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Humidity Control in Reefer Containers

Effects of Humidity Control on climate and products

23-09-2004

J.E. de Kramer-Cuppen, R.A.M. Canters, J.D.H. Kelder, R.G.M. v.d. Sman, G.J.P.M. v.d Boogaard

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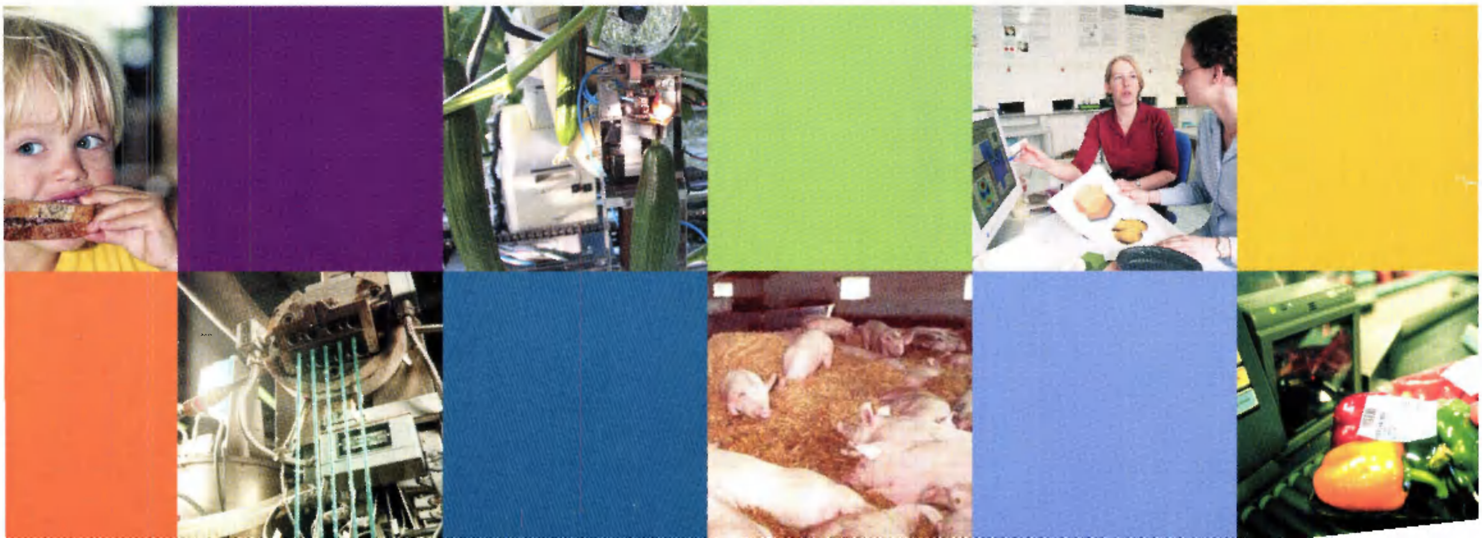

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1 Summary

1.1 Goal and methods

In this study the effect of humidifier use on storage RH and weight loss is investigated. As a general rule RH should be kept as high as possible to prevent weight loss. A humidifier can increase RH in a reefer container. Product itself, however, works as a water source too and in many cases RH will be high without the use of a humidifier. The main topics in this report are:

- a theoretical analysis of the possible effectiveness of humidifiers,
- model simulations of transport of apple, nectarine, banana and tomato,
- model descriptions that give insight in the physics of container climate dynamics,
- experiment results on Humicon use and mass transfer rate from container climate to package climate for various package types.

1.2 Relative humidity and weight loss

Produce loses weight by transfer of water vapor to the surrounding air. The driving force is the so-called 'water pressure deficit'. This is the difference between the water content of the air in the skin pores and the water content of the air surrounding the product. Since the air in the skin pores is approximately at product temperature and 100% RH, the water pressure deficit depends on the temperature difference between product and air and the RH of the (surrounding) air.

A few percent weight loss is normal for most products, weight losses < 0.5 % can be achieved in more optimal circumstances. Problems occur when weight loss is higher than a few percent, e.g. 3%.

1.3 Humidifier effectiveness

If weight loss during transport is an issue for a fruit or vegetable during storage, weight loss is 3% or more. For transport in a 40ft reefer container transport this amounts to more then 300 kg weight loss per trip. Humicon water supply is too small to make a significant difference in weight loss. In cases where Humicon can keep humidity at 95 % weight loss is not an issue. If Naturefresh could be used for its full capacity, its water supply might be large enough to be somewhat effective.

1.4 Product transport simulations

For the simulations the flow rates 0.0 ml/s (no humidification), 0.03 ml/s (Humicon maximum flowrate) and 0.3 ml/s (Naturefresh maximum flowrate) were used. The droplet sizes are d = 1 μm for Humicon and d = 75 μm for Naturefresh. Naturefresh works somewhat inefficiently due to the larger droplet size. Humicon, however, has a very small flow rate.

A humidifier in a container carrying 15.000 kg of produce could reduce weight loss by the amounts that are shown in the following table. A trip length of 3 weeks is assumed, with outside climate of Tamb = 20°C and RH = 85 %.

Tamb = 20°C	Maximum use Humicon	Maximum use Naturefresh	Tsup
Apple	-5 kg/trip	-19 kg/trip	1.5 °C
Nectarine	-25 kg/trip	-80 kg/trip	0.5 °C
Banana	-3 kg/trip	-18 kg/trip	14.4 °C
Tomato	-15 kg/trip	-57 kg/trip	9 °C

For banana, simulations were repeated for a lower outside temperature:

Tamb = 10°C	Maximum use Humicon	Maximum use Naturefresh	Tsup
Banana	-36 kg/trip	-90 kg/trip	14.4 °C
Tomato	-13 kg/trip	-54 kg/trip	9 °C

The exact amount of weight loss per trip, is influenced by humidifier use and efficiency, cultivar, product quality and outdoor conditions. However, the amount of weight loss reduction is not large. It seems not really worthwhile to use a humidifier. Only for nectarine and banana with low outside temperature, using Naturefresh at maximum dosage could be interesting. Also, if Naturefresh effectiveness would be increased by decreasing the droplet size while making maximum dosage of 0.3 ml/s possible, Naturefresh use could be interesting for other products.

In cool down situation weight loss is about 10-20 times higher then during steady state. Since supply air in cool down has a high RH, close to 100%, adding humidification does not help to reduce this weight loss significantly. However, it might be interesting to investigate the exact supply RH during cool down, since this has not been measured in detail. If supply RH is lower then 95%, adding a humidifier with flowrate of 0.3 ml/s or larger might be interesting.

1.5 Mass transfer measurements in a reefer container equipped with Humicon

Various tests have been conducted in a 40 ft container equipped with Humicon. One real pallet with boxes and product was used, the rest of the load was simulated. The measurements show that using Humicon will lead to a slightly higher RH in the container. How much higher will depend on the amount of cooling. Also, measurements showed an evenly distribution of the vapor in the container. Relative humidity is not or slightly dependent on position in the pallet or box type. When larger amounts of vapor will be distributed, like in the Naturefresh system, the distribution probably will be about the same.

The time constant for the spreading of vapor is in the order of a few minutes, so any change in humidity will take only a relatively small time to take effect in the whole container.

1.6 General conclusions

- Weight loss during storage/transport will reduce if the supply air RH is increased
- If weight loss during transport is an issue for a fruit or vegetable during storage, weight loss is more then 3%.
- Humicon can not increase supply air RH enough to make a significant difference in weight loss
- Naturefresh could be somewhat effective in weight loss reduction for certain products if droplet size is reduced and constant maximum water inflow is possible
- The transfer of water vapor from the T-bar into the boxes has a small time constant (in the order of a few minutes), so any change in humidity by a humidifier will take effect in the whole container. This holds true for open and closed boxes, without plastic product packaging.

2 Introduction

2.1 General

Relative humidity (RH) and dehydration-induced weight loss play an important role in refrigerated container transport. As a general rule RH should be kept as high as possible to prevent dehydration. But product itself works as a water source too and in many cases RH will be high without the use of a humidifier. In this study the effect of humidifier use on storage RH and weight loss is investigated. First, a theoretical analysis of the possible effectiveness of the humidifiers Humicon and Naturefresh is given. Secondly, model simulations of transport of four perishable products are shown. Transport without humidification is compared to transport with maximum water inflow from Humicon and Naturefresh. Also, the used macro climate model is explained, as well as the distribution model developed in Quest. Both give more insight in the physics of container climate dynamics. Thirdly, a number of experiments performed in a 40 ft container equipped with Humicon are described. Conclusions are drawn on the mass transfer rate from container climate to package climate for various package types. In this introduction some more background information is given on the relation between climate and weight loss and practical weight loss values for various products.

2.2 Fundamentals of climate and weight loss relation

Produce loses weight by transfer of water vapor to the surrounding air. The driving force is the so-called 'water pressure deficit'. This is the difference between the water content of the air in the skin pores and the water content of the air surrounding the product. Since the air in the skin pores is approximately at product temperature and 100% RH, the water pressure deficit depends on the temperature difference between product and air and the RH of the (surrounding) air.

Firstly, if the produce is warmer than the surrounding air, the rate of transfer will increase with increasing temperature difference. As the produce cools down, dehydration occurs: the bigger the temperature difference between cargo and cooling air, the more the produce will dry out. Secondly, when the air speed is increased, the boundary layer around the product is replaced more often and the transfer rate increases. Finally, the rate of transfer, and hence the rate of weight loss, increases with lower RH. If the circulation air has a high RH, the dehydration process will be slower compared to circulation with dry air.

Therefore, increasing RH influences the weight loss of the product. The weight loss of a product is the result of water loss and loss of mass by respiration. In this research weight losses by respiration is not considered, taking into account that evaporation is the main factor for weight losses.

2.3 Weight loss information for various products

To give the reader an idea of the weight losses found in practice, the weight loss information from the commodity overview is summarized in the following tables. For many products the exact amount of weight loss not described in literature. For other products a value is given without reference to the exact circumstances (packaging, manner of transport) or timescale. Therefore, these values are indicative but one should be careful in drawing general conclusions for a specific product. A few percent weight loss is normal for most products, weight losses < 0.5 % can be achieved in more optimal circumstances. Problems occur when weight loss is higher than a few percent, e.g. 3%.

In Table 1 the weight loss percentages for various products are shown. Column 2 shows the normally possible weight loss in %/week, column 3 the weight loss when optimal conditions are used, column 4 the normal loss in %, where the timescale is unknown (time is probably transport time) and column 5 shows the % of weight loss where problems occur. In Table 2, for products stored at relatively high RH, general weight loss and humidity information from the commodity overview is summarized per product.

Product	***normal %/week***	***opt %/week***	***% normal loss***	***% problem loss***
Apple	2.5 - 3.5	0.1 - 0.2		
Avocado	2.5			
Banana			0.5 – 1	3
Broccoli				> 4
Grape	> 3.5	B.A.: 0.4	2 – 3	
Lemon			1 – 2	
Mandarin			1 – 2	
Orange			1 – 2	
Peach and Nectarine				3 – 4
Pear			1	
Pineapple				8 – 10 (< 85 %)
Potato			1 – 3	
Sweet pepper			2 – 3	

Table 1 Weight loss percentage information for various products

Apple	The weight loss due to respiration and evaporation depends heavily on the humidity. At 3°C weight losses of 0.5% per day can be reached at 86% RH, while at 95% weight losses are restricted to 0.35%. [9] Under optimal conditions weight losses can be restricted to 0.1 - 0.2% per week. [8]
Avocado	Avocados have to be protected from all forms of moisture (seawater, rain and condensation water) to prevent mold, rot and fruit spoilage. [1] Weight loss due to the release of water vapor does not generally occur. [1] Other sources speak of medium water losses of 2.5% per week [8] Average weight loss of Hass avocados at RH of 95%, 60% and 5% are respectively 0.2, 0.5 and 1.0% per day at 20°C. Ripening was advanced by 3 to 4 days for fruits held at 60% or 5% RH compared with those at 95%. [14] Water losses (2-6%) of avocados will accelerate the severity of cold damage at 5°C storage. [15]
Banana	Normal weight loss caused by a reduction in moisture content depends on the variety and may amount to 0.5 - 1% (3% in unfavorable instances) Where humidity is too low, the ripening process may be incomplete and weight may be lost through the release of water vapor. The bananas are packaged in perforated polyethylene film, to ensure the necessary humidity. [1].
Broccoli	A maximum of 4% weight loss is acceptable to avoid wilting, shriveling, and senescence symptoms on the broccoli. Benefits of high RH within wrapped packages include weight loss alleviation, less cross-contamination, delaying senescence and good retention of quality attributes, although risk of fungal development due to water condensation could increase. [17]
Grape	Low humidity stimulates weight losses and shriveling of the grapes. If shriveling of the grapes is to be avoided, relative humidity should be approx. 90 - 95%. However, relative humidity ranges of 85 - 90% are recommended in order to avoid moistening of the packaging materials, such as wood wool, and consequent mold growth on the grapes. The cargo must be protected from seawater, rain and condensation water as moistening of the cargo and packaging materials increases the risk of spoilage. Shriveling and drying of the grapes may be avoided by packaging them in perforated polyethylene film inside the fruit crates. [1] High humidity in combination with high temperature (>5°C) greatly affects the growth of Botrytis. During transport a SO_2 pad can be added. SO_2 inhibits the growth of Botrytis. Water loss of grapes is considered as high (3.5% per week and higher) [8] The normal weight loss due to a reduction in the moisture content of the product is 2 - 3%. [1] Weight losses of cv 'Black Alicante' is about 1% each 20 days of storage at 0.5°C and 95% RH. [9] A too high level of RH or insufficient air circulation can cause cracks in the grapes. [9] Wetness of the surface of the grapes will not enhance the surface colonization potential of *Botrytis cincerea*. With a high humidity (93%) airborne conidia of B. cincerea will have an equal potential to infect dry and wet berry surfaces. [22]
Grapefruit	Waxing to prevent loss of aroma and weight is required because the washing process removes the natural wax layer. The film of wax sprayed onto the peel only partially seals the pores so that the fruits are still able to respire. [1]

	It is essential to protect grapefruit from moisture (seawater, rain, condensation, and snow) as moisture in particular promotes green and blue mold and black rot. In general, due to the high water content of grapefruit of approx. 87%, a relative humidity of 85 - 90% is required. Only lemons, oranges and mandarins with a dark green peel color are able to withstand a relative humidity of 82 - 85%. [1]
Kiwi	Optimum humidity 90 - 95% [1] [2] [10] [11] Kiwifruit must be protected from all forms of moisture, to prevent mold, rot and fruit spoilage. [1]
Lemon	Waxing to prevent loss of aroma and weight is required because the washing process removes the natural wax layer. The film of wax sprayed onto the peel only partially seals the pores so that the fruits are still able to respire. [1] The normal weight loss due to a reduction in the moisture content of the product is approx. 1 - 2%. [1]
Mandarin	Waxing to prevent loss of aroma and weight is required because the washing process removes the natural wax layer. The film of wax sprayed onto the peel only partially seals the pores so that the fruits are still able to respire. [1] The normal weight loss due to a reduction in the moisture content of the product is approx. 1 - 2%. Seawater, rain and condensation water promote green and blue mold growth. [1]
Mango	If optimum relative humidity values are not maintained, weight loss may occur due to release of water vapor. [1]
Orange	Waxing to prevent loss of aroma and weight is required because the washing process removes the natural wax layer. The film of wax sprayed onto the peel only partially seals the pores so that the fruits are still able to respire. [1] It is essential to protect oranges from moisture (seawater, rain, condensation, and snow) as moisture in particular promotes green and blue mold and black rot. In general, due to the high water content of citrus fruit of approx. 86%, a relative humidity of 85 - 90% is required. Only lemons, oranges and mandarins with a dark green peel color are able to withstand a relative humidity of 82 - 85%. [1] The normal weight loss due to a reduction in the moisture content of the product is approx. 1 - 2%. Losses of volume occur due to breakage of the packaging and theft. Less volume is lost when wire-bound boxes and sealed cartons are used instead of other types of packaging. [1]
Peach and nectarine	Optimum humidity: 90 - 95% (sometimes 85 - 90% is recommended) [1], [5] [11] Since peaches have a tendency to dry out, care should be taken to comply exactly with the recommended humidity. [1] A weight loss of 3-4% of the original weight will usually result in noticeable shrivel. [11]
Pear	The normal weight loss due to a reduction in the moisture content of the product is < 1% [1] To an even more serious extent than apples, shriveling due to moisture loss frequently occurs in pears. The RH in the cooled compartment must therefore be kept as high as possible. Moisture encourages mould growth. Use of plastic foil do indeed prevent shriveling, their drawback is that the air inside has very high relative humidity, which in turn is conducive to mould growth. [11] Optimum RH 80-95% [1], 90-95% [5],[11]
Pepper, bell	It is essential to maintain high relative humidity levels, as sweet peppers have a tendency to shrivel

	rapidly. Weight loss amounts to approx. 2 - 3 %, depending on the prevailing humidity, and is a consequence of the thin skin surrounding the fruit, leading to a rapid onset of shriveling and shrinkage of the sweet peppers. On the other hand, protection from moisture (seawater, rain and condensation water) is advisable, to prevent the sweet peppers from turning moldy and rotting. [1].
Pineapple	Max airflow 15 cmh [7]. Recommended ventilation conditions: air exchange rate 40 - 60 times per hour with constant supply of fresh air, so as constantly to remove the ripening gases arising and to keep the CO_2 content of the hold air low. Spoilage may occur as a result both of inadequate ventilation (danger of rotting) and of excessive ventilation (drying-out, weight loss). [1] Vigorous ventilation is not necessary and 1 air exchange per hour will suffice. [11] Since the fruit transpires heavily, it would shrivel severely at relative humidities of < 85%. Moisture on the fruit, such as seawater, condensation water, rain or the like, results in rapid spoilage. [1] Spoilage may occur as a result both of inadequate ventilation (danger of rotting) and of excessive ventilation (drying-out, weight loss). The fruit's respiration process and excessive ventilation may cause weight losses of 8 - 10%. It is possible to protect the cargo from weight loss by treatment with wax emulsions (dipping, spraying). [1]
Plum	Optimum humidity: 90 - 95% [5] [10]
Potato	Mature, firm-skinned tubers exhibit only 1 - 3% weight losses due to transpiration.
Tomato	At relative humidities < 80%, tomatoes lose weight and their quality is degraded by evaporation. At relative humidities > 90% there is considerable risk of mold growth and rot. During cooling of the product, a relative humidity of < 80% should be maintained, to check any possibility of mold attack initially by the low relative humidity and subsequently by a low travel temperature. After the reduction period, the relative humidity should be increased to the values indicated above, to prevent drying-out of the product and thus greater weight and quality loss. [1]

Table 2 General weight loss information for various products

2.4 Disclaimer

The experiments and calculations done within this project are simulations of real transports. Despite all efforts to mimic real situations as good as possible, translation of results to real life situations should be made very carefully to avoid errors. Experimental set-ups and model calculations do not show all possible conditions during real transport according to real life situations. Parameters have to be chosen for product, packaging, stacking, container settings and outside conditions. For example, quality of fresh products can vary a lot due to seasonal effects, initial quality, cultivar, location of growth, etc. Therefore, results of the experiments and calculations described here are only indicative for real transports.

