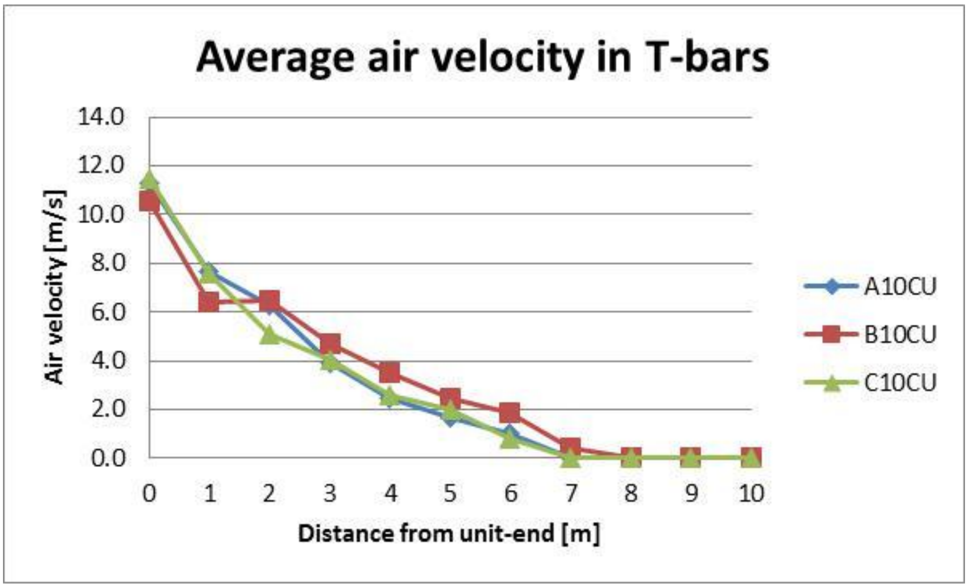

**Figure 9: Air velocity for stowage patterns A, B, C, with a stacking height of 10 layers.**

*Measurements in the Headspace*

In general after the first meter from the unit-end the air velocity decreases quickly, then decreases slower and is zero in the back of the container. Figure 10 shows that in the headspace the average air velocities at the air inlet of the unit are low, between 3.5 – 4.0 m/s. After 6 meters from the unit in none of the stowage pattern measured air velocity is higher than 0 m/s.

During measurements in stowage pattern B a defrost between measurement 1 and 2 caused an increase in air velocity. This delay in decrease of velocity caused a difference of 1 meter in reach of air into the container. Taking that into account no notable differences are shown between stowage patterns A, B and C.

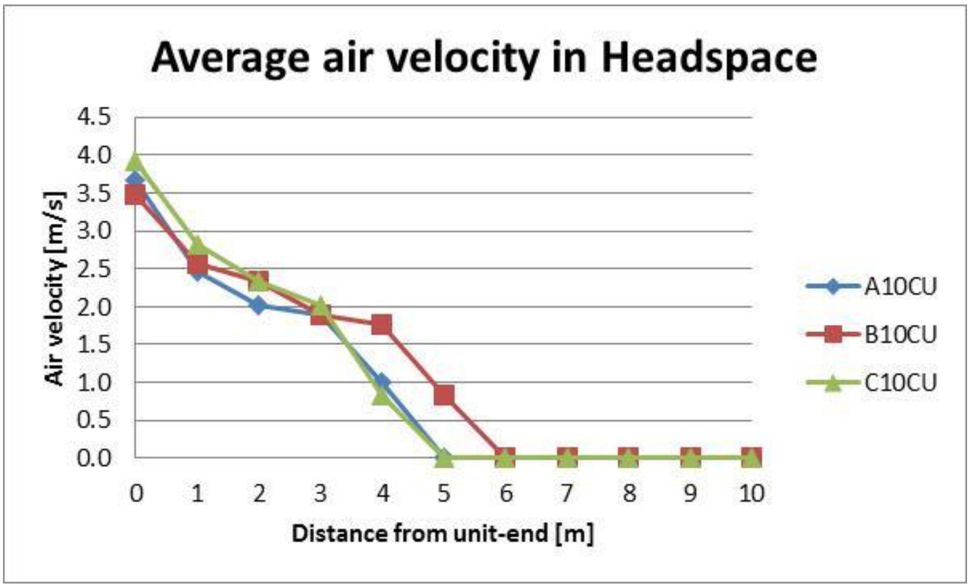

**Figure 10: Air velocity for stowage patterns A, B, C with a stacking height of 10 layers.**

*Measurements in the chimneys*

For stowage pattern B and C also air velocity is measured in the chimneys. For pattern B this is done in the first and the last 2 chimneys. For pattern C this done in the last two and only 2 chimneys. The results are shown below in Table 3. Test 1 and 2 is done with stowage pattern B, Test 4 and 6 with pattern C.

**Table 3: calculated air velocities in the chimneys in stowage pattern B and C during Test 1, 2, 4, 6.**

| **Measurement** | ***v*-tube 7 [m/s]** | ***v*-tube 8 [m/s]** | ***v*-tube 9 [m/s]** | ***v*-tube 10 [m/s]** |
|---|---|---|---|---|
| Test 1 | 1.8 | 1.8 | 1.2 | 0 |
| Test 2 | 1.8 | 1.8 | 1.2 | 0 |
| Test 4 | N/A | N/A | 0 | 0 |
| Test 6 | N/A | N/A | 1.2 | 1.2 |

The results in Table 3 show that air velocity measured in the chimneys is low. Close to the unit-end air velocity in the chimneys is higher than the air velocities measured in the chimneys at the door-end. In the last chimney the air velocity is zero (comparing test 1 and 2).
In Test 6 the air velocity is 1.2 m/s in the chimneys at the door-end. This is a notable difference compared with the measurement in those chimneys in the other tests. The difference is the extra cover on the T-bars, which will be described in paragraph 3.4.4.

