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QUEST

Quality and Energy efficiency in Storage and Transport of agro-materials

Progress report

March 2004 - August 2004

Consortium

Agrotechnology & Food Innovations
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Carrier Transicold, Container Products Group, Division of Carrier Corp.
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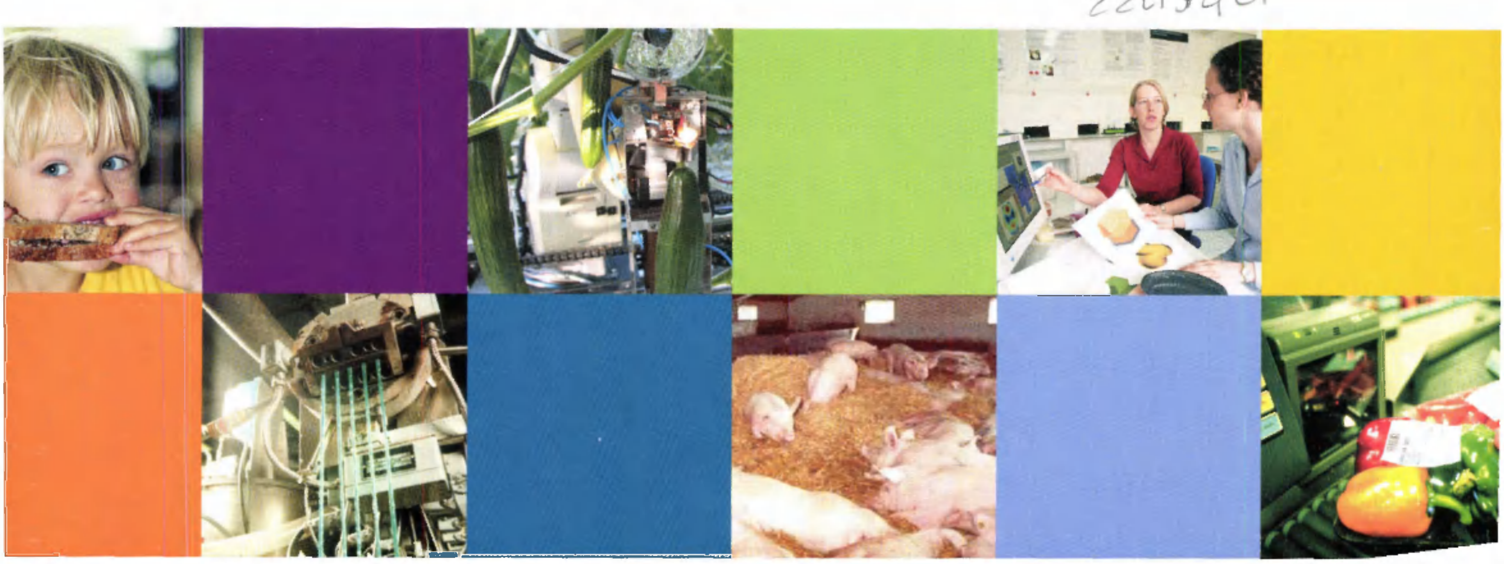
The Greenery B.V.
Frugi Venta
Haluco B.V.
R&R Mechatronics B.V.

Report 265



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Colophon

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Content

1 Progress

1.1 Activities in relation with planning last half year

The main activities in the different tasks in the third half year of the Research phase were the following:

1. Selection of products and markets

Conducting a full-scale test with QUEST-regular was not possible due to reorganization at Fyffes and very low product prices and high production in the USA. Haluco shipped almost no containers in 2004, in 2002 it were over 200 containers. Due to reorganization of the Fyffes department for pineapple import, the pilot of a shipment of pineapple from Panama to Holland was postponed. A collaboration agreement was signed between A&F and Fyffes to make measurement and testing during Fyffes transport possible. Appointments have been made for inventory measurements during regular Fyffes transport of pineapple from Costa Rica to Europe. After these measurements a pilot with Fyffes could be organized.

A strategy meeting was held in June 2004, in which it was decided to focus the remaining part of the QUEST regular product research on banana, avocado and pineapple. To achieve market acceptance and application of QUEST technology in practice it is important to prove the advantage on product quality. This is most convincing if done with high value produce (avocado, pineapple) and great volume commodity (banana). The aim will be to show an improvement of product quality (longer storage time and/or longer shelf life) with the QUEST Regular technology. Preliminary studies with banana, see chapter 2, showed that quality improvement is possible by using cycling temperature regimes instead of a fixed set-point. However, more detailed study is necessary to show quality improvement instead of quality preservation, which was the aim for the broad product range.

2. Market introduction strategy

A strategy meeting was held in June 2004, in which the partners discussed the possibilities for market introduction and the necessary project focus to achieve market acceptance and application of QUEST technology in practice. It was discussed that the energy reduction will be interesting when the technique is applied on a considerable amount of reefers. However, to achieve application on many reefers, an improvement of product quality with QUEST technology must be proven. Also, it was discussed how parties can benefit from the use of QUEST technologies. PONL benefits if the QUEST technique is wanted, and therefore PONL as a shipping line supplying this technology is wanted as well. Carrier will benefit if the QUEST technique is wanted and therefore Carrier machines will be wanted as well. Fyffes will benefit if the QUEST technique reduces the number of cargo's where problems occur and if energy will be saved. To bring QUEST technology to the market, the main issue is to have results from a practical shipment where product quality loss is reduced by applying QUEST technology. The commodity should have a high value and the improvement of quality should be feasible. It is also important to get the support/approval of main stakeholders in the market like the PPECB, New Zealand export boards etc. A clear communication plan for this should be written. Further steps, for co-operation between parties in further development of the QUEST technology, will be taken when first results of a pilot are available. Priorities for the current project are to prove the advantage on product quality with QUEST technology. This will be done with high value produce (avocado, pineapple) and the great volume commodity (banana). The aim will be that we can show an improvement of product quality (longer storage time and/or longer shelf life) with the QUEST technology.