3 Effectiveness humidifiers for weight loss reduction

Fruit and vegetables lose weight by transpiration if they are stored or transported. The transpiration rate depends on the product, in particular its skin type, and the water pressure deficit. If product and surrounding air have the same temperature, transpiration will become negligible if the air is saturated. If the air is not saturated, water loss can be reduced by increasing the RH. The effectiveness of the water added by Humicon and Naturefresh will be evaluated in this chapter. Two viewpoints are taken: first, the amount of water that can be added to replace weight loss and second, the change in RH of the supply air that can be achieved.

3.1 The maximum amount of water added

The amount of water added externally is the maximum amount of water loss that can be reduced, since the external water source will replace part of the product transpiration. Therefore, the amount of water that can be added by the humidifier determines the maximum effectiveness. In case all water applied becomes part of the air in the container, Naturefresh and Humicon can reduce water loss with 181 kg and 14 kg respectively:

Maximum (theoretical) water inflow Naturefresh:	2.5 lb/h = 0.3 ml/s = 26 kg/day
Maximum water inflow Humicon:	0.22 lb/h = 0.03 ml/s = 2.6 kg/day
Max. water input per week Naturefresh:	48 gallon = 181 kg
Max. water input per trip Humicon:	3.6 gallon = 13.6 kg

The mass of product in a container is approximately 10.000 - 20.000 kg, so to reduce weight loss by 1% more than 100 - 200 kg water input is necessary. The Humicon system can only reduce weight loss by maximal 0.14 – 0.07 % per trip or 0.18 % - 0.09 % per week if the tank is refilled.

3.2 The effect of the water inflow on supply air RH in steady state

The effect of the water input on RH in the container depends on the RH of the supply air before water input, the water inflow and the circulation rate. The maximum water inflow for Naturefresh is 0.3 ml/s and for Humicon: 0.03 ml/s. The circulation rate in a reefer container app. 70 m^3/min (=1.2 m^3/s). In the steady state situation, where the supply air has a constant RH, the water content of the air can be increased by 0.26 g/m^3 (Naturefresh) and 0.026 g/m^3 (Humicon).

The maximum water content depends on the temperature of the air, the water content x is (RH) % of x_{max}. Therefore, the RH increase by a humidifier is a function of water inflow and temperature. In the following figure, the maximum water content is shown as a function of temperature. In the lower part of the figure The amount of water that is necessary to increase the RH with 1 % is compared to the maximum water inflow of Naturefresh and Humicon.

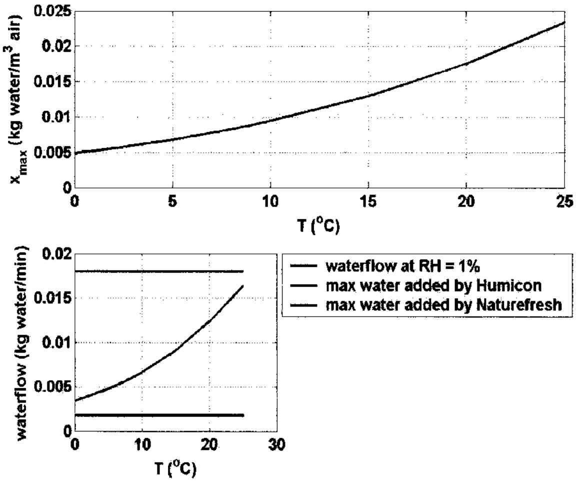

Figure 1 Water content of air compared to water inflow humidifiers

In the following graph the possible RH increase of the supply air is shown. The maximum RH increase of the supply air in steady state is 1 - 5 % (Naturefresh) and 0 - 0.5 % (Humicon).

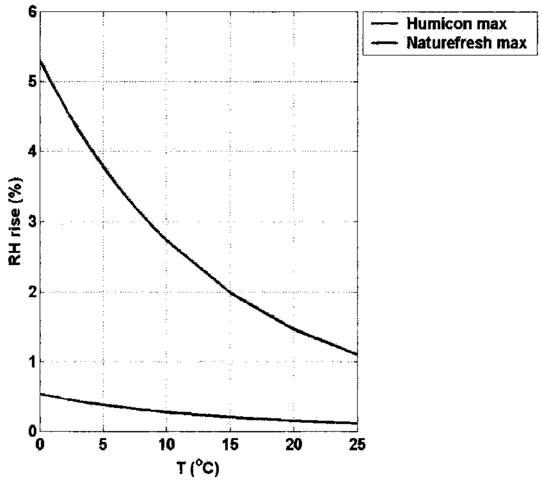

Figure 2 Maximum possible RH increase by humidifiers

3.3 Product quality improvement by raising RH and weight loss prevention

Most perishable products are sensitive for weight loss. Only bulbs like unions, garlic and flower bulbs are stored at RH conditions below 80%. For most other perishable products the optimal RH is a balance between problems caused by a low RH (such as firmness, appearance, discoloration and costs, weight loss is kg product) and the risk of problems caused by a too high humidity (such as mould grow and discoloration). The effect of dehydration is usually preferred above the effects of too high RH. The main reason being that the effects of dehydration do not show immediately and have less impact on the product quality then problems caused by high RH.

The introduction already showed that a few percent weight loss is normal for most products and weight losses < 0.5 % can be achieved in more optimal circumstances. Problems occur when weight loss is higher than a few percent, e.g. 3%. Even for leafy products like spinach and lettuce with high moisture loss, 3 – 5 % weight loss can be tolerated. Also, the storage time in which this amount of moisture is lost is relatively short (10-14 days). Another kind of product that is sensitive for weight loss is bunched carrots. If carrots lose too much weight, they loose their color and crispness. But also in this case "optimal" weight loss is approximately 2% (98% RH). When stored at higher RH (and thus lower weight loss) the possibility of problems caused by bacterial decay are considered a greater problem.

A rule of thumb is that weight loss during transport becomes an issue for fruit and vegetables if weight loss is 3% or more.

3.4 General conclusions effectiveness humidifiers for weight loss reduction

If weight loss during transportation is an issue for a fruit or vegetable during storage, weight loss is 3% or more. For transport in a 40ft reefer container transport this amounts to more then 300 kg weight loss per trip. Humicon water supply is too small to make a significant difference in weight loss. In cases where Humicon can keep humidity at 95 % weight loss is not an issue. If Naturefresh could be used for at full capacity, its water supply might be large enough to be effective.

4 Simulations for apple, nectarine, banana and tomato

4.1 Model descriptions

4.1.1 Macro climate model

To illustrate the effect of humidification on weight loss for various products, the A&F macro climate model (also used in Quest) was adapted. This model is a combination of a cooling unit model and a climate model. Given the setpoints and the return air conditions, the cooling unit model part computes the energy consumption of the unit and also the conditions of the supply air, i.e. its temperature, humidity, and respiratory gas concentrations. The climate model part predicts the change in product temperature, humidity and gas conditions in the container box and the return air as a function of the box and product parameters, the conditions of the supply air, the ventilation settings and outdoor conditions.

4.1.2 Distribution model

The Quest distribution model was adapted for humidity calculations as well. The temperature and humidity part of the model is described in Appendix 5. In appendix 4 some remarks are made on the moisture loss physics used in the distribution model. Simulations with this model were not performed in this project, to make room for effectiveness studies and explanation.

4.2 Quest Macro Climate Model adaptations for humidification

A humidifier with an adjustable water inflow rate was added. For the simulations the flow rates 0.0 ml/s (no humidification), 0.03 ml/s (Humicon maximum flowrate) and 0.3 ml/s (Naturefresh maximum flowrate) were used. The droplet sizes $d = 1\ \mu m$ for Humicon and $d = 75\ \mu m$ for Naturefresh flowrate were used to calculate the needed mass transfer coefficient and the transfer rate of mist droplets to water vapor.

The underlying equations and the influence of the droplet size are explained below. Naturefresh works somewhat inefficiently due to the larger droplet size. Humicon has a relatively small flow rate.

4.2.1 Modeling mass transfer mist droplets to water vapor

The mass transfer is described with the following mass balance:

$$dM_{mist}/dt = J_{mist,in} - J_{ma} - J_{mist,out}$$

Here M_{mist} [kg] is the total mass of mist droplets contained in the volume of air V_{air} [m^3] inside the container. Time t is defined in [s]. We can define the mass density of mist droplets, c_{mist} [kg/ m^3]:

$M_{mist} = c_{mist}.V_{air}$

There are three mass fluxes: $J_{mist,in}$ [kg/s] is the constant mass flow rate of mist droplets generated by the atomizer, $J_{mist,out}$ [kg/s] is the mist droplets entering the cool unit via the return air, and J_{ma} [kg/s] is the mass transfer from the mist droplets to the water vapor phase. For the last two mass flow rates, we have the following flux laws:

$J_{mist,out} = c_{mist}\ \Phi_v$

$J_{ma} = k_{ma}.A_{mist}.(c_{sat}(T_a) - c_{air})$

Here Φ_v [m^3/s] is the volumetric flow rate of the air, k_{ma} [m/s] is the mass transfer coefficient, A_{mist} [m^2] is the total surface area of all mist droplets, $c_{sat}(T_a)$ [kg/m^3] is the saturated mass density of water vapor in air at temperature T_a, and c_{air} [kg/m^3] is the actual water vapor concentration. In the flux law of $J_{mist,out}$ we have assume that the air is perfectly mixed and thus has a uniform c_{mist}.

The mass transfer coefficient follows from the correlation of flow around a sphere. The kinematic viscosity of dry air $\nu = 0.13*10^{-4}\ m^2/s$, the diffusion constant for air - water vapor $D = 2.6*10^{-5}\ m^2/s$. If we assume that the droplet has a diameter of $d = 10^{-6}$ m, and that the average airflow velocity $u = 3$ m/s, the Reynolds number is: $Re = u.d/\nu = 0.23$, and the Sherwood number is $Sh=2+0.66.Re^{0.5}.Sc^{0.33} = 2.3$. Here, the Schmidt number is $Sc=0.5$. Also, $Sh=k_{ma}.d/D$, so $k_{ma} = 58.5$ m/s. For larger droplets, the value of k_{ma} decreases.

It should be noted that A_{mist} is proportional to the number of mist droplets, and thus with c_{mist}. It is computed as follows:

$A_{mist} = c_{mist} V_{air}\ 6/(\rho_w\ d)$

Here, V_{air} is the volume of air in the container, approximately 60 m^3, and ρ_w is the mass density of water $10^3\ kg/m^3$. J_{ma} becomes:

$J_{ma} = c_{mist}\ k_{ma}\ V_{air}\ 6\ (c_{sat}(T_a) - c_{air})/\ (\rho_w\ d)$

We define:

$\phi_{ma} = 6\ k_{ma}\ V_{air}\ /(\rho_w\ d)$ and $c_{air} = (1-\chi)\ c_{sat}(T_a)$.

Where $1-\chi$ [-] is the water content fraction, c_{sat} is taken $5*10^{-3}$ kg/ m^3 and ϕ_{ma} has unity: [m^3/s]. $1-\chi$ is approximately 0.95. k_{ma} is related to Sh, and hence $\phi_{ma} \sim 1/d^2$. This gives:

$\phi_{ma} = 6\ V_{air}\ Sh\ D\ /\ (\rho_w\ d^2)$

Using the above defined variables, we redefine the mass flux from mist droplets to air as:

$J_{ma} = c_{mist}\ k_{ma}\ V_{air}\ 6\ \chi\ c_{sat}(T_a)/\ (\rho_w\ d) = c_{mist}\ \phi_{ma}\ \chi$

In steady state we have: $dM_{mist}/dt = 0$ kg/s and thus:

$J_{mist,in} = J_{ma} + J_{mist,out} = c_{mist}\ (\ \Phi_v + \chi\ \phi_{ma}\ )$

Redefining the generated mass flux of mist droplets as:

$J_{mist,in} = \ \Phi_v\ c_{in}$

The final mist density in the return air is:

$c_{mist} = \ \Phi_v\ c_{in}\ /\ (\ \Phi_v + \chi\ \phi_{ma}\ )$

The mister operates efficiently if the mist evaporates quickly. The amount of mist droplets in the container should be much less than the amount of inserted mist droplets: $c_{mist} << c_{in}$.This is the case if $\chi\ \phi_{ma} >> \Phi_v$. Assume air has humidity 98% (and thus χ=0.02). Φ_v is approximately 1.2 m^3/s at full speed and 0.6 m^3/s at half speed. With d = 10^{-6} m (Humicon), $\chi\ \phi_{ma} \approx 2\ 10^3\ m^3/s$ and thus is much larger then Φ_v. For d = 75 10^{-6} m (Naturefresh), $\chi\ \phi_{ma} \approx$ 0.66 m^3/s and thus is in the same order of magnitude as Φ_v. Assume air has humidity 80% (and thus χ=0.2). With d = 10^{-6} m (Humicon), $\chi\ \phi_{ma} \approx 2\ 10^4\ m^3/s$ and thus is much larger then Φ_v. For d = 75 10^{-6} m (Naturefresh), $\chi\ \phi_{ma} \approx$ 6.6 m^3/s and thus is somewhat larger then Φ_v. The droplet size of Naturefresh prevents the mister from working efficiently. For Humicon this is no problem.

The following Matlab code was used to calculate the mass transfer coefficient for various droplet sizes:

```
d=[1e-6 75e-6 100e-6 200e-6 300e-6] %droplet diameter (m), 75 mu for Naturefresh, 1 mu for Humicon
T = 273;            %Temperature (K)
u = 3;          %average airflow velocity (m/s)
nu_dryair = 0.132e-4;   %kinematic viscosity of dry air (m^2/s)
D = 2.6e-5;     %diffusion constant air-water vapor (m^2/s)
rhow = 1000;        %density of water (kg/m^3)
Va = 60;            %volume of air (m^3)
```

```
c_sat = 4.8e-3;      %(kg/m^3)

Sc = nu_dryair/D;
Re = u*d/nu_dryair
Sh = 2+0.66*Re.^0.5*Sc^0.33
kma = Sh*D./d
fac_kma = kma*6
phima_frac= Sh*D*Va*6*c_sat./rhow
phima = kma*Va*6*c_sat./(rhow.*d)      % = phima_frac./d.^2

% results:
% d =       1e-006     7.5e-005   0.0001     0.0002     0.0003
% Re =      0.22727    17.045     22.727     45.455     68.182
% Sh =      2.2516     4.1787     4.5157     5.5578     6.3574
% kma =     58.541     1.4486     1.1741     0.72251    0.55097
```

It is clear to see that decreasing the droplet size, gives a large increase of the mass transfer coefficient and therefore increases mister efficiency.