### *3.4.3 Effect of stacking height*

The next graphs show the difference in air velocity measured on stowage pattern A with stacking height of 8 and 10 layers. For each tube the results are presented in one graph.

*Measurement in the T-bar.*

Figure 11 shows that after 6 meters from the unit-end the air velocity is decreased to zero with ten layer stack. For an eight layer stack this is 5 meters. The initial air velocity at the air inlet of the unit is 11.3 m/s for the ten layer stack and 10.6 m/s for the eight layer stack. Taking into account that measurement close to zero can be exactly between 0 and 1Pa, which means between 0 and 1.2m/s, there is no notable difference air velocity in the T-bars and thus there is no observable difference in air distribution in the container between the stacking height of eight and ten layers of crates.

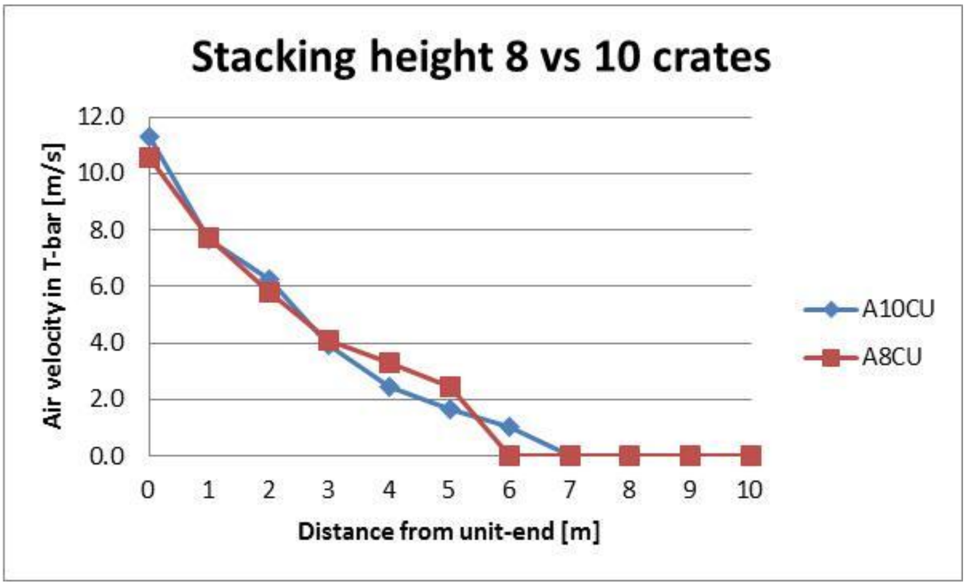

**Figure 11: Air velocity in T-bar in stowage pattern A with 8 and 10 layers of crates.**

*Measurement in the Headspace*

Figure 12 shows that the air velocity in the return air (headspace) close to the unit-end is 3.5 – 3.7 m/s for a stacking height of 10 layers of crates and 1.2 m/s for a stacking height of 8 layers. Due to the bigger cross-section of the headspace in a eight layer stack the air velocity is much lower but the air flow (m$^3$ of air per hour) is the same as in a ten layer stack.

In case of a stacking height of 8 layers the air velocity decreases to zero 1 meter from the unit. In case of 10 layers this happens on 4 and 5 meters from the unit-end.

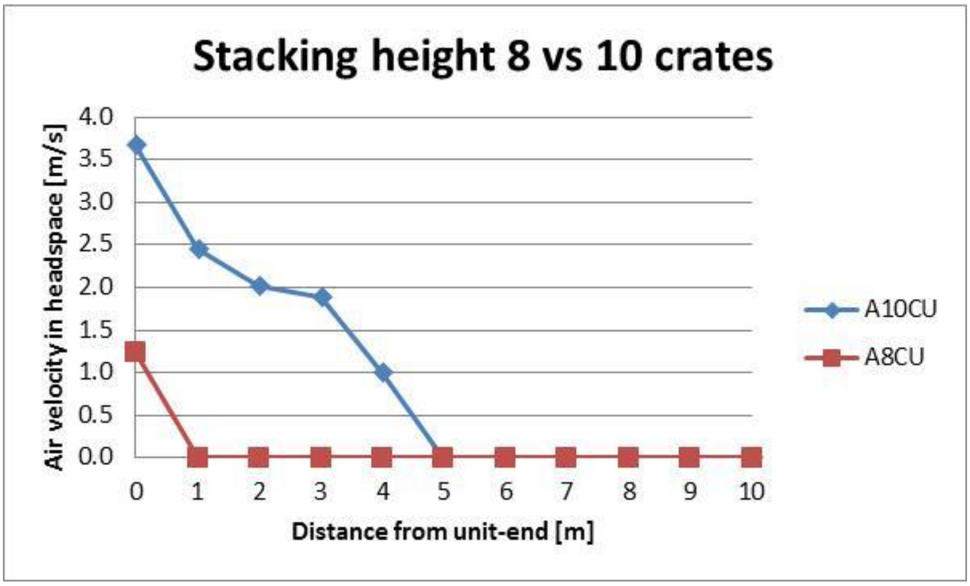

**Figure 12: Air velocity in stowage pattern A with stacking height of 8 and 10 layers.**

### *3.4.4 Effect of extra covering the T-bar in the first 6 meters from the unit-end*

The graphs in Figure 13 and Figure 14 show the air velocity in the container with an extra cover on the T-bars on the right side over the first 6 meters from the unit-end in order to force more air to the back of the container.