4.3 Product choice for simulations

In appendix 3, the mass transfer coefficient of various products are shown. The simulations should show the influence of humidification for products that are sensitive (high Kskin) and less sensitive (low Kskin) to weight loss. Also, products should be chosen for high and low temperature range, since at higher temperature more water is needed to increase RH. Apple and nectarine are preferred since these products were chosen for the detailed product research. For the low temperature range nectarine is a good representative for weight loss sensitive products. Apple is a good representative for less sensitive products. For the high temperature range, tomato (sensitive) and banana (less sensitive) are good representatives. Therefore, apple, nectarine, tomato and banana are chosen for the simulations.

4.4 Simulations

Simulations were made for 10 day transport of a 40ft reefer container filled with , apple, nectarine, tomato and banana. Both steady state and cool down situations were studied. No humidification was compared to maximum possible humidification by Humicon and Naturefresh. Feedback control on RH is not used. This shows the maximum possible effect of the humidifiers. The results are summarized in tables. In these tables the flowrate of humidification is given in (ml/s), with the corresponding mass loss in steady state after 10 days, $\Delta M_{ss}(\%)$,the mass loss with cool down after 2 days, $\Delta M_{cd,2d}(\%)$, the mass loss with cool down after 10 days, $\Delta M_{cd,10d}(\%)$ and the steady state mist content of the air in the box,

$c_{mist,10d}$ (g/m3). All graphs are shown in Appendix 1. Below some examples and explanation of the graphs is given.

The following graph shows simulation results for 10 day transport of apple with constant maximum humidification of Humicon. On the left-hand top side the temperature of the product (Tp), the return air (Tret) and the supply air (Tsup) are shown. Product is set to supply air temperature at the start of the simulation, to show the steady state effect of humidification. Product temperature increases somewhat due to its own heat production. On the left-hand bottom side the relative humidity of the return air (RHret) and the supply air (RHsup) are shown. Initial (and outside) RH is set to 85%, but increases rapidly. Here RHret and Tret are taken below the air inlet and above the evaporator coil. On the right-hand top side the moisture loss of the product (Mp) is shown as a percentage of product weight. For constant temperature and RH. Moisture loss increases linearly in time. On the right-hand bottom side the water droplet content of the air in the container (cmist) is shown. For Humicon this is a very small amount, since the water droplets evaporation rate is large compared to the air circulation, as explained above.

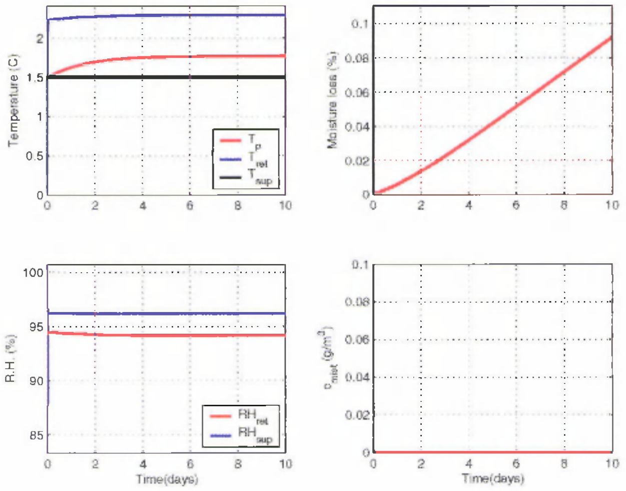

Figure 3 Apple steady state: humidification 0.03 ml/s, ventilation 60 cmh, circulation 1.2 cms

The following graph shows simulation results for 10 day transport of apple with constant maximum humidification of Naturefresh and cool down. During the decrease of the product temperature from 15 °C to 1.5 °C (see left-hand top side), moisture loss increases more quickly than during steady state (see right-hand top side).

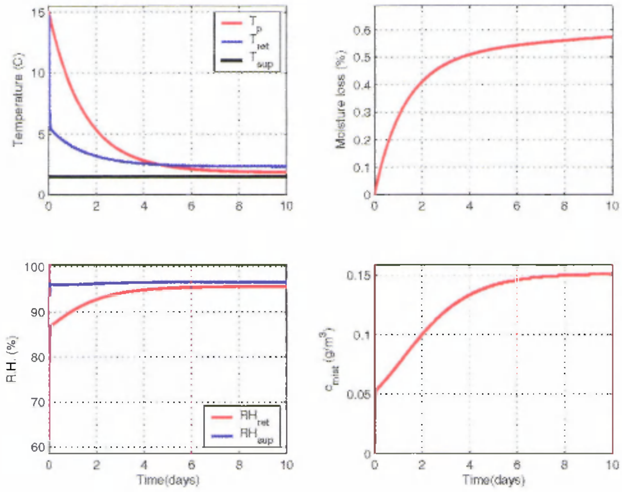

Figure 4 Apple cool down: humidification 0.3 ml/s, ventilation 60 cmh, circulation 1.2 cms

4.4.1 Apple simulations

The results for apple transport simulations are shown in the following table, see appendix 1 for the graphs.

Flowrate (ml/s)	ΔM_{ss} (%)	$\Delta M_{cd,2d}$ (%)	$\Delta M_{cd,10d}$ (%)	$c_{mist,10d}$ (g/m3)
0	**0.107**	**0.432**	**0.648**	**0.000**
0.03	**0.092**	**0.429**	**0.634**	**0.000**
0.3	**0.047**	**0.410**	**0.574**	**0.151**

Table 3 Apple simulation results, , Tamb = 20 °C

The apple simulations show a small amount of weight loss, as can be expected for a product that is relatively insensitive to weight loss and is stored at a low temperature. Adding a humidifier reduces weight loss by 0.015 %/10 days or 0.060%/10 days. This is comparable to the results of the product quality research[1], taken into account the increase in supply RH

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[1] The product research report shows that if a humidification system could increase the supply RH by 5% (maximum for Naturefresh), apple would lose approximately 0.025%/week less water if circulation rate is 1/h. For a container filled with 15.000 kg of apple, this would result in approximately 11 kg less weight loss for a 3-week trip. If a humidification system could increase the supply RH by 0.5% (maximum for Humicon) this would result in approximately 1.1 kg less weight loss for a 3-week trip. Since the circulation rate of a container usually is 1/min, weight loss will be larger, see simulations.

that the humidifiers can accomplish (+0.5 % and +5 % respectively) and the much smaller circulation rate in the product experiments. A humidifier in a container carrying 15.000 kg of apple could reduce weight loss by approximately 0.23 and 0.90 kg/day, that is 4.8 or 18.9 kg/trip of 3 weeks. The exact amount of course, is influenced by humidifier use and efficiency, apple cultivar, apple quality and outdoor conditions. However, the amount of weight loss reduction is so small that it seems not to be worthwhile to use a humidifier in this case.

In cool down situation weight loss is about 20 times higher. Since supply air in cool down has a high RH, close to 100%, adding humidification does not help to reduce this weight loss significantly. However, it might be interesting to investigate the exact supply RH during cool down, since this has not been measured in detail. If supply RH is lower then 95%, adding a humidifier with flowrate of 0.3 ml/s or larger might be interesting.

4.4.2 Nectarine simulations

The results for nectarine transport simulations are shown in the following table, seeappendix 1 for the graphs.

Flowrate (ml/s)	ΔM_{ss} (%)	$c_{mist,10d}$ (g/m3)
0.00	**0.533**	**0.000**
0.03	**0.454**	**0.001**
0.30	**0.278**	**0.161**

Table 4 Nectarine simulation results, Tamb = 20 °C

The nectarine simulations show about 0.05 %/day weight loss. This is much more then apple, but not a very large value, as can be expected for a product that is relatively sensitive to weight loss and is stored at a low temperature. Adding a humidifier reduces weight loss by 0.079 %/10 days or 0.255%/10 days. This is comparable to the results of the product quality research[2], taken into account the increase in supply RH that the humidifiers can accomplish (+0.5 % and +5 % respectively) and the much smaller circulation rate in the product

---

[2] The product research report shows that if a humidification system could increase the supply RH by 5% (maximum for Naturefresh), nectarine would lose approximately 0.05%/week less water if the circulation rate is 1/h. For a container filled with 15.000 kg of nectarine, this would result in approximately 22 kg less weight loss for a 3-week trip. If a humidification system could increase the supply RH by 0.5% (maximum for Humicon) this would result in approximately 2.2 kg less weight loss for a 3-week trip. Since the circulation rate of a container usually is 1/min, weight loss will be larger, see simulations.

experiments. A humidifier in a container carrying 15.000 kg of nectarine could reduce weight loss by approximately 1.2 and 3.8 kg/day, that is 25 or 80 kg/trip of 3 weeks. The exact amount of course, is influenced by humidifier use and efficiency, nectarine cultivar, nectarine quality and outdoor conditions. However, the amount of weight loss reduction is not large. It seems not really worthwhile to use a humidifier in this case.

4.4.3 Banana simulations

The results for banana transport simulations are shown in the following tables, see see appendix 1 for the graphs.

Flowrate (ml/s)	ΔM_{ss} (%)	$\Delta M_{cd,2d}$ (%)	$\Delta M_{cd,10d}$ (%)	$c_{mist,10d}$ (g/m3)
0.00	**0.107**	**0.191**	**0.324**	**0.000**
0.03	**0.098**	**0.189**	**0.315**	**0.001**
0.30	**0.049**	**0.175**	**0.262**	**0.102**

Table 5 Banana simulation results, Tamb = 20 °C

Flowrate (ml/s)	ΔM_{ss}(%)	$c_{mist,10d}$ (g/m3)
0.00	**0.325**	**0.000**
0.03	**0.212**	**0.000**
0.30	**0.038**	**0.111**

Table 6 Banana simulation results, Tamb = 10 °C

The banana simulations show about 0.01 %/day weight loss. This is comparable to apple, a small value. For banana the ventilation rate is high and outside air water content has a large influence. Therefore, steady state simulations were also done for a lower outside temperature, 10 °C and RH = 85%. Weight loss for that situation is about 3 times higher than for 20°C and RH = 85%. Banana is relatively insensitive to weight loss, due to the peel. For Tamb = 20°C, adding a humidifier reduces weight loss by 0.009 %/10 days or 0.058%/10 days. This is comparable to the results for apple. The difference between the maximum effect of Humicon and Naturefresh is somewhat larger, due to the higher storage temperature. A humidifier in a container carrying 15.000 kg of banana could reduce weight loss by approximately 0.13 and 0.87 kg/day, that is 3 or 18 kg/trip of 3 weeks. For Tamb = 10°C, adding a humidifier reduces weight loss by 0.113 %/10 days or 0.287%/10 days. In this case, a humidifier in a container carrying 15.000 kg of banana could reduce weight loss by approximately 1.7 and 4.3 kg/day, that is 36 or 90.4 kg/trip of 3 weeks. The exact amount of course, is influenced by humidifier use and efficiency, banana cultivar, banana quality and outdoor conditions. However, the amount of weight loss reduction is not very large. It seems only worthwhile to use a humidifier in case water inflow is high (about 0.3 ml/s), ventilation is high and outside water content is low. For banana, a tropical produce, low outside transport temperature and/or RH during a large part of the trip will not be very common.

In cool down situation weight loss is about 10 times higher. Since supply air in cool down has a high RH, close to 100%, adding humidification does not help to reduce this weight loss significantly. However, it might be interesting to investigate the exact supply RH during cool down, since this has not been measured in detail. If supply RH is lower then 95%, adding a humidifier with flowrate of 0.3 ml/s or larger might be interesting.

4.4.4 Tomato simulations

The results for tomato transport simulations are shown in the following table, see see appendix 1 for the graphs.

Flowrate (ml/s)	ΔM_{ss}(%)	$c_{mist,10d}$ (g/m3)
0.00	**0.830**	**0.000**
0.03	**0.783**	**0.001**
0.30	**0.649**	**0.148**

Table 7 Tomato simulation results, Tamb = 20 °C

Flowrate (ml/s)	ΔM_{ss}(%)	$c_{mist,10d}$ (g/m3)
0.00	**0.777**	**0.000**
0.03	**0.736**	**0.001**
0.30	**0.606**	**0.157**

Table 8 Tomato simulation results, Tamb = 10 °C

The tomato simulations show about 0.08 %/day weight loss. This is much more then apple, as can be expected for a product that is sensitive to weight loss and is stored at a relatively high temperature. For Tamb = 20°C, adding a humidifier reduces weight loss by 0.047 %/10 days or 0.181%/10 days. This is comparable to the results for nectarine. A humidifier in a container carrying 15.000 kg of tomato could reduce weight loss by approximately 0.7 and 2.7 kg/day, that is 15 or 57 kg/trip of 3 weeks. For Tamb = 10°C, adding a humidifier reduces weight loss by 0.041 %/10 days or 0.171%/10 days. A humidifier in a container carrying 15.000 kg of tomato could reduce weight loss by approximately 0.6 and 2.6 kg/day, that is 13 or 54 kg/trip of 3 weeks. The exact amount of course, is influenced by humidifier use and efficiency, tomato cultivar, tomato quality and outdoor conditions. However, the amount of weight loss reduction is not very large. It seems not worthwhile to use a humidifier in this case.

4.5 Simulation conclusions

A humidifier in a container carrying 15.000 kg of produce could reduce weight loss by the amounts that are shown in the following table. A trip length of 3 weeks is assumed, with outside climate of Tamb = 20°C and RH = 85 %.

Tamb = 20°C	**Maximum use Humicon**	**Maximum use Naturefresh**	**Tsup**
Apple	-5 kg/trip	-15 kg/trip	1.5 °C
Nectarine	-25 kg/trip	-80 kg/trip	0.5 °C
Banana	-3 kg/trip	-18 kg/trip	14.4 °C
Tomato	-15 kg/trip	-57 kg/trip	9 °C

For banana, simulations were repeated for a lower outside temperature:

Tamb = 10°C	**Maximum use Humicon**	**Maximum use Naturefresh**	**Tsup**
Banana	-36 kg/trip	-90 kg/trip	14.4 °C
Tomato	-13 kg/trip	-54 kg/trip	14.4 °C

The exact amount of weight loss per trip, is influenced by humidifier use and efficiency, cultivar, product quality and outdoor conditions. However, the amount of weight loss reduction is not large. It seems not really worthwhile to use a humidifier. Only for nectarine and banana with low outside temperature, using Naturefresh at maximum dosage could be interesting. Also, if Naturefresh effectiveness would be increased by decreasing the droplet size while making maximum dosage of 0.3 ml/s possible, Naturefresh use could be interesting for other products.

In cool down situation weight loss is about 6-20 times higher then during steady state. Since supply air in cool down has a high RH, close to 100%, adding humidification does not help to reduce this weight loss significantly. However, it might be interesting to investigate the exact supply RH during cool down, since this has not been measured in detail. If supply RH is lower then 95%, adding a humidifier with flowrate of 0.3 ml/s or larger might be interesting.

5 Tests of the Humicon and determining of the mass transfer coefficient

5.1 Goal and method

Various tests have been conducted in a 40 ft container equipped with Humicon. One real pallet with boxes and product was used, the rest of the load was simulated. The measurements show the difference in humidity between a container with Humicon and one without it. Furthermore, they give insight into the mass transfer coefficient of water vapor from the air in the container into the stack of boxes in the load. Enforcing a step in relative humidity is the method used to determine this.

5.2 Mass transfer theory

In this section the basics of mass transfer will shortly be described.

The basic equation for the mass transport is the following:

$$\dot{m}_{outbox} = \dot{m}_{outpallet} \qquad (2.1)$$

Mass flow out of the boxes is equal to the mass flow out of the pallet

This can be written as follows:

$$\dot{m}_{outbox} = V \cdot \frac{dC_{box}}{dt} \qquad (2.2)$$

and

$$\dot{m}_{pallet} = \oiint J \cdot dA = \oiint -D\frac{dC}{dn}dA = \oiint P(C_{air} - C_{box})dA = P \cdot A(C_{air} - C_{box}) \quad (2.3)$$

These last two equations lead to the following differential equation:

$$C'_{box} + \frac{P \cdot A}{V}C_{box} = \frac{P \cdot A}{V}C_{air} \qquad (2.4)$$

This is a first order differential equation with the starting condition:

$$C_{box}(0) = C_0 \qquad (2.5)$$

The equation has as a homogeneous solution:

$$C_{box} = Const \cdot e^{-\frac{PA}{V}t} \qquad (2.6)$$

The inhomogeneous solution can be found by posing:

$$C_{box} = u(t) \cdot e^{-\frac{PA}{V}t} \qquad (2.7)$$

This leads to:

$$u'(t) = C_{air} \frac{PA}{V} e^{\frac{PA}{V}} \qquad (2.8)$$

When a step in RH is enforced, C_{air}=const, the following solution is found:

$$u(t) = C_{air} \cdot e^{\frac{PA}{V}t} + Const \text{ In which Const is a constant} \qquad (2.9)$$

So C_{box} becomes:

$$C_{box} = C_{air} + Const \cdot e^{-\frac{PA}{V}t} \text{ with boundary condition } C_{box}(0)=C_0 \qquad (2.10)$$

So finally this expression is found:

$$C_{box} = C_{air} + (C_0 - C_{air}) \cdot e^{-\frac{PA}{V}t} \qquad (2.11)$$

5.3 Experimental setup

The experiments are conducted in a 40 ft reefer container equipped with a Carrier cooling unit and Humicon. Because loading it fully with product is too costly, only one pallet is used. This pallet is placed in a box-like structure to guide the air through the pallet, like the other pallets would do in a fully loaded container. The T-bar floor is covered with perforated hardboard to simulate the airflow resistance of the other pallets.

Figure 5 Box that guides air through the pallet

Figure 6 Stack of boxes in the pallet

5.4 Results

5.4.1 Testing of the Humicon

The results below show that Humicon is capable of adding enough vapor to the container to raise the RH to 95%. It must be noted that the external temperature was on average about the same as the internal temperature, so not much cooling was needed. Normally, when the temperature differences are larger, part of the vapor, extracted from the container, is lost by cooling actions. In Figure 7 the humidity on various spots in the pallet is depicted with Humicon switched on and with active dehumidification.

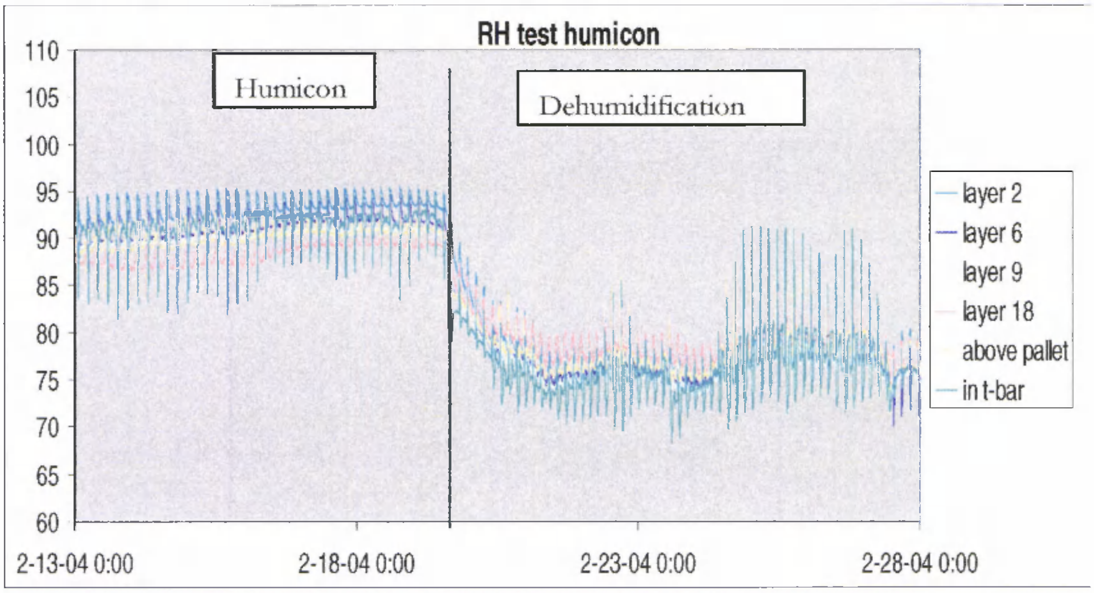

Figure 7 Testing of the Humicon

To see how fast the humidification takes place an experiment is conducted, creating a step in humidity without load and without ventilation from outside. In the figure below the humidity vs. time can be seen.

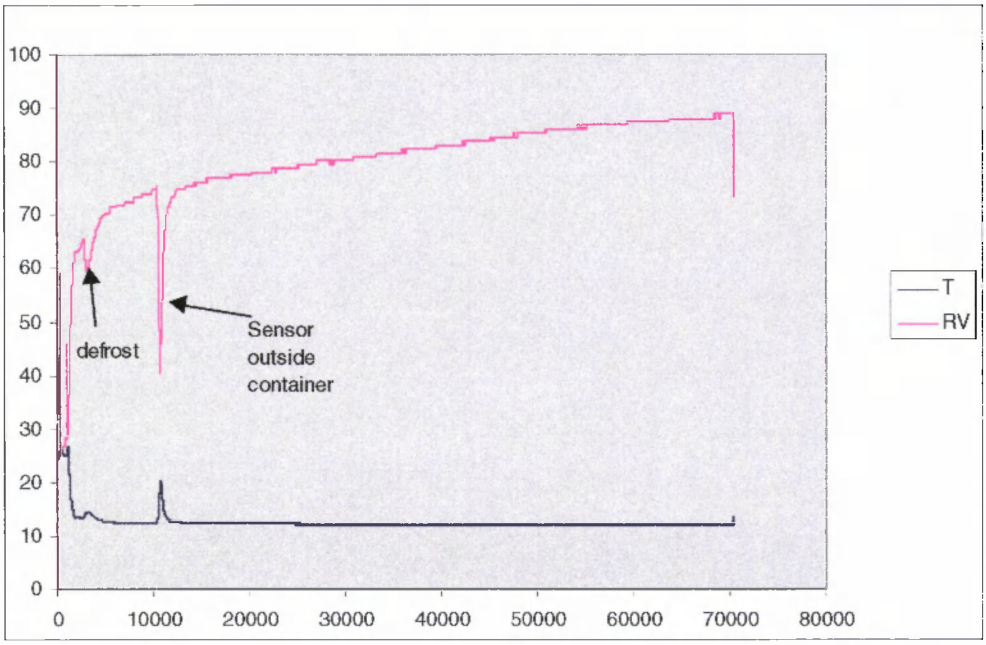

Figure 8 Speed of humidification

This is the ideal situation for Humicon use, with only a few cooling actions.
From this graph the humidification rate can be extracted. At 12°C the maximum water content of air is 10.74 g/m^3. A rise of humidity of 20 % in 19.5h of 80m^3 air means a humidification rate of 8.8g/h. This is a lot below the given humidification rate of the Humicon of 96g/h. Most probably this is caused by extraction of moist out of the air by the cooling actions.

5.4.2 Determining the mass transfer coefficient

The first experiment to determine the mass transfer coefficient for different box types was conducted in combination with a Quest experiment, in which also the heat transport coefficient was determined. Various variations in temperature and RH have been enforced on a pallet of apples. In the figure below the temperature and RH profiles can be seen.

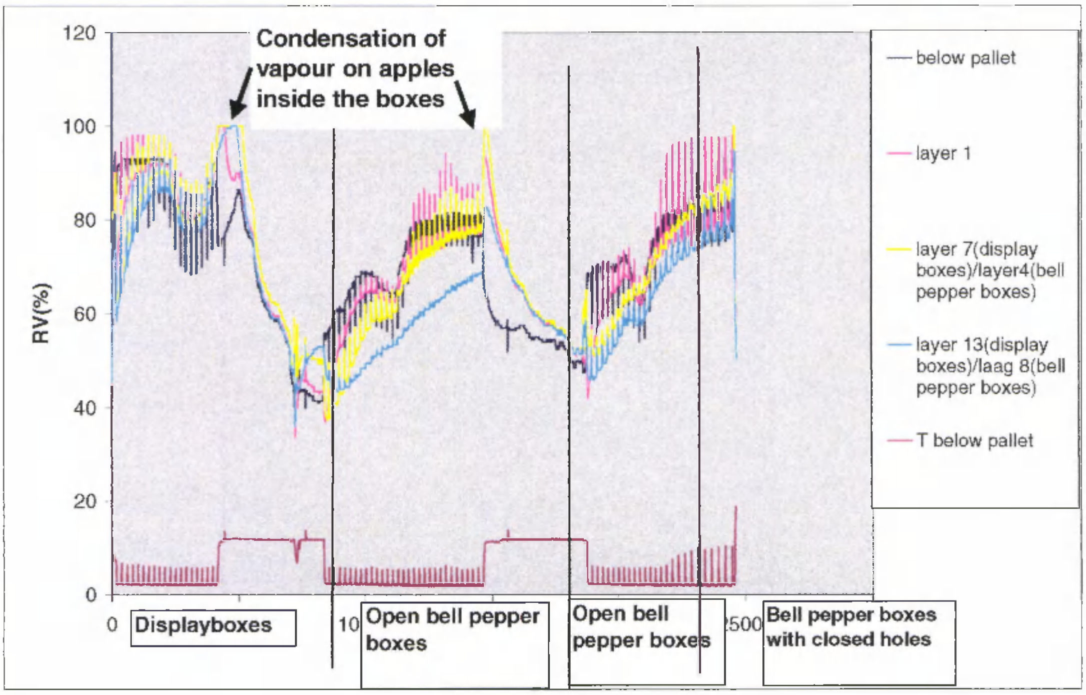

Figure 9 Steps in RH, applied to a pallet

It appears the RH values in the pallet follow the RH in the T-bar almost instantaneously. This means that the humidity in the pallet when the Humicon is used will always be evenly distributed. Even for the bell pepper boxes with closed holes there is almost no difference. Only when condensation occurs, the humidity in the pallet will differ from the air outside the pallet.

5.4.2.1 Display boxes

The following experiment consists of a enforced step in humidity, without temperature changes this time. First a step in humidity was enforced with a load of apples in open display boxes. In the figure below the result of that step in humidity can be seen. The RH in the boxes seems to follow the RH outside the pallet almost instantaneously. This means the mass transfer coefficient for this type of boxes cannot be determined, but is so high no problems in humidification will occur during transport.

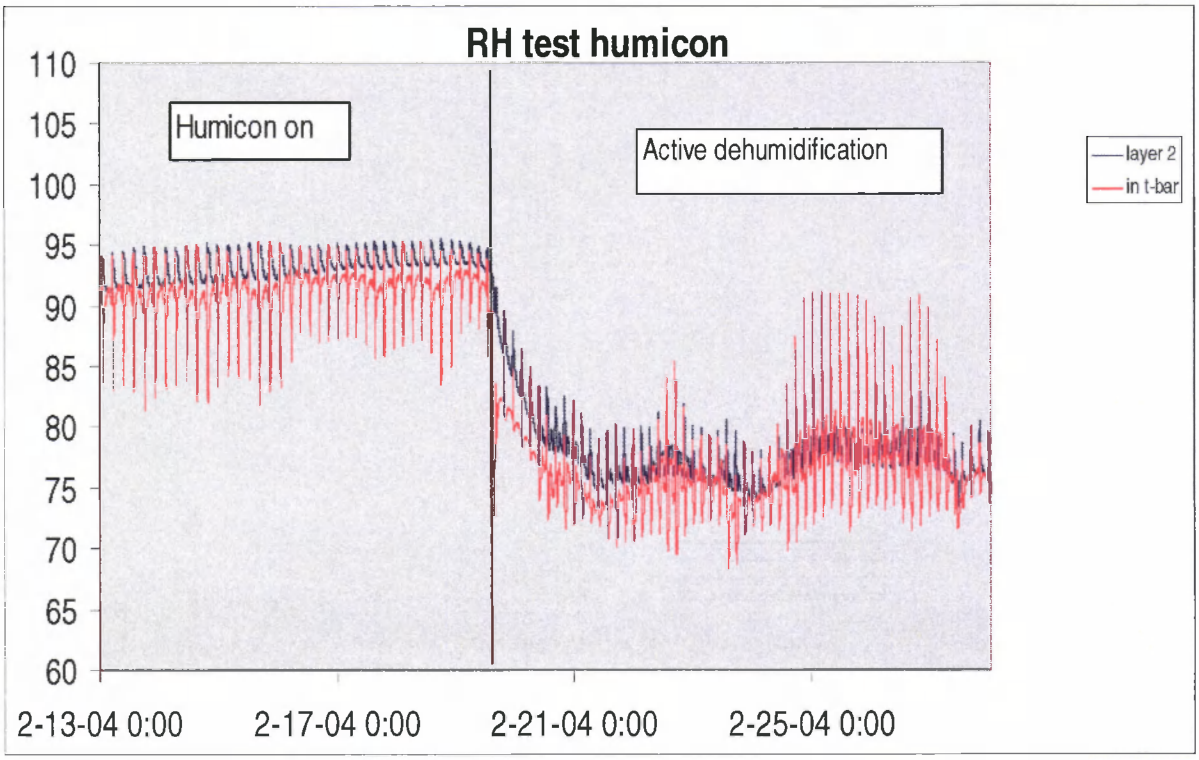

Figure 10 A step in humidity applied to a pallet

5.4.2.2 Bell pepper boxes

In a next experiment was tried to find also the mass transfer coefficient for more closed boxes In this case bell pepper boxes were chosen. Again the speed of humidification is the limiting factor in the distribution of vapor.

5.4.2.3 Bell pepper boxes with closed holes

The same result is obtained for the closed bell pepper boxes. In this experiment also an even distribution of vapor is found over the whole pallet. So even in the most closed box, the changes in humidity are slower than the speed with which the vapor is distributed.

5.4.3 Discussion and conclusions

After the testing of the Humicon the following conclusions can be drawn:
The Humicon works well, but the adding of vapor is slower than expected on basis of the specifications. This might either be caused by a lower output of the Humicon itself or by the reefer unit, which might have condensed most of the water in the cooling actions.
This leads to the conclusion that the Humicon probably will take very long to add a significant amount of vapor in the situation of a heavily cooled container.
The determination of the mass transfer coefficient has been worked out for the display boxes. The conclusion is that the distribution of the vapor in these display boxes is faster than the changes in the container RH.

The determination of mass transfer coefficients has also been conducted for bell pepper boxes with or without holes. Also for these boxes the result is that the (de)humidification is slower than the time needed to distribute the vapor over the pallet.

5.5 Conclusions

The overall conclusions for the experiments are:

- Using Humicon will lead to a slightly higher RH in the container. How much higher will depend on the amount of cooling.
- The vapor in the container will in all cases be evenly distributed.
- When larger amounts of vapor will be distributed, like in the Naturefresh system, the distribution probably will be about the same. The time constant for the spreading of vapor is in the order of a few minutes, so any change in humidity will take only a relatively small time to take effect in the whole container.

6 Discussion and Conclusions

6.1 Humidifier effectiveness

If weight loss during transport is an issue for a fruit or vegetable during storage, weight loss is more then 3%. For transport in a 40ft reefer container transport this amounts to more then 300 kg weight loss per trip. Humicon water supply is too small to make a significant difference in weight loss. In cases where Humicon can keep humidity at 95 % weight loss is not an issue. If Naturefresh could be used for its full capacity, its water supply might be large enough to be somewhat effective.

6.2 Product transport simulations

For the simulations the flow rates 0.0 ml/s (no humidification), 0.03 ml/s (Humicon maximum flowrate) and 0.3 ml/s (Naturefresh maximum flowrate) were used. The droplet sizes are d = 1 μm for Humicon and d = 75 μm for Naturefresh. Naturefresh works somewhat inefficiently due to the larger droplet size. Humicon, however, has a very small flow rate.

A humidifier in a container carrying 15.000 kg of produce could reduce weight loss by 3-25 kg/trip (Humicon, maximum possible water inflow) and 9-80 kg/trip (Naturefresh, maximum possible water inflow). A trip length of 3 weeks is assumed, with outside climate of Tamb = 20°C and RH = 85 %. For banana and tomato, simulations were repeated for a lower outside temperature. For the banana case, weight loss reductions up to 36 and 90 kg/trip were found. The exact amount of weight loss per trip, is influenced by humidifier use and efficiency, cultivar, product quality and outdoor conditions. However, the amount of weight loss reduction is small. It seems not worthwhile to use a humidifier. Only for nectarine and banana with low outside temperature, using Naturefresh at maximum dosage could be interesting. Also, if Naturefresh effectiveness would be increased by decreasing the droplet size while making maximum dosage of 0.3 ml/s possible, Naturefresh use could be interesting for other products.

In cool down situation weight loss is about 10-20 times higher then during steady state. Since supply air in cool down has a high RH, close to 100%, adding humidification does not help to reduce this weight loss significantly. However, it might be interesting to investigate the exact supply RH during cool down, since this has not been measured in detail. If supply RH is lower then 95%, adding a humidifier with flowrate of 0.3 ml/s or larger might be interesting.

6.3 Mass transfer measurements in a reefer container equipped with Humicon

- Temperature and RH is stable at various heights within a pallet and RH in pallet follows the container air RH (with the used experimental set-up)

- During high RH, condensation can occur at the ceiling and top of the pallet. Defrost periods play a role in occurrence of these condensation events.
- Relative humidity is not or slightly dependent on position in the pallet or box type.
- Using Humicon will lead to a slightly higher RH in the container. How much higher will depend on the amount of cooling.
- The vapor in the container will in all cases be evenly distributed.
- When larger amounts of vapor will be distributed, like in the Naturefresh system, the distribution probably will be about the same. The time constant for the spreading of vapor is in the order of a few minutes, so any change in humidity will take only a relatively small time to take effect in the whole container.