*Measurements in the T-bar*

Figure 13 shows that the average air velocity at the air inlet is between 10.8 – 11.5 m/s and decreases to zero at 7 meters from the unit-end without extra cover and at 8 meters with extra cover. The initial air velocity for both situations is practically the same. The decrease in air velocity is less from 3 meters from the unit-end with an extra cover. There is a notable higher air velocity in the case of an extra cover and air reaches further into the container. Compared with the calculated air velocity in the chimneys in Table 3 there is a relation between the measured pressure in the last chimneys at 7 and 9 meters. In both chimneys the calculated air velocity is 1.2 m/s. In Figure 13 at 7 meters the average velocity is also 1.2 m/s.

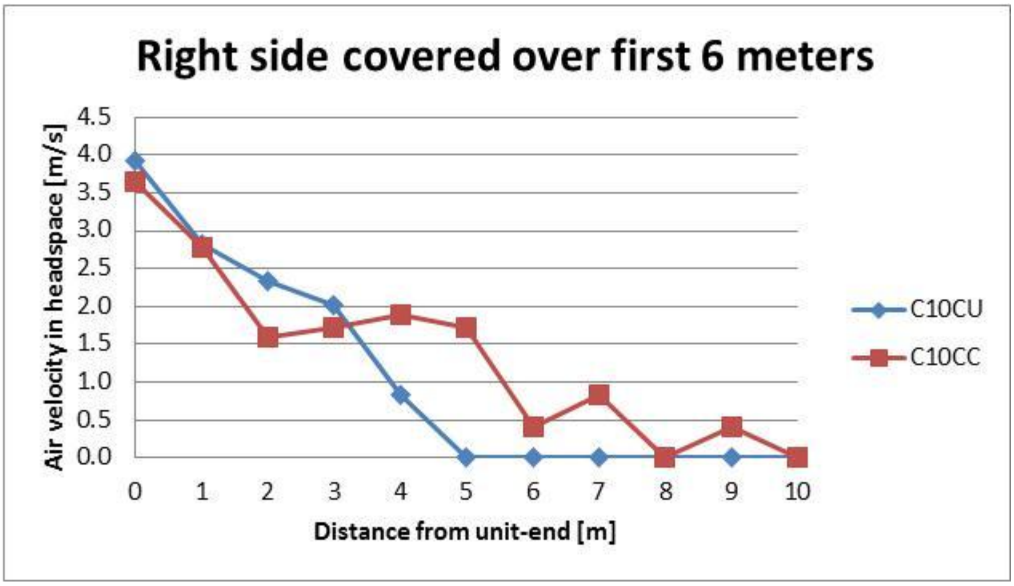

**Figure 13: Air velocity in stowage pattern C with and without extra cover on the T-bars.**

*Measurements in the headspace*

Figure 14 shows that the average air velocity decreases to zero at 5 meters from the unit-end without extra cover and at 8 meters with extra cover. The initial air velocity in case of an extra cover and without is respectively 3.6 m/s and 3.9 m/s. Although the decrease of the air velocity in the headspace measured with an extra cover is changeable, for an unknown reason, there is a notable higher air velocity compared to the case without an extra cover and air reaches further into the container. At 7 and 9 meters the increase in average air velocity is due to the chimneys. In Table 3 the calculated air velocity in these chimneys is 1.2 m/s. The air velocities at 7 and 9 meters are respectively 0.8 m/s and 0.4 m/s.

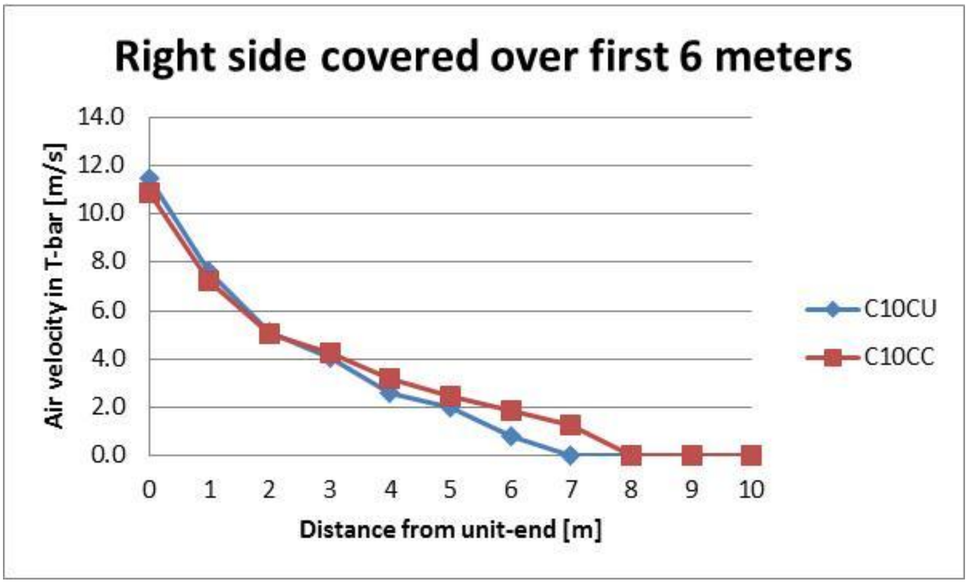

**Figure 14: Air velocity in stowage pattern C with and without extra cover on the T-bars.**

### 3.5 Air distribution in different stowage floor plans: discussion

- In all of the tested stowage patterns hardly any air reaches the door-end.
- There is no significant difference in airflow distribution between the three tested stowage patterns.
- Covering the air slit between the last crates and the door does not affect air flow distribution in the tested stowage patterns (see Figure 7 and Figure 8).
- Covering the first 6 meters of the container T-bars helps to deliver more air towards the door-end (see Figure 13 and Figure 14).
- The air distribution does not change when the stacking height is reduced from 10 to 8 layers of crates (see Figure 11 and Figure 12).

# 4 Defrost settings

As mentioned in section 2 defrost control involves two decisions: when to start and when to terminate a defrost. Both criteria involve settings which may be specified by the shipper. Control of defrost starts is governed by the so-called defrost interval, which may usually be set at 6, 12, 24 hours or AUTO. In case of AUTO setting the artificial intelligence in the reefer unit's controller determines automatically when to start a defrost. It is beyond the scope of this project, but experience in other projects has learned the authors that the AUTO setting is adequate in the current generation of reefer units.
Control of defrost termination is governed by the set Defrost Termination Temperature.

## 4.1 Defrost termination temperature

The defrost termination temperature (DTT) is a setting in the cooling unit accessible after selecting bulb mode. When the unit starts a defrost, it will continue defrosting until the defrost termination temperature is reached. The evaporator coil must be clean (free of ice) after reaching the DTT. The DTT is measured in the plenum space below the evaporator fans and above the evaporator coil. After stopping a defrost the evaporator fans, which are switched off during defrost, start again and accumulated heat is blown into the container. The higher the DTT the more heat is blown in the container load. After a defrost the coil is clean and with minimum pressure air is forced through the evaporator coil into the container. Ice on the coil will lead to a higher pressure which is needed to force the air through the coil. There is a relation between the amount of ice on the coil and needed pressure. If, after a defrost, the pressure is higher than the minimum pressure the coil is not free of ice and thus the air circulation decreases. In that case the DTT must be set higher in order to prolong the defrost time and completely clean the coil.
In order to determine the optimal defrost termination temperature at 'bulb mode' static pressure is measured in the unit of a 40ft HC reefer container. 'bulb mode' is a set of defaults meant for flower bulb transport, nevertheless for the test the bulb mode's DTT was changed from default (18°C) to 4°C and the setting RH was changed at maximum in order to avoid dehumidification during the tests. Two tubes were installed in the plenum space, on both sides under each evaporator fan. These tubes were then connected with a pressure transducer to measure the pressure difference with the atmospheric pressure outside the container. The pressures were logged during at least 12 hours while the unit was running at 50Hz power supply. In the container the humidity level was maintained at different levels in order to simulate a 'considerable' moisture load during bulb transport and a worst case situation with maximum moisture load created by humidifiers. The setpoint temperature in the container was -1.5°C. Measurements are repeated at a maximum and minimum defrost termination temperature at a fixed defrost interval of 6 hours. In Table 4 the DTT test programme is shown.

Table 4: DTT test programme.

| Test | DTT | Moisture load |
|---|---|---|
| 1 | 18°C | 0.3 l/h |
| 2 | 4°C | 0.3 l/h |
| 3 | 4°C | 0.9 l/h |

## 4.2 Defrost termination temperature: results

In this paragraph the results of the pressure measurements in order to optimize the defrost termination temperature (DTT) are presented graphically. In the graphs average of the pressures measured on both sides in the plenum space is shown. For lily bulb transport the pressures on both sides are equal. For other chilled commodities during transport the ventilation vent is open which causes differences in moisture load since the vent is located on one side of the unit.

### Test 1: Defrost termination temperature of 18°C

In test 1 the defrost termination temperature was set at 18°C and in the container a moisture load of 0.3 l/h was established. The air temperature was set at -1.5°C. The defrost interval was set at 6 hours for experiment convenience. Figure 15 shows 3 defrosts where the pressure drops to zero and rises over 300 Pa because switching off and on of the evaporator fans. After each defrost the measured pressure is around 130 Pa. This means that the coil is clean after each defrost with a DTT of 18°C and a normal moisture load.

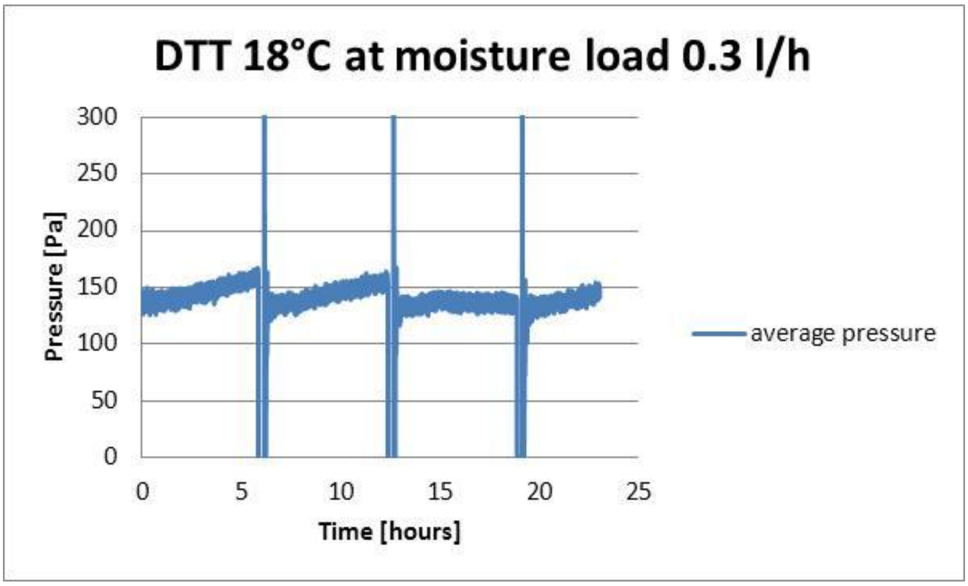

Figure 15: Pressure measured in plenum above the coil with defrost termination temperature of 18°C.