6.4 General conclusions

- Weight loss during storage/transport will reduce if the supply air RH is increased
- If weight loss during transport is an issue for a fruit or vegetable during storage, weight loss is more then 3%.
- Humicon can not increase supply air RH enough to make a significant difference in weight loss
- Naturefresh could be somewhat effective in weight loss reduction for certain products if droplet size is reduced and constant maximum water inflow is possible
- The transfer of water vapor from the T-bar into the boxes has a small time constant (in the order of a few minutes), so any change in humidity by a humidifier will take effect in the whole container. This holds true for open and closed boxes, without plastic product packaging.

References

Sprenger-Instituut (1984) Produktgegevens groenten en fruit, handboek bij de afzet van groenten en fruit, Sprenger Instituut, Wageningen, The Netherlands

M. van Hoof (2004) Humidity control in reefer containers, overview of commodities, A&F, Wageningen, The Netherlands

M. van Hoof (2004) Humidity control in reefer containers, effects of humidity control on product quality and postharvest decay of apple and nectarine, A&F, Wageningen, The Netherlands

Technical information on Humicon and Naturefresh system (2002-2004), supplied by Y. Chen and M. Griffin, Carrier Tr., Syracus, U.S.

P.H. Leijendeckers (1998) Polytechnisch zakboekje, PBNA, Arnhem, The Netherlands

D.P. Whitelock, G.H. Brusewitz, A.J. Ghajar (1999) Thermal/physical properties affect predicted weight loss of fresh peaches, Transactions of ASAE 42: 1047-1053, American Society of Agricultural Engineers, U.S.

G. van den Boogaard, A. Polderdijk (2001) Literature study on the effects of MA on plums, peaches and nectarines, ATO report no. B493, Wageningen, The Netherlands

C.H. Crisosto, A.A. Kader, The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, Agriculture Handbook Number 66 (http://www.ba.ars.usda.gov/hb66/094nectarine.pdf)

Transport Information service, peaches, nectarines (http://www.tis-gdv.de)

C.H. Crisosto Stonefruits Physiological Disorder Fact Sheets. (http://postharvest.ucdavis.edu/Produce/Disorders/index.shtml)

Appendix 1 - Simulation graphs

Apple Simulations

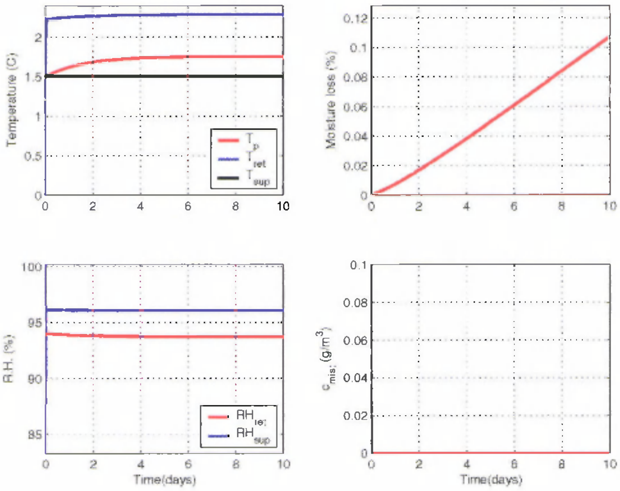

Figure 11 Apple steady state: no humidification, ventilation 60 cmh, circulation 1.2 cms

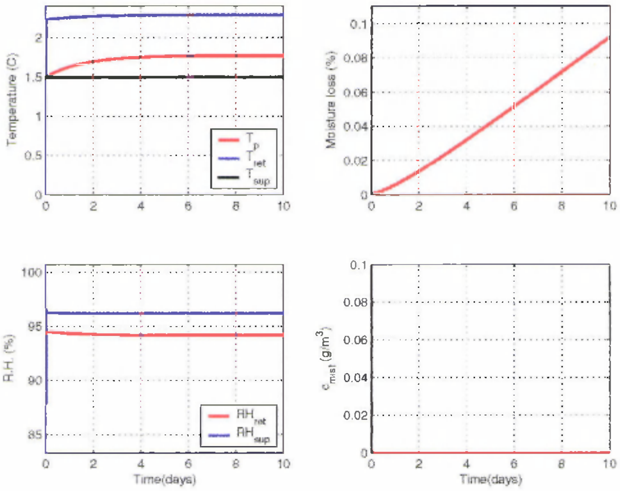

Figure 12 Apple steady state: humidification 0.03 ml/s, ventilation 60 cmh, circulation 1.2 cms

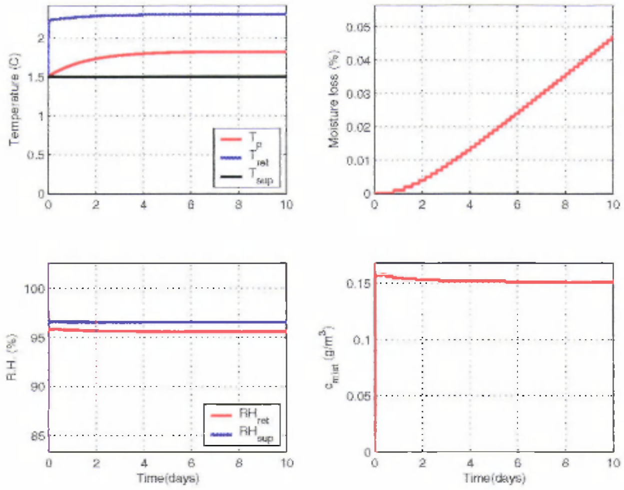

Figure 13 Apple steady state: humidification 0.3 ml/s, ventilation 60 cmh, circulation 1.2 cms

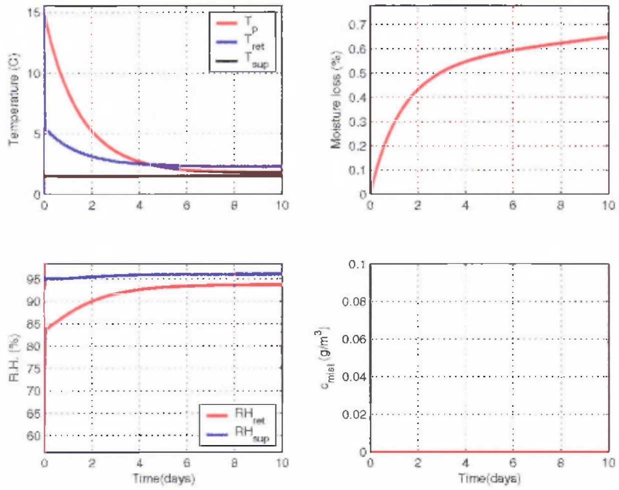

Figure 14 Apple cool down: no humidification, ventilation 60 cmh, circulation 1.2 cms

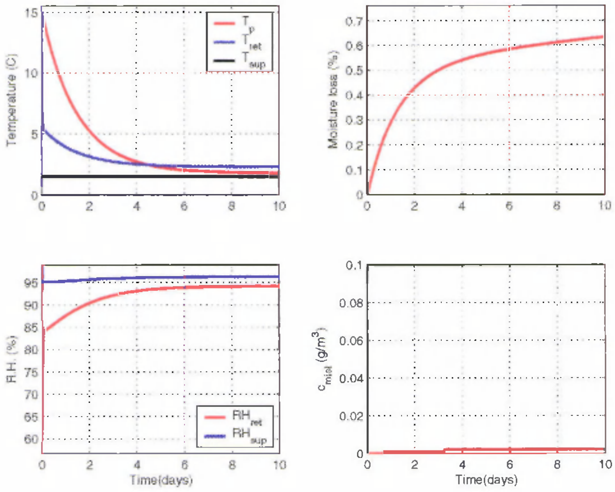

Figure 15 Apple cool down: humidification 0.03 ml/s, ventilation 60 cmh, circulation 1.2 cms

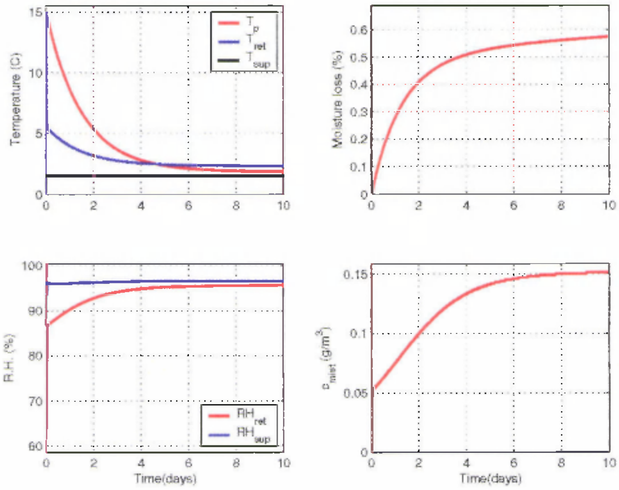

Figure 16 Apple cool down: humidification 0.3 ml/s, ventilation 60 cmh, circulation 1.2 cms

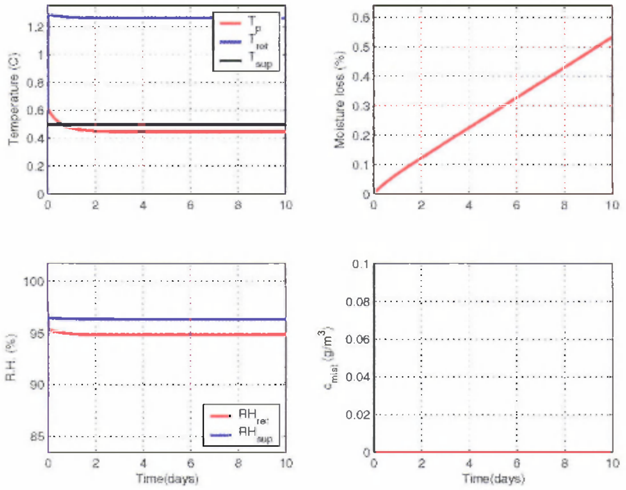

Figure 17 Nectarine steady state: no humidification, ventilation 60 cmh, circulation 1.2 cms

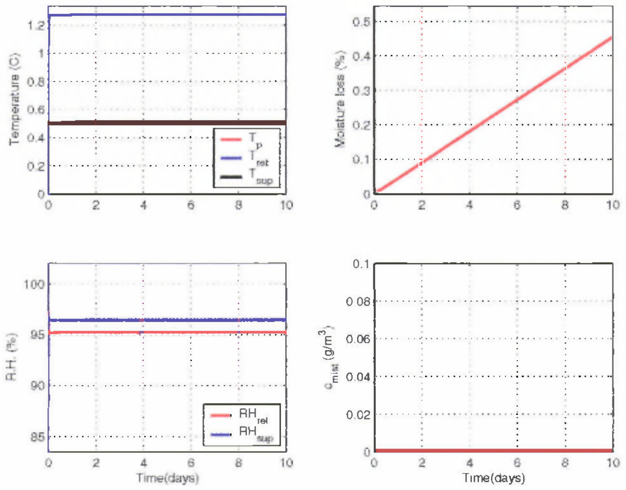

Figure 18 Nectarine steady state: humidification 0.03 ml/s, ventilation 60 cmh, circulation 1.2 cms

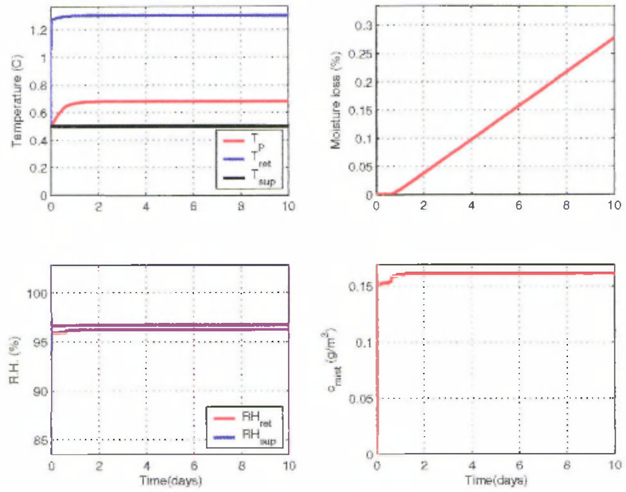

Figure 19 Nectarine steady state: humidification 0.3 ml/s, ventilation 60 cmh, circulation 1.2 cms

Banana simulations

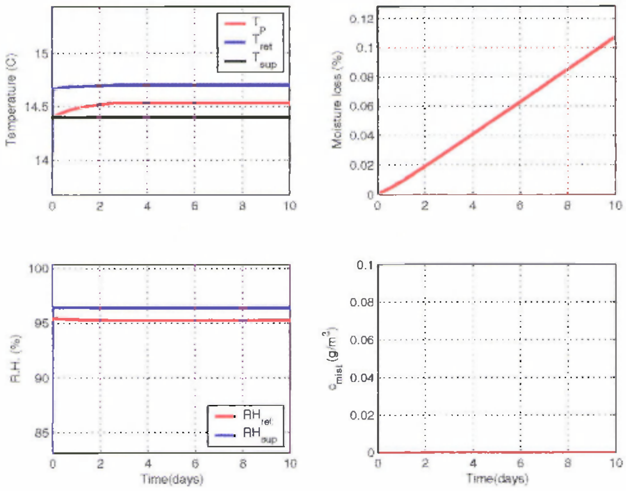

Figure 20 Banana steady state: no humidification, ventilation 100 cmh, circulation 1.2 cms, Tamb 20 °C

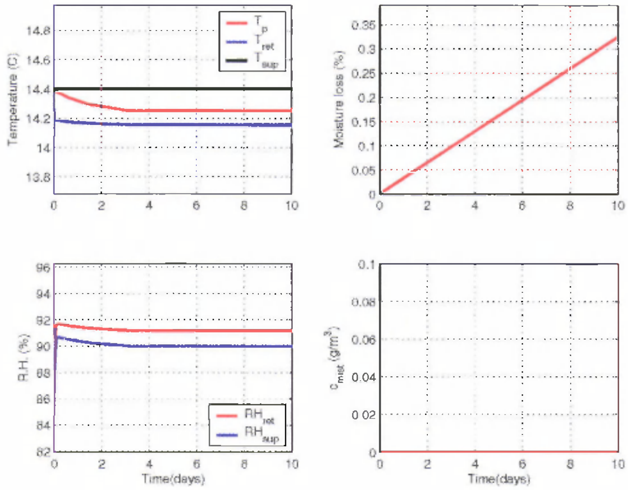

Figure 21 Banana steady state: no humidification, ventilation 100 cmh, circulation 1.2 cms, Tamb 10 °C

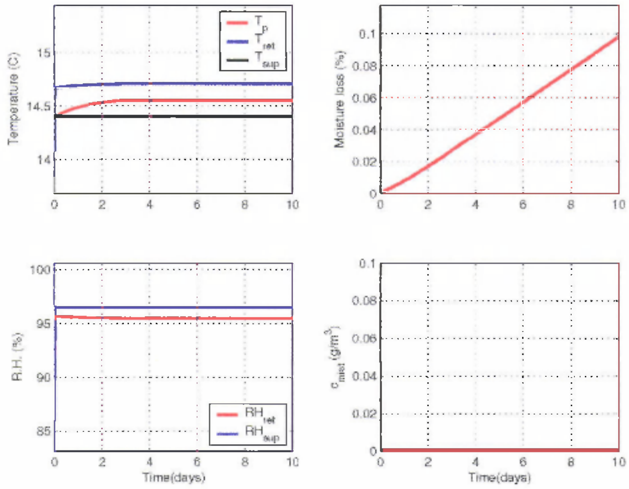

Figure 22 Banana steady state: humidification 0.03 ml/s, ventilation 100 cmh, circulation 1.2 cms, Tamb 20°C

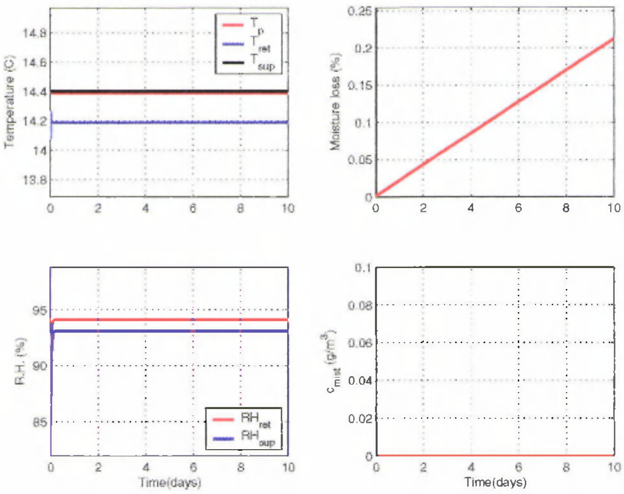

Figure 23 Banana steady state: humidification 0.03 ml/s, ventilation 100 cmh, circulation 1.2 cms, Tamb 10°C