After the second defrost the slope of the pressure increase is lower than before due to an empty reservoir of the humidifier. Hence between 15 and 18 hours there is no frost formation The next defrost took place after a period of almost no moisture load. Still the pressure after defrost is 128 Pa.

**Test 2 and 3: Defrost termination temperature of 4°C**

In test 2 the defrost termination temperature was set at 4°C with a moisture load of 0.3 l/h and a defrost interval of 6 hours. Figure 16 shows that after each defrost the measured pressure is constantly around 136 Pa. This means that also with a DTT of 4°C and normal moisture load the coil is clean.

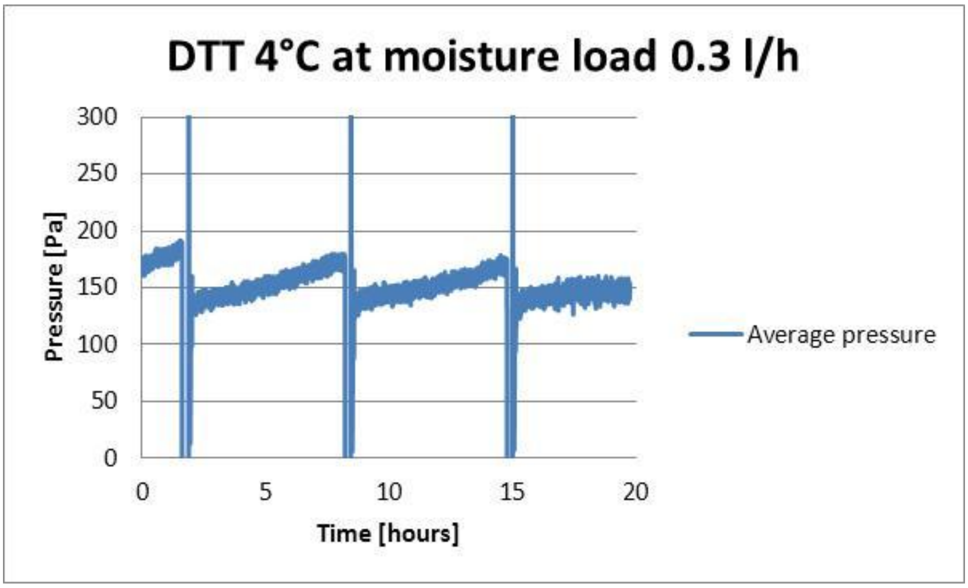

**Figure 16: Measured pressure with DTT of 4°C and normal moisture load (Test 2).**

Figure 17 shows defrosts for a DTT of 4°C and defrost interval of 6 hours but a high moisture load of 0.9 l/h. At high moisture load the pressure increases much more in time until pressures between 350 and 400 Pa instead of maximum 180 Pa with a normal moisture load (see Figure 15 and Figure 16). After each defrost the measured pressure is around 130 Pa. This is equal to the pressures measured after defrosts at termination temperature of 18°C. So all frost melts during a defrost.

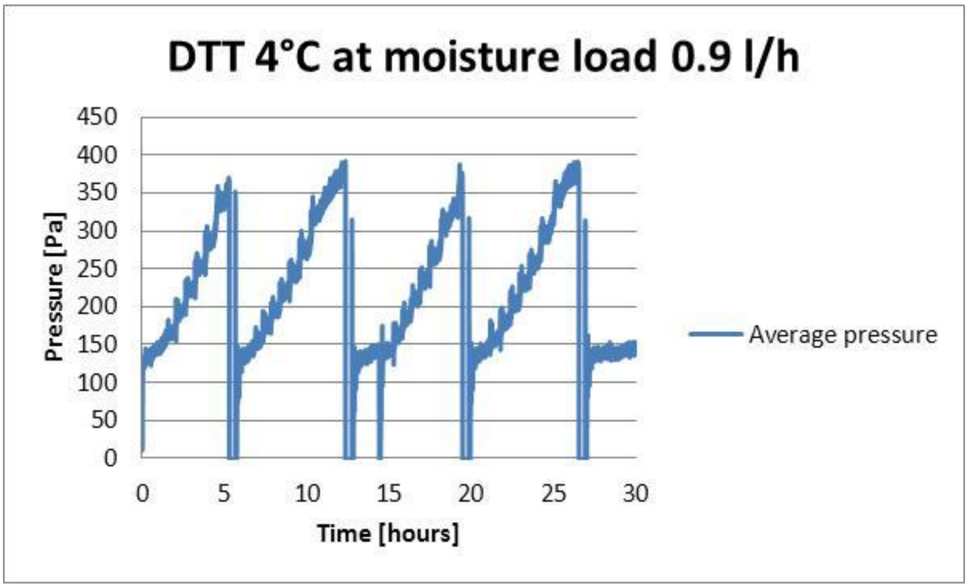

**Figure 17: Measured pressure with a DTT of 4°C and a high moisture load (Test 3).**

## 4.3 Defrost termination temperature: discussion

- For lily bulbs, shipped with closed vents, a defrost termination temperature of 4°C suffices, while by default the reefer unit uses an 18 °C defrost termination temperature. This conclusion is based on tests in a Carrier unit. Whether the same is true for other types of units remains to be seen, but most likely they are comparable.

# 5 Heat ingress through the walls $Q_{ext}$ (heat source 1)

The insulation value of reefer containers is commonly expressed in its so-called U-value. The U-value is expressed in W/°C. For example if the U-value of a containers is 50 W/°C while its interior temperature is 0 °C and ambient temperature is 30 °C then the heat ingress $Q_{ext}$ is 50 x (30 – 0) = 1500 W. The lower the U-value the smaller $Q_{ext}$ and hence the better the insulation.

Based on hearsay the a priory assumption was that the insulation value (U-value) of specific reefer container designs of specific container manufacturers was worse (larger) than other designs of other manufacturers. Moreover it is generally known that the insulation value of reefer containers gets worse over time. Big unknown is how big these differences are. To get an impression the insulation of two reefer containers is measured. These two should represent the extremities that may occur in lily bulb shipments, for which containers older than 5 years are usually not recommended. Container owners willing to lend out their containers for these measurements were sought and found. The worst container should be of the supposedly worst design and about 5 years old, while the best container should be of the supposedly best design and brand-new. For a 'worst' container and a 'best' container the insulation value is measured.

The tests are executed according to ATP-standards in our test facility.

## 5.1 Results

The insulation value of a 'worst' and a 'best' 40ft HC container is measured according to the ATP standard.

**Table 5, results of the U-value measurements.**

| container | design | Age [years] | U-value [W/°C] |
|---|---|---|---|
| 'Worst' | Supposedly worst | 4 | 54.76 |
| 'Best' | Supposedly best | 2 | 46.38 |

The difference in insulation value between 'worst' and 'best' is about 15%.

## 5.2 Discussion

In Table 6 heat load through the walls is shown for the 'worst' and 'best' container.

**Table 6: heat load through 'worst' and 'best' container walls.**

| | |
|---|---|
| ambient temperature | 28.5 °C |
| carriage temperature | -1.5 °C |
| **heat ingress through walls ('best' ctr)** | **1391 W** (46.38 x (28.5 - -1.5)) |
| **heat ingress through walls ('worst' ctr)** | **1643 W** (54.76 x (28.5 - -1.5)) |

It is known that the critical insulation point of a container is located at the door-end of a container (the door gaskets), but the insulation value for 'worse' containers is not limiting the functionality of insulation.

- The difference in insulation value of an 'worst' and 'best' 40ft HC reefer container is only 15%.
- The distribution of cold air around the load seems more important for a steady transport temperature and to avoid local heating and thus increasing heat production of the lily bulbs.

# 6 Respiratory heat production $Q_{resp}$ (heat source 2)

## 6.1 Heat production $Q_{resp}$ of lily bulbs

Lily bulbs are a living produce and will produce heat due to respiration. For some samples of bulbs and storage medium peat $CO_2$-production is measured at transport temperature (-1.5°C) and at 7°C. $CO_2$-production is measured in closed bottles as shown in Figure 18.

**Figure 18: closed bottles for $CO_2$-production measurements; left bulbs; right peat.**

## 6.2 Results

In Chapter 2 the autonomous respiration heat of frozen lily bulbs is described as a heat source. The question is if the heat production is a major heat source that can be pointed as an important reason for temperature differences in a reefer container with lily bulbs. The relation between respiration and heat production is explained by the chemical equation of respiration presented in equation 3:

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{r_{resp}} 6CO_2 + 6H_2O + E_r \qquad [3]$$

Where $E_r$ is oxidation energy of glucose (ATP + heat). The $O_2$-uptake and the CO2-production is the result of respiration of the bulbs and linearly correlated with the heat production.

In order to determine the heat production of lily bulbs, stored in crates together with peat, the $O_2$ uptake or the $CO_2$ production can be measured over a period of time. From that information the heat production can be calculated. In this experiment the $O_2$ concentration seems a better indicator for heat production than the $CO_2$ concentration because of internal uptake in the water

of $CO_2$ by the lily bulbs itself and higher difference of concentration inside and outside the bottle for $CO_2$. The ratio of lily bulbs and peat is a crate is 7 : 3 (14kg and 6kg).
The $O_2$- and $CO_2$-contration of lily bulbs and peat is measured in a closed bottle with a total volume of almost 2 litres. Before measurements the bulbs and peat in each bottle are weighted. After a period of almost 24 hours the $O_2$ and $CO_2$ measurement is repeated. In Table 7 the concentration measurement of the headspace is shown with the calculated heat production, in W/ton, of lily bulbs at -1.5°C and 7°C. Three portions of the same bulbs are measured. One portion of peat is measured. The assumed density of lily bulbs and peat is respectively 1000 kg/m$^3$ and 300 kg/m$^3$.