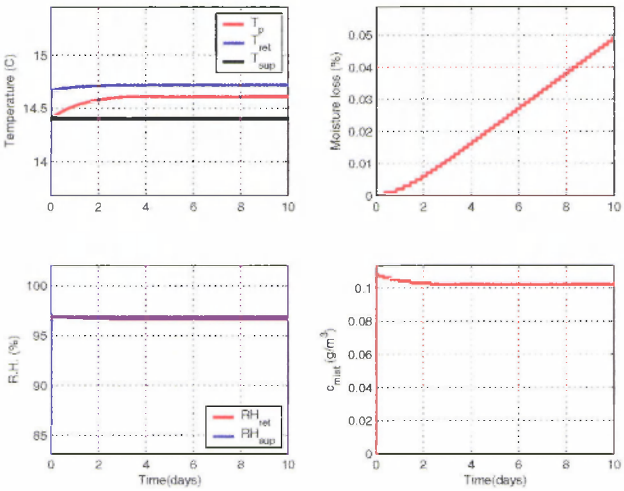

Figure 24 Banana steady state: humidification 0.3 ml/s, ventilation 100 cmh, circulation 1.2 cms, Tamb 20°C

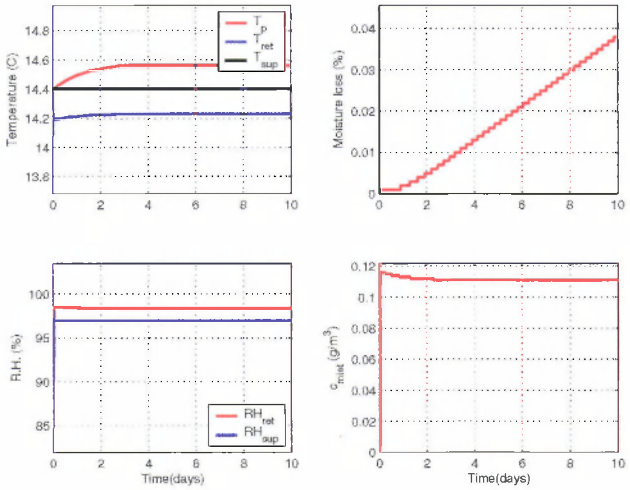

Figure 25 Banana steady state: humidification 0.3 ml/s, ventilation 100 cmh, circulation 1.2 cms, Tamb 10°C

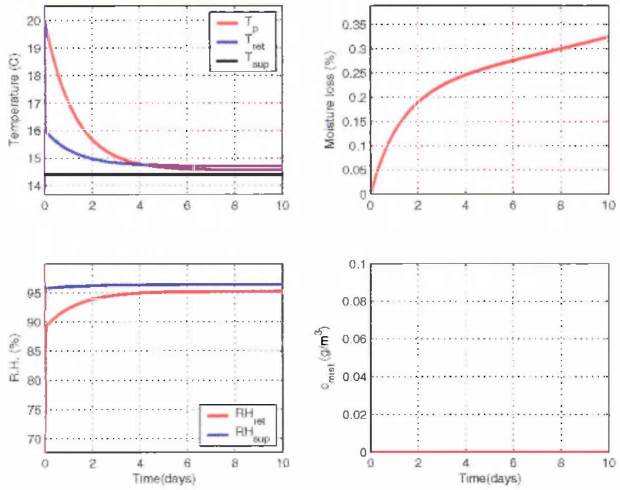

Figure 26 Banana cool down: no humidification, ventilation 100 cmh, circulation 1.2 cms

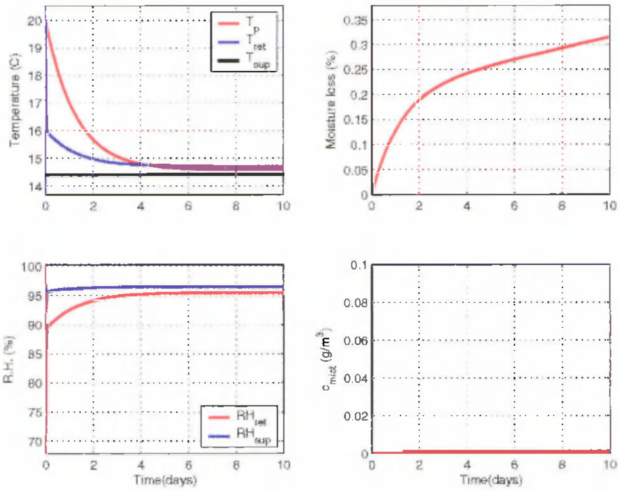

Figure 27 Banana cool down: humidification 0.03 ml/s, ventilation 60 cmh, circulation 1.2 cms

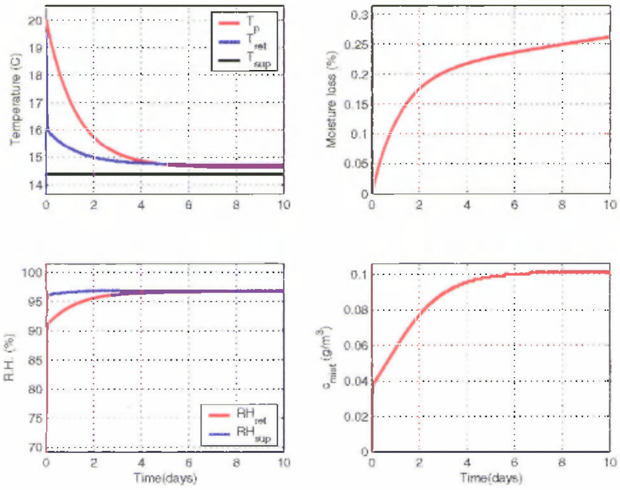

Figure 28 Banana cool down: humidification 0.3 ml/s, ventilation 60 cmh, circulation 1.2 cms

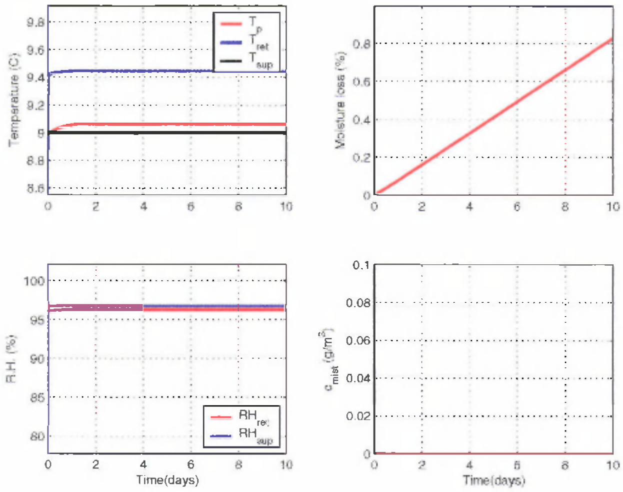

Figure 29 Tomato steady state: no humidification, ventilation 60 cmh, circulation 1.2 cms

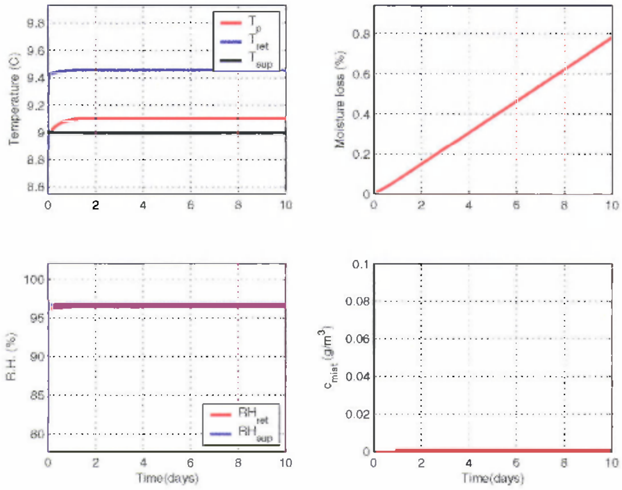

Figure 30 Tomato steady state: humidification 0.03 ml/s, ventilation 60 cmh, circulation 1.2 cms

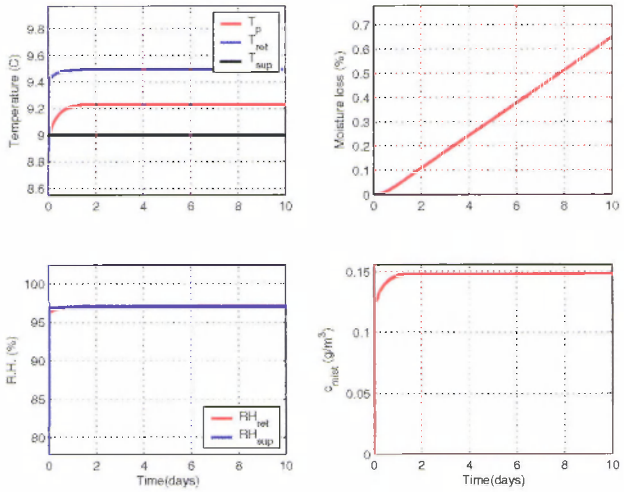

Figure 31 Tomato steady state: humidification 0.3 ml/s, ventilation 60 cmh, circulation 1.2 cms

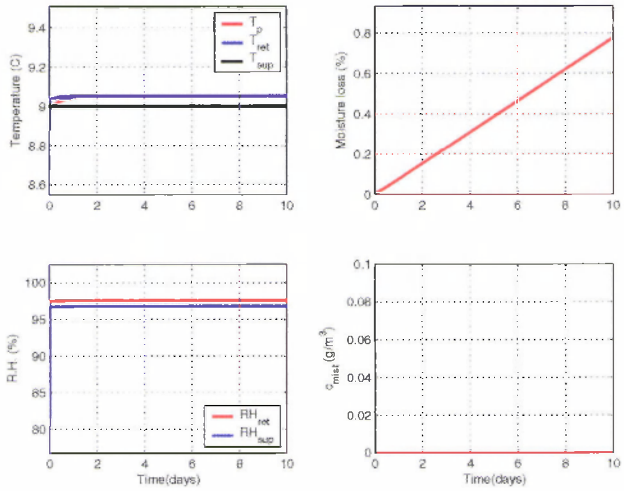

Figure 32 Tomato steady state: no humidification, ventilation 60 cmh, circulation 1.2 cms, Tamb = 10°C

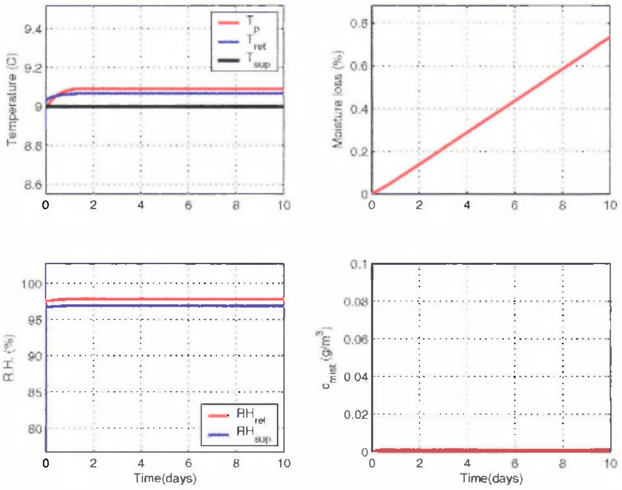

Figure 33 Tomato steady state: humidification 0.03 ml/s, ventilation 60 cmh, circulation 1.2 cms, Tamb = 10°C

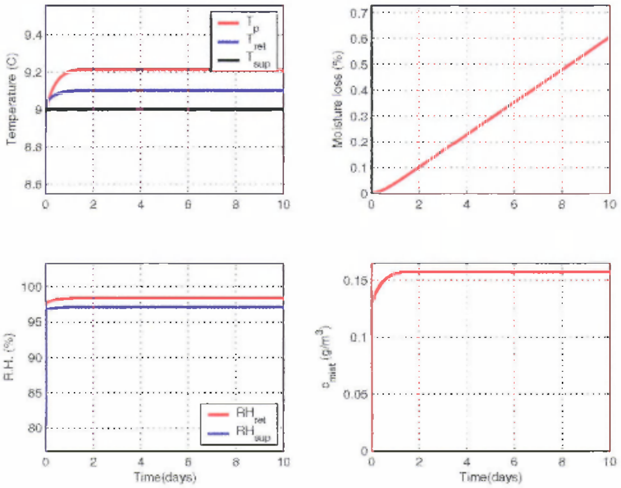

Figure 34 Tomato steady state: humidification 0.3 ml/s, ventilation 60 cmh, circulation 1.2 cms, Tamb = 10°C

Appendix 2 – Simulation parameters

The parameters most relevant for the transport simulations are:

Description	Parameters	Apple	Tomato	Banana	Nectarine	units
Setpoint transport temperature	T sp	1.5	9	14.4	0.5	°C
Reference temperature	T ref	10	10	13	10	°C
Max. rate of O2 consumption at Tref	S O2 max ref	38	80	10	112	nmol/kg/s
Max. rate of fermented CO2 production at Tref	S CO2 max ref	38	80	40	124	nmol/kg/s
Respiration quotient	Rq	0.99	0.91	0.99	*0.9*	-
Mass transfer coefficient	K skin	5.90E-10	3.00E-08	2.20E-10	25E-09	kg/s/m2/Pa
Heat production at oxidation of 1 mole CO2	Q O2	468.9	*447*	469	*469*	KJ/mol CO2
Heat production at fermentation of 1 mole CO2	Q f	64	*64*	64	*64*	KJ/mol CO2
Heat transfer coefficient product in packaging	Lambda eff	0.4	*0.5*	0.4	0.4	W/m/K
Specific heat product	c pp	4.00	4.00	3.35	4.00	KJ/kg/K
Mass density product	rho p	780	1005	984	983	kg/m3
Water activity product	aw p	0.98	0.98	0.98	0.98	-
Diameter product	d p	0.08	0.06	0.04	0.08	m
Length packaging	pack length	0.6	0.3	0.6	0.5	m
Width packaging	pack width	0.4	0.4	0.4	0.4	m
Height packaging	pack height	0.18	0.15	0.18	0.09	m
Mass product in packaging	pack content	12.5	5	13	5	kg
Nr of layers in pallet		12	*15*	12	15	-
Thickness packaging material	pack thickness	4.00E-03	4.00E-03	4.00E-03	3.00E-03	m
Fraction ventilation holes in packaging	ratio vent hole area	0.25	0.1	0.25	0.1	ratio
Mass packaging	box mass	0.7	0.36	0.7	0.36	kg
Specific heat packaging	c pm	1.70E+03	1.70E+03	1.70E+03	1.70E+03	J/kg/K

Appendix 3 - Comparison mass transfer coefficients of various products

In the following tables, various products are sorted on value mass transfer coefficient and transport temperature.

product	***T***	***K (E-10)***
Orange low T	2.2	1.40
Kiwi	0	1.50
Avocado	4	1.5
Grape	-0.5	4.00
Apple	1.5	5.90
Pear	-0.5	7.65
Nectarine	0.5	250

Product	***T***	***K (E-10)***
Orange low T	2.2	1.40
Orange high T	7.2	1.40
Kiwi	0	1.50
Avocado	4	1.5
Pineapple	7.5	*1.5*
Banana	14.4	2.20
Grape	-0.5	4.00
Apple	1.5	5.90
Pear	-0.5	7.65
Bell pepper	9	13.4
Nectarine	0.5	250
Tomato	9	300

Product	***T***	***K (E-10)***
Orange high T	7.2	1.40
Pineapple	7.5	*1.5*
Banana	14.4	2.20
Bell pepper	9	13.4
Tomato	9	300

For the low temperature range nectarine is a good representative for weight loss sensitive products. Apple is a good representative for less sensitive products. For the high temperature range, tomato (sensitive) and banana (less sensitive) are good representatives. Therefore these products are chosen for the simulations.

Appendix 4 – Distribution model moisture loss remarks

Physics of moisture loss

During shipment product inevitably loses water due to evaporation. The rate of these losses q_m and the final weight loss can be estimated from equation 1.

$$q_m = mt \cdot A_m \cdot \Delta Cw \qquad (1)$$

In equation 1 A_m is the effective mass transfer area of the product, ΔCw the difference in water vapour concentration between the airflow and the product just below the skin, and mt the total mass transfer coefficient given by equation 2.

$$\frac{1}{mt} = \frac{1}{mt_{air}} + \frac{t_s}{D_s} + R_m \qquad (2)$$

The mass transfer from the surface of the product to the air mt_{air} can be obtained from the heat transfer correlations in the stack. Skin thickness t_s and the diffusion coefficient through the skin D_s (both values may be difficult to separate) have to be determined experimentally. In the box additional resistances to mass transfer R_m may be present, e.g. a plastic bag or a wax coating of the product.

From equations 1 and 2 follow several options to prevent moisture loss.

- we may decrease mt_{air} by using "closed" boxes, or by stacking boxes in a fashion so as to limit the airflow through the stacks,
- we may add additional transfer resistances such as a wax coating or a plastic liner inside the boxes,
- at low temperature the vapour flux from the product is small, as the saturated vapour concentration is small. It is important to note that the vapour flux is driven by an absolute concentration difference, and not the relative humidity of the air. A fixed relative humidity therefore gives a higher moisture loss at higher temperature,
- moisture loss can be reduced by saturating the inlet air into the container, which is the rationale behind the Humicon/EverFresh concepts.