**Table 7: $CO_2$-production of lily bulbs and calculated heat production (last column) at -1.5°C and 7°C.**

| | | | | start measurement | | end measurement | | | |
|---|---|---|---|---|---|---|---|---|---|
| **free volume** | **product** | **weight [g]** | **T storage** | **% O2** | **% CO2** | **% O2** | **% CO2** | **accumulation time [min]** | **W/ton** |
| 1484 | bulbs | 442 | 7ºC | 21.2 | 0.2 | 14.2 | 4.1 | 1430 | 55.6 |
| 1569 | bulbs | 420 | 7ºC | 21.2 | 0.2 | 14.1 | 4.1 | 1430 | 63.0 |
| 1540 | bulbs | 433 | 7ºC | 20.8 | 0.5 | 14.3 | 4.2 | 1430 | 54.8 |
| 1822 | peat | 189 | 7ºC | 21 | 0 | 20.5 | 0.3 | 1430 | 8.3 |
| | | | | | | | | | |
| 1597 | bulbs | 396 | -1.5ºC | 20.7 | 0.2 | 18.9 | 1.6 | 1410 | 17.5 |
| 1495 | bulbs | 457 | -1.5ºC | 20.7 | 0.1 | 18.6 | 1.6 | 1410 | 16.5 |
| 1563 | bulbs | 450 | -1.5ºC | 20.5 | 0 | 18.9 | 1.6 | 1410 | 13.4 |
| 1864 | peat | 164 | -1.5ºC | 20.9 | 0 | 20.8 | 0.1 | 1410 | 2.1 |

At storage temperature of 7°C the average heat production of the measured lily bulbs is 57.8 W/ton. The same lily bulbs at -1.5°C produce 3.6 times less heat, namely 15.8 W/ton. Peat at -1.5°C produces 4 times less heat than peat at 7°C. For a ton of load (30% peat, 70% bulbs) in a reefer container at -1.5°C the heat production is 11.7 W/ton, at 7°C this is 43 W/ton.

The heat productions at -1.5 °C usual carriage temperature are low as compared to many other chilled range commodities. Unripe bananas for example typically produce 60 W/tonne.

## 6.3 Discussion

- The average heat production of a mixture of 30% peat and 70% lily bulbs at a temperature of -1.5°C is 11.7 W/ton. This is low compared with for example unripe bananas carried at +13.5 °C with a heat production of 60 W/ton.
- The heat production of lily bulbs at 7°C is 3.6 times higher than at the standard transport temperature of -1.5°C. Not completely frozen lily bulbs will have a higher heat production which may cause local temperature increase during the transport period. Optimization of air distribution around and through the load will help lower the product temperature and avoid local increase of heat production.
- Warning: other cultivars and other stage of life can result in other respiration heat. Especially after early harvest the respiration will be higher.

## 6.4 Comparing heat ingress through walls ($Q_{ext}$) to respiratory heat production ($Q_{resp}$)

Table 8 compares the two main heat load sources for a reefer container loaded with 20 tonnes of lily bulbs and peat.

**Table 8: comparison of heat load factors.**

| | |
|---|---|
| ambient temperature | 28.5 °C |
| carriage temperature | -1.5 °C |
| container U-value | 50 W/°C |
| **heat ingress through walls** | **1500 W** (50 x (28.5 - -1.5)) |
| amount of lily bulbs | 20 tonnes |
| specific autonomous heat production | 11.7 W/tonne |
| **autonomous heat production at -1.5°C** | **234 W** (11.7 x 20) |
| **autonomous heat production at 7°C** | **860 W** (43 x 20) |

It appears that the autonomous heat production (234W) is less than 20% of the heat ingress through the walls (1500W). The big difference between these two factors, in combination with the knowledge that the non-smooth exterior of the plastic crates will always facilitate some airflow between crates, indicates that the container stuffing should aim at facilitating airflow around the load instead of forcing air through the load. Temperature differences in a container will mostly be influenced by the heat load through the walls.

# 7 Discussion

When comparing all the results reported above one thing catches the eye:

1. Proper stowage and measures aimed at increasing the air flow towards the containers door-end are the most important factors to improve temperature homogeneity in reefer containers (section 3). Therefore shippers should take measures to force air to the container's door-end. That is: block vertical air flow through vertical slits between pallets and between pallets and side walls in the part of the container closest to the unit-end.

Furthermore, but not as important as increasing air flow towards the door-end:

1. Aim at circulating air around the cargo, instead of through the cargo, if one could think of measures to manipulate this. Motivation is that this project's results (section 6) show that heat ingress through the walls $Q_{ext}$ is far larger than autonomous heat production $Q_{resp}$. Moreover the non-smooth exterior of the plastic crates facilitates some airflow between crates anyway.
2. Request a lower than default Defrost Termination Temperature (DTT). The measurements in section 4 prove that for Carrier units at setpoint -1.5 °C and closed vent lids (no fresh air exchange) a DTT = 4 °C suffices, while default DTT is 18 °C. No measurements have been done at 60Hz power supply. Also no measurements haven been done for other cooling units, like Thermo King, Daikin, Starcool. Therefore it is recommended to maintain a little safety margin and use a DTT of 8 °C.
3. Request 'AUTO' defrost interval (section 4). The reefer unit's artificial intelligence will automatically tailor the defrost interval to the rate of frost formation.

Factors of minor importance are:

1. Differences between types and age of reefer containers (see section 5). Any ATO-certified reefer container of less than 5 years old should be suited for lily bulb transport.
2. Stacking height. The measurements in section 3 show that reducing stacking height from 10 to 8 crates has no effect at all on temperature. Of course stacking height should stay below the red 'till cargo' line.

Factors that might even have a negative effect:

3. Don't apply a filler (e.g. cardboard) to cover the part of the T-bar floor at the door-end which is not covered by cargo. The measurements (Figure 7 and Figure 8) reveal that all effort should be aimed at directing more air to the container's door-end. In that situation covering the T-bar might be counter-productive.

Table 9 gives an example of a complete set of reasonable climate-specifications in a lily bulb shipment. Of course the optimal temperature setpoint depends on season and cultivar, and maybe even the vent should be a little (for example 10 CMH) open early in the season.