Two further points should be made:

- in some cases (for example inside the stack) the airflow may become saturated with vapour (relative humidity = 100%) and the mass transfer coefficient is no longer relevant, as the vapour content of the air becomes the limiting factor,
- in general, prevention of moisture loss and an effective removal of respiratory heat are contrary objectives. This has to be borne in mind when choosing box or stacking pattern, or when adding mass transfer resistances.

Appendix 5 – Distribution model description

Temperature and humidity distribution in reefer containers

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Introduction

Proper distribution of temperature and humidity in climate controlled sea containers is crucial to the uniform quality of fruits and vegetables. Non-uniform temperature distribution may cause accelerated ageing in high temperature regions, or chill injury in low. Furthermore, high relative humidity values in a container may result in condensation on low temperatures surfaces, inducing additional spoilage of the product or weakening of the packaging material. Low values of the relative humidity on the other hand may cause local accelerated drying and weight-loss of product. The ability to predict - and correct - climate non-uniformities is therefore of great importance.

Temperature distributions strongly depend on the airflow pattern inside the container (van Nieuwenhuizen, 1976[a,b]; Irving, 1988; Tanner and Amos, 2003). However, a detailed calculation of temperature and humidity distributions, taking the coupling between the temperature- and the water vapor field into account has not been undertaken.

This report presents the coupled temperature and humidity distribution calculated inside a 40 foot sea container as a function of the airflow distribution and (thermal) properties of the stow and the container itself. Enthalpy and molar vapor balances at diverging and converging nodes and application of the appropriate heat and mass transfer correlations yielded a system of algebraic equations that was solved using the Matlab code.

Discretisation practice

Temperatures and humidities will be calculated using the airflow distribution obtained from an airflow model. An identical network and node distribution is therefore employed (Kelder 2004, figure 1).

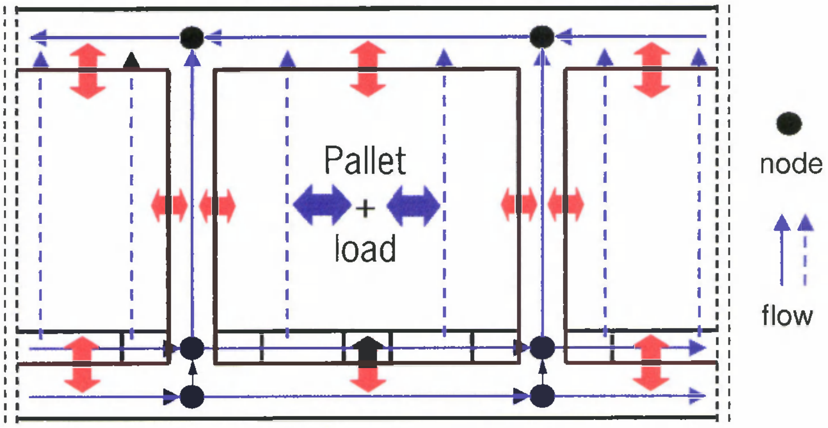


figure 1: Exchange of heat (red arrows) and moisture (blue arrows) between the cargo and the air circulation. Location of the nodes.

In the T-bar floor and in the palletspaces, temperatures are calculated at the nodes. As the airflows in the palletspaces have little opportunity to absorb heat, temperatures in left and right palletrow are assumed to be equal. At the level of the T-bar floor and the palletspace the temperature model is therefore 2-dimensional. However, the different upward airflows around and through the palletstacks may have different heating rates, locally rendering the model 3-dimensional.

As the airflows in the container exchange heat with the cargo and with the environment, additional nodes have been defined. Unlike the airflows, the cargo and the container frame possess a significant thermal capacity.

Each palletised stack of boxes is assumed to have a uniform temperature, which is projected on the centre of the stack. Due to the discretisation practice most stacks are cut into two parts each having their own temperature. Thus 37 additional temperature nodes are created. When two nodes are located in the same stack the temperatures are set equal to obtain one centre value.

In line with the axial discretisation of the container interior, both side-walls, the T-bar floor and the ceiling are each divided into 19 sections. The doors are assigned two additional sections. For every section the node is located at its centre (please refer to figure 2), so no allowance is made for the variable properties of the container frame (steel outer structure, isolation and inner aluminum liner). A total of 78 nodes is required to account for the temperatures of the exterior frame of the container.

Finally, temperature nodes are located outside the container to account for the environmental temperature. Each section of the exterior frame has its own external temperature node, and adding two nodes for the temperatures of the cooling unit brings their total number to 80. The external temperature nodes are located on the outer surface of the container, implying a negligible resistance to heat transfer in the boundary layers around the container. Though in the current model the exterior nodes are set to constant value, it is possible to implement variable temperatures to simulate e.g. the impact of changes in solar heat input.

Discretisation of the water vapor concentration is very similar to that of the temperature. For every air temperature a water vapor concentration is calculated using a similar procedure around the nodes. Furthermore, at the center of each stack a uniform vapor concentration is defined. As the container is assumed hermetically sealed (no direct water vapor exchange with the environment), nodes for the sections of the walls and for the exterior of the container are not required.

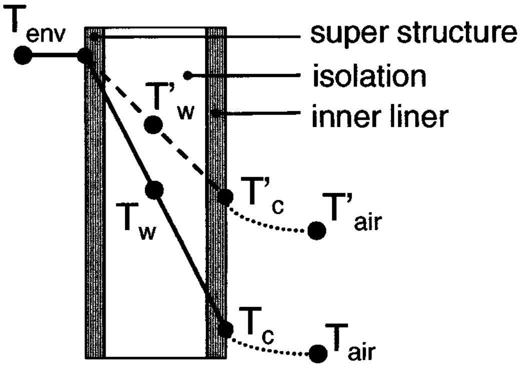


figure 2: Extrapolation of the wall temperature T_c inside the container.

However, the treatment of the vapor concentration on the inside of the container exterior, and inside the pallet stacks deserves some further explanation. To calculate the vapor flux from the airflow to the inner liner of the container (condensation at the interior walls), the water concentration at the surface is needed. The extrapolated inner surface temperature T_c or T'_c (please refer to figure 2) is used to calculate this concentration. The detailed method of calculation of the vapor flux is presented in paragraph 3.1.

Governing equations

Heat and mass balances

For the temperature/humidity model the airflow distribution is considered given, which is a valid assumption when the temperature and humidity field are independent of the airflow distribution. This implies forced convection is dominant over natural convection, and the amount of water vapor is negligible relative to the airflows. For the turbulent flows in the container, the value of $Gr/Re^2 < 0.01$ indeed indicates that the inertial forces are dominant over the buoyant forces. Secondly, air of relatively low temperatures (<15 degrees °C) can only contain a maximum of 1.6% of vapor by volume, satisfying the second condition.

Compared to cargo and container, the airflows have a negligible thermal capacity, and their temperatures therefore instantaneously adapt to changing boundaries. Similar to the conservation of mass in the airflowmodel, conservation of enthalpy H_i is now employed around each node. For an ideal gas of constant specific heat capacity Cp, H_i is given by $m_i \cdot Cp \cdot (T_i - T_0)$, and taking T_0 equal to zero we obtain equation 1.

$$\sum_i \left(H_i + q_{h_i}\right) = \sum_i \left(m_i \cdot Cp \cdot T_i + q_{h_i}\right) = 0 \tag{1}$$

Between the upstream node (j-1) and the current node j each airflow may absorb heat from or release heat to the walls of the container or the product. This is expressed by the heat fluxes q_h (equation 2).

$$q_h = h_t \cdot A_h \cdot \Delta T = h_t \cdot A_h \cdot \left(T_w - T_j\right) \tag{2}$$

We assume the heat capacity $m \cdot Cp$ of the flow in the channel between two nodes to be constant. For each wall the flow is in contact with, the total heat transfer coefficient h_t and transfer surface A_h may have a different value. Paragraph 3.2 is dedicated to the estimation of h_t under relevant circumstances. As is clear from equation 2 the driving force ΔT is defined as $T_w - T_j$, where T_w is the (constant) average temperature of the wall and T_j the temperature of the air at the end of the passage.

Mass flows are not relevant to the enthalpy balance of the different sections of container exterior and cargo, but the specific heat capacity Cp is significant and a transient term is present (equation 3).

$$Cp \cdot M_p \cdot \frac{dT_w}{dt} + \sum_i q_{h_i} + Q_p + Q_{ce} = 0 \tag{3}$$

In equation 3 M_p is the mass of the cargo or wall and Q_{ce} a source term arising from condensation of evaporation of water vapor. Q_{ce} is the product of the water vapor flux q_m (equation 5) and the latent heat ΔH_e and provides the link between the temperature and the humidity distribution. Q_p is a source term for the heat produced by the respiration of the product (please refer to section 3.2.6) and is only relevant for the stow.

To calculate the water vapor distribution additional molar balances are established using the molar water concentration Cw_i (equation 4).

$$\sum_i \left(\frac{m_i}{\rho} \cdot Cw_i + q_{m_i}\right) = 0 \tag{4}$$

Condensation or evaporation changes the water content between the upstream node j -1 and the current node j as result of additional water fluxes q_m (equation 5).

$$q_m = Sw \cdot \sum mt \cdot A_m \cdot \Delta Cw \qquad (5)$$

The flux of equation 5 depends on the mass transfer coefficient mt (please refer to paragraph 3.3) and the mass transfer area A_m which is taken equal to the heat transfer area A_h. For the driving force ΔCw we take $Cw_w - Cw_j$, where Cw_w is the (constant) average saturated vapor concentration at wall temperature T_w, and Cw_j the water concentration of the air at the end of the passage. The intricacies of defining ΔCw are the same as for ΔT.

From the definition of ΔCw follows that the water vapor concentration between nodes may increase or decrease, depending on evaporation or condensation respectively. This is true for the produce in the stacks (provided this has not been packed in material impermeable to water vapor) and for the lowest surface of the T-bar floor where water may accumulate. The vertical walls and the ceiling are smooth however and possess no storage capacity for water. To make sure only condensation takes place here, switch Sw is built into equation 5. It equals 1 if ΔCw is negative, and equals 0 otherwise.

Consideration of all passages and nodes yields an algebraic system of the coupled temperatures and water vapor concentrations in the entire domain.

Calculation of the heat transfer

Depending on local geometry and flow velocities the flow may be from the deep laminar regime (in small slits between stacks), via the transitional regime (at the end of the T-bar floor) to a fully turbulent state (entrance of the T-bar floor and the exit from the headspace). The impact of flow regime on heat transfer is even more pronounced than on frictional losses, and in the next sections the appropriate correlations will be developed.

Heat transfer in channels

To capture all flow regimes a correlation was constructed covering the laminar, the transitional and the fully turbulent region. When using the hydraulic radius d_h in the underlying circular tube correlations we arrive at a heat transfer correlation suitable for all open passages in the network model.

The average laminar heat transfer according to Hausen (equation 6) applies to the developing case and therefore depends on the dimensionless Graetz number Gz and hence on the length of the channel L (KakaÇ, 1987).

$$Nu = 3.66 + \frac{0.0668}{Gz^{1/3} \cdot (0.04 + Gz^{2/3})} \tag{6}$$

For fully turbulent heat transfer we use the developed experimental correlation of Gnielinski (equation 7) for smooth passages as presented in Kakaç (1987).

$$Nu_s = \frac{(f/2) \cdot (Re - 1000) \cdot Pr}{1 + 12.7 \cdot (f/2)^{1/2} \cdot (Pr^{2/3} - 1)} \tag{7}$$

Since the thermal entrance length in turbulent flow is very short, no reference to the channel length L is present in equation 7. The friction factor f can be calculated using Chen's correlation (equation 8) for the developed friction factor for rough tubes, with the tubes absolute roughness ε set to zero.

$$\begin{gathered} f = \left(3.48 - 1.7372 \cdot \ln\left(\frac{2 \cdot \varepsilon}{d_h} - \frac{16.2426}{Re} \cdot \ln c \right) \right)^{-2} \quad ; \\ c = \frac{1}{6.0983} \cdot \left(\frac{2 \cdot \varepsilon}{d_h} \right)^{1.1098} + \left(\frac{7.149}{Re} \right)^{0.8981} \end{gathered} \tag{8}$$

For laminar flow the heat transfer is not affected by the roughness of the tube wall. For turbulent flow however the rough wall Nusselt number Nu_r must be obtained by multiplying Nu_s by Norris's factor (equation 9).

$$Nu_r = Nu_s \cdot \left(\frac{f_r}{f} \right)^a \quad ; \quad a = 0.68 \cdot Pr^{0.215} \tag{9}$$

We can obtain f_r in equation 9 from equation 8 by setting the absolute roughness $\varepsilon > 0$. The correction is valid for f_r/f values up to four; for higher values of the wall roughness no additional increase of heat transfer was obtained (Kakaç, 1987). For severe distortions of the flow and temperature field by sharp corners an additional local increase in heat transfer occurs. It can be accounted for by multiplying Nu_r according to equation 10.

$$Nu_r^{90} = Nu_r \cdot \left(1 + \frac{2.0152}{(L/d_h)^{0.614}} \right) \tag{10}$$

In the transitional zone spanning Reynolds numbers 2000 – 4000, a linear interpola-tion is performed between the maximum laminar value at Re = 2000 of equation 6 and the minimum fully turbulent value at Re = 4000 of equation 9.

Heat transfer through the wall

In several cases a heat transfer coefficient has to be designated to heat transfer by conduction through a wall, e.g. when the different walls of the container or the cardboard boxes of the stack are concerned.

The heat transfer coefficient h_w of the external container walls (left and right wall, floor, roof and doors) is calculated by dividing the isolation value $H_c = 40$ W/K (Van der Sman, 2000) by the total outside area $A_c = 135$ m^2 of the container yielding $h_w = 0.3$ W/m^{2}K. This is probably a rather crude assumption, as floor, walls, doors etc, do not have the same thickness and consist of different material. However, the current procedure to establish the isolation value H_c prevents discrimination between their different heat transfer properties. A probably more succesfull avenue to calculate the heat transfer coefficients of the different walls would be using their geometric and material properties.

We can estimate the heat transfer coefficient h_b of the walls of the cardboard boxes in the stack exposed to the vertical airflows using the thickness of the box $t_b = 0.0025$ m and the conductivity of air $\lambda = 0.025$ W/mK. The resulting value of $h_b = \lambda/t_b = 10$ W/m^{2}K provides a minimum value, as the conductivity of the paper fibres is certainly higher than that of air. A more accurate determination of h_b would be possible by measuring it following the procedure used to measure H_c.

Heat transfer outside the container

Currently the heat transfer resistance outside the container is neglected. The outer heat transfer coefficient h_{env} is given a very high value, implying the temperature of the environment T_{env} is applied on the outer surface of the container (figure 3).

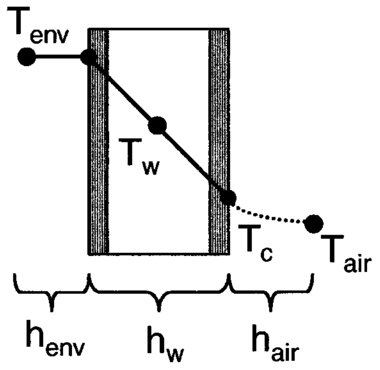


figure 3: Heat transfer coefficients outside, across, and inside the container wall

Heat transfer to and from the stow

Currently heat transfer to and from the stow is implemented in a rudimentary form. The stow is assumed to have a uniform temperature in every palletstack and exchanges heat with the airflows around the stack, and with the airflow passing through the stow (please refer to figure 1, drawn and dotted upward arrows). For the external airflow we can use the correlations given in paragraph 3.2.1 and 3.2.2, and for the exchange with the internal airflow we use equations 1 and 2 with $h = h_e$ and $A = A_e$ the effective internal heat transfer coefficient and transfer area respectively.

Both h_e and A_e strongly depend on the type of packaging employed and the product concerned. Their values were derived from the transient response of a single stack of packed produce to a temperature step on the inlet air (Canters 2004[a]). For "open" display boxes and "closed" bell pepper boxes containing apples the h_e and A_e values are given in table 1.

	h_e (W/m^{2}K)	A_e (m^2)
display box	2.3	48
bell pepper box	0.8	48

It should be noted that the h_e value is averaged over the stack as significant differen-ces in local response time were observed. Second this value was calculated relative to the inlet air temperature, which is probably not representative of the actual temperature difference between the produce and the air passing through the stack. Third, the exchanging area A_e is arbitrary, as only the product of $h_e \cdot A_e$ is obtained from the measurements. For the sake of a reasonable physical interpretation A_e is an estimate of the total surface area of the apples in the stack (Canters 2004[b]). Finally it seems difficult in the experiments to separate the heat transfer by air flowing around the stack from air flowing through it, especially since the flowrate through the stack was not recorded. It is therefore unclear to what extent the time-temperature profiles obtained in the single stack experiments depend on the heat transfer coefficients, or on the thermal capacity of the airflow(s).

Concerning the temperature variation in the stack, both in the horizontal plane and over the height (Tanner 2003, Canters 2004[a,b]), some progress has been made in constructing a network model on the stack (Nishchenko 2004, Botha 2004). A more detailed numerical description of the palletstack may also enable a more meaningful interpretation of the temperature response experiments at the stack level.

Total heat transfer coefficient

In many cases resistance to heat transfer is present in both airflow(s) and wall(s). The total heat transfer coefficient is then calculated from these resistances in series (equation 11).

$$\frac{1}{h_t}=\frac{1}{h_{env}}+\frac{t_w}{\lambda_w}+\frac{1}{h_{air}} \qquad (11)$$

For the sidewalls, the roof, the floor and the doors of the container the temperature of each section is assumed to be uniform and projected at the centre of the wall (figure 3). In the Matlab code the heat transfer resistance of the wall itself ($t_w/\lambda_w=1/h_w$) is then divided in two parts: one between T_{env} and T_w and one between T_w and T_c.

Heat generation of the stow

Due to the respiration of the product a heat source Q_p (equation 12) is added to the enthalpy balance of equation 3. The dependence on temperature T is experimentally determined and fit to a polynomial having coefficients a – d.

$$Q_p=M_p\cdot q_p=M_p\cdot(a\cdot T+b\cdot T^2+c\cdot T^3+d\cdot T^4) \qquad (12)$$

Currently a very active product having a high specific respiration rate q_p is implemen-ted (red bell pepper, Gerritsen 1988).

Calculation of the mass transfer

Mass transfer in channels

Pure heat and mass transfer are governed by equations only differing in main variable and dimensionless numbers (Bird, 1960). Consequently, empirical correlations for turbulent heat and mass transfer in channels have the shape of equation 13 and 14 respectively (Rohsenov, 1998).

$$Nu=a\cdot Re^b\cdot Pr^c \qquad (13)$$

$$Sh=a\cdot Re^b\cdot Sc^c \qquad (14)$$

If the heat transfer correlations is known, the mass transfer correlation can then be obtained by replacing the Nusselt number by the Sherwood number Sh and the Prandtl number by the Schmidt number Sc. Dividing equation 14 by 13 yields the well known Lewis or Chilton-Colburn analogy, with Le the Lewis number and c a constant depending on the correlation (Lukashov, 2001).

$$Sh = Nu \cdot \left(\frac{Sc}{Pr} \right)^{c} = Nu \cdot Le^{c} \qquad (15)$$

This analogy is valid if heat- and mass transfers are independent, which is true for small temperature differences and small vapor fractions. For laminar flow, heat and mass transfer do not depend on Prandtl and Schmidt number and the mass transfer can be obtained by equating the Sherwood to the Nusselt number.

As the exterior walls of the container are impermeable to water vapor, and the stack only allows for mass transfer to and from the convective flow passing through the boxes, the number of mass transfer correlations is substantially smaller that that of the heat transfer relationships. For reasons of uniformity any superfluous mass transfer correlations have been maintained as dummy procedures in the Matlab calculation procedure.

Mass transfer to and from the stow

As a result of the product skin acting like a barrier, condensation and evaporation do not occur symmetrically inside the stack. When water condenses on the product, we can derive the mass transfer coefficient mt_a from the heat transfer coefficient (please refer to paragraph 3.2.4) by setting Sh = Nu, since the flow through the stack is in the laminar regime. In case of evaporation however, water has to diffuse through the skin of the product in an additional step. Both condensation and evaporation can be accounted for using the total mass transfer coefficient mt_t of equation 16, which employs the same condensation/evaporation switch Sw as equation 5. The thickness of the skin t_s and the diffusion coefficient for water D_s must be estimated experimentally. Just below the skin the vapor concentration is assumed fully saturated, and therefore a function of temperature.

$$\frac{1}{mt_t} = \frac{1}{mt_{air}} + (1 - Sw) \cdot \frac{t_s}{D_s} \qquad (16)$$

It should be stressed that the remarks concerning heat transfer to and from the stow (please refer to paragraph 3.2.4) apply in equal measure to the mass transfer, and the resulting water vapor distributions in a stack.

Vapor generation of the stow

No autonomous water generation (sweating) of the product is considered. Water may condense on the product, whence it immediately disappears and plays no further role. Or water may evaporate from the product, which is assumed not to affect product properties and further water availability. On the time scales and the total water losses during transport (< 3% by weight) concerned, it is justified to consider the product as a constant from the point of view of container climate. Of course the resulting vapor fluxes or drying rates can then be used to estimate product weight losses provided these losses are moderate.

Conclusions and recommendations

We constructed a 2D/3D balance model bridging the gap between simple 0D climate models (Van der Sman, 2002) and full-scale 3D CFD simulations. This model predicts the temperature of airflows, container frame and stow, as well as the relative humidity of airflows and stow.

However, three considerable challenges remain. First, a better description of the heat and mass transfer to and from the produce in the stacks is needed. It will be no small feat to account for the spatial distribution of temperature and water vapor without inflating the model to an impractical size. Without better descriptions of these transfer processes however, further development of the distributed model is a rather pointless exercise. Second, making the temperature/humidity model transient increases its applicability. This is certainly possible in the Matlab environment, but we expect the longer transient runs to require on the order of days.
Third, a thorough validation of the model, both at the stack level and on a macroscopic scale should be performed. As a first step the non-uniform stack model should be tuned using appropriate experiments. On integrating stack model and the container model, transient tests involving loaded container should tune and validate the temperature/humidity model.

References

S. Aravinth. Prediction of heat and mass transfer for fully developed turbulent fluid flow through tubes. *Int. J. Heat Mass Tr.*, 43:1399-1408, 2000.

C. Botha, A. Rychahivskyy. *3D climate problem in transport container.* Twaio-report Technische Universiteit Eindhoven, 2004.

R.A.M. Canters (a). *Model voor temperatuurgedrag in pallets – eerste test in de hightechcel.* Intern rapport Agrotechnology & Food Innovations B.V., 2004.

R.A.M. Canters (b). *Model voor temperatuurgedrag in pallets – containerproef met vergelijking van verschillende doostypen.* Intern rapport Agrotechnology & Food Innovations B.V., 2004.

R.B. Bird, W.E. Stewart, E.N. Lightfoot. *Transport Phenomena.* John Wiley & Sons, 1960.

A. Gerritsen, G.H. van Nieuwenhuizen. *Naar een optimaal vervoer en opslag van enkele groenten- en fruitsoorten (een literatuuronderzoek).* Sprenger Instituut, rapport nr. 569, 1988.

A.R. Irving. Refrigerated shipping containers: Understanding their operation and using them effectively for the carriage of horticultural produce. *CSIRO Food Res. Q.*, 48:1-18, 1988.

S. Kakaç, R.K. Shah, W. Aung eds. *Handbook of single-phase convective heat transfer.* John Wiley & Sons, 1987.

J.D.H. Kelder. *Flow distribution in a reefer container – a 3-dimensional resistance model.* Intern rapport Agrotechnology & Food Innovations B.V., 2004.

V.V. Lukashov, On the determination of the surface temperature of an evaporating liquid. *Theoretical Foundations of Chemical Engineering,* 37(4):325-329, 2003.

H.F. Th. Meffert. Luchtstroming in geconditioneerde transportmiddelen. *Koude & Luchtbehandeling,* 96:22-25, 2003.

G.H. van Nieuwenhuizen. *Bepaling van de eigenschappen van een geconditioneerde 40 ft container (Climatainer) van Pakhoed B.V.* Sprenger Instituut, rapport nr. 82, 1976.

G.H. van Nieuwenhuizen, H.J. van Laar. *Metingen aan het vochtbeheersingssysteem van de Climatainer van Pakhoed B.V.* Sprenger Instituut, rapport nr. 132, 1976.

N. Nishchenko. *Relation between micro- and macroclimate in transport container.* Twaio-report Technische Universiteit Eindhoven, 2004.

W.M. Rohsenov, J.P. Hartnett, Y.I. Cho eds. *Handbook of heat transfer.* McGraw-Hill, 1998.

R.G.M. van der Sman. *Report on container experiments.* Intern rapport Agrotechnological Research Institute - ATO B.V., 2000.

D.J. Tanner, N.D. Amos. Modelling product quality changes as a result of temperature variability in shipping systems. *International Congress of Refrigeration*, Washington D.C., paper 0243, 2003.

List of symbols

a	-	constant
A_c	m^2	container outer surface area
A_e	m^2	effective transfer area inside stack
A_h	m^2	heat transfer area
A_m	m^2	mass transfer area
b	-	constant
c	-	constant
Cp	$J/kg \cdot K$	specific heat capacity
Cw	$mole/m^3$	molar vapor concentration
d	-	constant
d_h	m	hydraulic radius
D	m^2/s	diffusion coefficient
$f = \Delta p \cdot d_h / 0.5 \cdot \rho \cdot v_a^2 \cdot L$	-	friction factor of smooth channel
f_r	-	friction factor of rough channel
$Gr = d^3 \cdot \rho^2 \cdot g \cdot \beta \cdot \Delta T / \mu^2$	-	Grashof number
$Gz = \lambda \cdot L / \rho \cdot Cp \cdot d_h^2 \cdot v_a$	-	Graetz number
h	$W/m^2 \cdot K$	heat transfer coefficient
h_e	$W/m^2 \cdot K$	effective heat transfer coefficient in stack
H	J	total enthalpy
H_c	W/K	isolation value container
L	m	length of passage
Le = Sc/Pr	-	Lewis number
m	kg/s	mass flow rate
mt	m/s	mass transfer coefficient
Mp	kg	total mass of produce in stack
$Nu = h \cdot d_h / \lambda$	-	Nusselt number
Nu_r	-	Nusselt number in rough turbulent flow
Nu_r^{90}	-	Nusselt number in rough turbulent flow after 90 degree turn
Nu_s	-	Nusselt number in smooth turbulent flow
$Pr = Cp \cdot \mu / \lambda$	-	Prandtl number
q_h	W	heat flux
q_m	mole/s	molar vapor flux

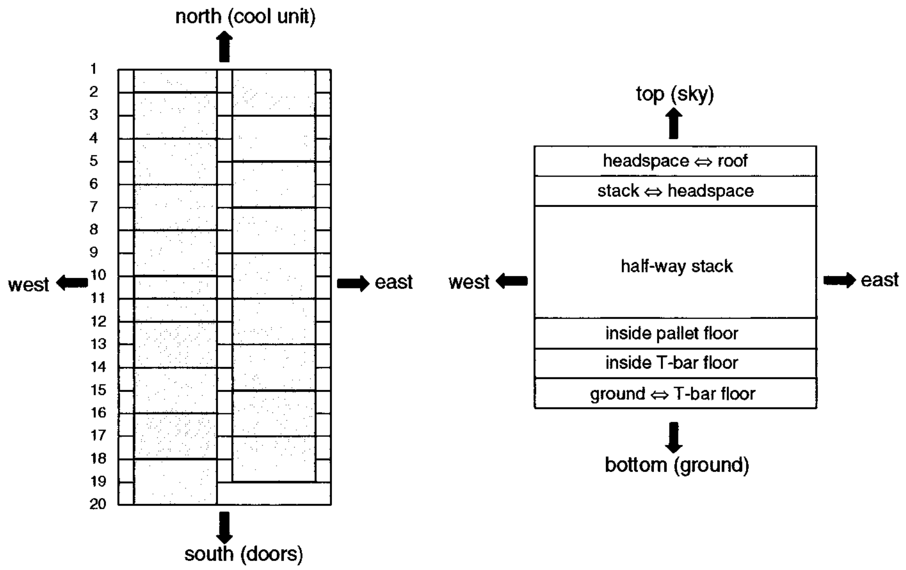
Q_{ce}	W	heat source due to condensation/evaporation
Q_p	W	heat source due to respiration of product
q_p	W/kg	specific heat source due to respiration of product
$Re = \rho v \cdot d_h/\mu$	-	Reynolds number
$Sc = \mu/\rho \cdot D$	-	Schmidt number
$Sh = mt \cdot d_h/D$	-	Sherwood number
Sw	-	switch to control condensation/evaporation
t	s or m	time or thickness
T	°C	temperature
T_0	°C	reference temperature
T_c	°C	temperature on the inside of the container wall
v_a	m/s	average velocity
ΔCw	mole	vapor concentration difference
ΔH_e	J/mole	evaporation enthalpy of water
ΔT	°C	temperature difference
ε	m	absolute surface roughness
λ	W/m ·°C	thermal conductivity
μ	Pa ·s	dynamic viscosity
ρ	kg/m^3	density

Subscipts & indices:

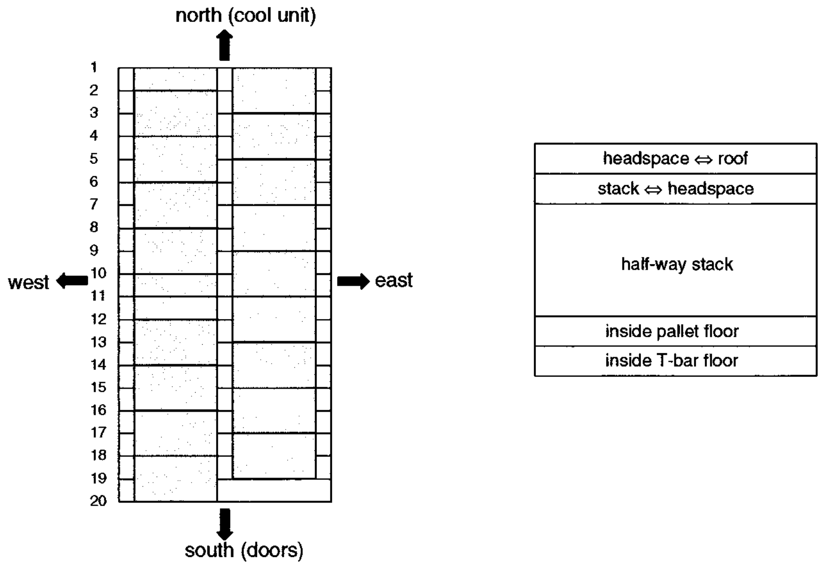
air	of the air
b	of the box
env	of the environment
i , j	of flow i, j
s	of the product skin
t	total
w	of the / on the wall

Layout of the container in distribution model

General lay-out and discretisation of the container, top (left) and rear (right) view.



General lay-out and discretisation of the container, humidity model



Calculation of the heat and vapor fluxes

The heat and vapor fluxes q_h and q_m to a wall depend on the driving force ΔT and ΔCw respectively (figure B1).

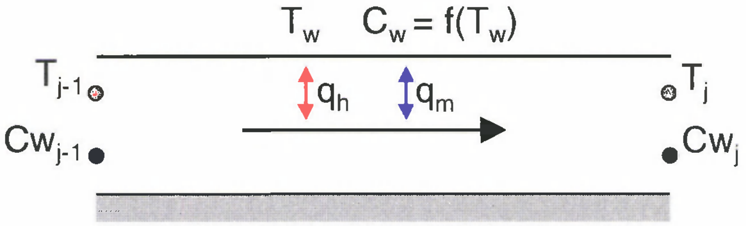


figure B1: Nodes and fluxes in a heat and mass exchanging passage

Using only the nodes j-1 at the entrance of the passage and j at the exit, an obvious choice to define the average driving force for heat transfer is $\Delta T = 0.5\ (T_j - T_{j-1})$. When substituting this ΔT in equation 1 and 2 and acknowledging that the mass flow m between two nodes is constant we obtain equation B1.

$$Cp \cdot m \cdot T_{j-1} + (T_w - 0.5 \cdot (T_{j-1} - T_j)) \cdot h_t \cdot A_h - Cp \cdot m \cdot T_j = 0 \quad \Leftrightarrow$$

$$T_j = \frac{Cp \cdot m \cdot T_{j-1} + h_t \cdot A_h \cdot (T_w - 0.5 \cdot T_{j-1})}{Cp \cdot m + 0.5 \cdot h_t \cdot A_h} \qquad (B1)$$

When $h \cdot A_h >> Cp \cdot m$ (as is the case in narrow slits), and T_{j-1} close to zero (as is true in a refrigerated container) equation B1 simplifies to equation B2.

$$T_j = 2 \cdot T_w - T_{j-1} \qquad (B2)$$

For an inlet temperature T_{j-1} at or close to zero this would mean that the exit tempera-ture from the channel would reach twice the temperature of the wall transferring heat to it. This is physically impossible and this implementation of ΔT therefore leads to incorrect results. Along similar lines it can be shown that the exit temperature T_j could become infinite when using $\Delta T = (T_w - T_{j-1})$. We therefore use as the driving force the temperature difference based on the exit temperature of the channel: $\Delta T = (T_w - T_j)$. This choice probably introduces a numerical error in the calculations, which can only be alleviated refining the discretisation. As the issues of a representative driving force for the vapor fluxes are identical, we use $\Delta Cw = (Cw_w - Cw_j)$ for the approximation.