**Table 9, example of a reasonable carriage specification for lily bulb shipments.**

| **Setting** | **Value** | **Comment** |
|---|---|---|
| Setpoint temperature | -1.5 °C | Requested supply air temperature |
| Defrost interval | AUTO | Governs the duration of the period between two defrosts. |
| Defrost termination temperature DTT | 8 °C | Defrost terminates when temperature sensed at the air-side of the evaporator coil exceeds the set DTT (default: 18 °C) |
| vents | closed | Fresh air exchange usually not need for lily bulbs. Adverse affect of fresh air exchange would be the necessity of more frequent defrosting. |
| dehumidification | OFF | Not specififying a relative humidity setpoint |

# 8 Conclusions

What lily bulb shippers can do to improve temperature homogeneity in reefer containers loaded with lily bulbs:

1. Take measures to force air to the container's door-end. That is: block vertical air flow through vertical slits between pallets and between pallets and side walls in the part of the container closest to the unit-end.
2. Aim at circulating air around the cargo, instead of through the cargo, if one could think of measures to manipulate this. Motivation is that this project's results show that heat ingress through the walls is far larger than autonomous heat production. Moreover the non-smooth exterior of the plastic crates prohibits complete blockade of airflow between crates anyway.
3. Request a lower than default Defrost Termination Temperature (DTT). This project's measurements prove that for Carrier units at setpoint -1.5 °C and closed vent lids (no fresh air exchange) a DTT = 4 °C suffices, while default DTT is 18 °C. A DTT of 8°C is probably secure for all types of cooling units running at 60Hz.
4. Request 'AUTO' defrost interval. The reefer unit's artificial intelligence will automatically tailor the defrost interval to the rate of frost formation.

What lily bulb shippers should not do to improve temperature homogeneity in reefer containers loaded with lily bulbs:

1. Don't worry about differences between types and age of reefer containers. Any ATO-certified reefer container of less than 5 years old should be suited for lily bulb transport.
2. Don't reduce stacking height till distinctly below the red 'till cargo line'. This project's measurements show that reducing stacking height from 10 to 8 crates has no effect at all on temperature.
3. Don't apply a filler (e.g. cardboard) to cover the part of the T-bar floor at the door-end which is not covered by cargo. This project's measurements (Figure 7 and Figure 8) reveal that all effort should be aimed at directing more air to the container's door-end. In that situation covering the T-bar might be counter-productive.

# Test log

| Date [dd-m-yyyy] | Description of activities |
|---|---|
| 30-08-2010 | Arrival of container with load of lily bulbs. Container connected to power supply at setpoint -1.5°C |
| 02-09-2010 | Testing equipment and measurement devices. |
| 03-09-2010 | Measurement of heat production of lily bulbs. |
| | |
| 03-09-2010 | Pressure measurements for stowage pattern B with and without covered T-bar end. |
| 06-09-2010 | Pressure measurements for stowage pattern A. T-bar end covered. |
| 07-09-2010 | Pressure measurements for stowage pattern C. T-bar end covered. |
| 10-09-2010 | Pressure measurements for stowage pattern A. T-bar end covered. Stacking height 8 crates. |
| | |
| 15-10-2010 | Pressure measurements for DTT at 4°C and humidifying 0.3 l/h. |
| 17-10-2010 | Pressure measurements for DTT at 18°C and humidifying 0.3 l/h. |
| 19-10-2010 | Pressure measurements for DTT at 4°C and humidifying 0.9 l/h. |
| | |
| 08-01-2011 | Start insulation value test 'best' container. |
| 09-01-2011 | End insulation value test 'best' container. |
| 03-02-2011 | Start insulation value test 'worst' container. |
| 04-02-2011 | End insulation value test 'worst' container. |

# Summary

Aim of this project was to assess what lily bulb shippers can do to improve temperature homogeneity in reefer containers loaded with lily bulbs.

The following questions are addressed by experimental research:

1. How is the current air flow distribution in loaded reefer containers? What is the ideal air flow distribution? Which measures are possible to bring the air flow distribution closer to the ideal situation?
2. What can be done to minimize the adverse effects of defrosting?
3. Where is the major heat source? Is it heat ingress through walls or is it respiratory heat production?
4. Could one reduce heat ingress by just selecting reefers with good insulation value?

It is concluded that lily bulb shippers can especially improve temperature homogeneity in reefer containers loaded with lily bulbs by:

1. Take measures to force air to the container's door-end. That is: block vertical air flow through vertical slits between pallets and between pallets and side walls in the part of the container closest to the unit-end.
2. Request 'AUTO' defrost interval. The reefer unit's artificial intelligence will automatically tailor the defrost interval to the rate of frost formation.
3. Request a defrost termination temperature of 8°C instead of the default 18°C.

What lily bulb shippers should not do to improve temperature homogeneity in reefer containers loaded with lily bulbs:

1. Don't worry about differences between types and age of reefer containers. Any ATO-certified reefer container of less than 5 years old should be suited for lily bulb transport.
2. Don't reduce stacking height till distinctly below the red 'till cargo line'. This project's measurements show that reducing stacking height from 10 to 8 crates has no effect at all on temperature.
3. Don't apply a filler (e.g. cardboard) to cover the part of the T-bar floor at the door-end which is not covered by cargo. This project's measurements reveal that all effort should be aimed at directing more air to the container's door-end. In that situation covering the T-bar might be counter-productive.

## Acknowledgements

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Moreover we thank Maersk Line for making available a 40ft HC reefer container for the air flow measurements and Defrost Termination Temperature experiments.