PONL will continue the market introduction after one or more successful pilot-tests with QUEST-regular.

3. Predictive models

a. Distribution model
The model of the temperature and humidity distribution in reefer containers has been tested and described. It will be validated with data collected in the pilots, when these become available. The steady state temperature distribution model was extended to be able to calculate dynamic situation, such as exist in pull down and during the QUEST regime, where the temperature setpoint is changed in time. The stationary version consists of a set of enthalpy equations, describing a set of nodes over the whole of the container. To make this set of equations instationary all temperatures in these equations were made time dependent. Also a dT/dt term was added in each equation. This leads to a set of ordinary differential equations, that can be solved using an ODE solver. The dynamic part is currently being tested and will be compared to results of the macroclimate model, which gives a dynamic mean temperature of the air and product. The first results of this dynamic distribution model look quite realistic. The next step is to validate the whole model with a pilot. Furthermore the humidity part of the model has yet to be adapted for unsteady state. Also, the model will be coupled to the macro-climate model and the results of the microclimate model will be incorporated. After that a series of simulations can be run to predict temperature and humidity distribution throughout the container.

b. Macroclimate model
The validation of the macroclimate model for QUEST Regular operation, the water tank test, was finished. To validate the model the heat transfer coefficient of the water containers was measured separately. With this heat transfer coefficient, simulations were done and the results were compared to the measurement data. The comparison showed that the temperature and consumed power were predicted very well, all within 10%. For the RH value during cooling there is some discrepancy. However, the final value is okay, and during warming the RH prediction is very good.

c. Microclimate model

The goal of the microclimate modelling is to be able to incorporate the effect product- and package-specific properties in the climate modelling on macro scale. The macro- and microclimate modelling meet each other in the network model. The network model results in climate predictions inside the container. From this, information about, for instance, coldest and warmest locations inside the container can be generated and be related to the energy consumption of the system. From experiments and expert knowledge it is known that temperature gradients do exist within a pile of boxes. To analyse different cooling regimes on their possibilities and risks these gradients need to be incorporated in the network model.
To be able to incorporate the effect of different product- and package-specific properties, modelling needs to be done from the scale of a single box up to a pile of boxes. In the past half year the box scale model is extended to the scale of a single layer. There is a model available which describes the average layer temperature as function of different product- and package-specific parameters. The box and layer model are being extended to a complete pallet. The pallet model case is a 3 by 3 box type pallet with apples. The method of modeling will be applicable to other configurations. To validate the microclimate model mass transfer and heat transfer measurements have been done in the container, with measurements at various locations in a pallet.

d. QUEST regular product research

The goal of the QUEST Regular research has been extended from reduction of energy use to obtaining less quality losses with use of a cycling cooling regime. The banana experiment, reported also in this section, showed that quality improvement compared to the standard storage condition is possible. However, the chosen conditions in that experiment were quite different from the conditions applied in the other Regular experiments so far. Therefore, further research is necessary.

In co-operation with the partners it has been decided to focus the remaining part of the QUEST Regular research on the following products:

- banana: high volume product
- pineapple: transport time close to after harvest life time
- avocado: higher value product with a known quality problem

Therefore, besides one kiwifruit experiment, no more experiments were performed for the products that were selected earlier during the project.

For the selected products it is being investigated if the cycling control regime is possible without higher quality losses or higher quality variations compared to standard storage conditions and if it is possible to obtain even quality enhancement. Results for kiwifruit and pineapple were found: there are no disadvantages for the product quality when the cycling control is used.

An experimental study was done in collaboration with Kasetsart University, Bangkok, Thailand. Thai bananas were stored at various temperatures with intermittent storage at 20°C. The test showed that the two investigated cultivars can have a longer storage life than at 12°C, if they are stored at lower temperature and subjected to the right cycle of intermittent warming. Shelf life was not taken into account. The effect on shelf of the best treatments need further investigation. Nonetheless, it seems that a cycling cooling regime may not only have no negative impact on some products, it may even mean that some products, especially those showing chilling injury, may have an improved quality. This suggestion is at present tentative only and needs rigorous testing. Additional research will be done on this topic for Cavendish banana as well as pineapple and avocado.

e. QUEST Pro product research
The investigation and modelling of avocado ripening was continued and resulted in a model description for the ethylene production and loss of firmness. This process-oriented description contains avocado maturity specific characteristics and constant process rates.

4. Monitoring system
A feasibility study on the development of an ethylene sensor has been carried out by Lionix. It will be possible to develop a sensor when the right receptive layer becomes available in the future. Currently, technology has not been developed far enough to produce a receptive layer that is distinctive enough.

The lab scale monitoring system (respiration setup) has been expanded with a temperature-controlled system and an on-line ethylene sensor. For faster temperature response inside the product vessel a fan has been placed at the bottom of the vessel, which creates additional air circulation in the vessel.
Experiments have been done to gain experience with the ethylene sensor. An experiment with bananas showed that the sensor is not only sensitive to ethylene but also to ethanol. Experiments with ethylene-air mixture samples showed that the sensor is accurate in the range of 1 ppm and 12 ppm, higher levels have not been tested, lower levels give no good responses (all compared with a calibrated GC).
Experiments with avocado are being conducted, they will give information about ethylene and ethanol levels during transport. Experiments with continuous ventilation and experiments with ethylene build-up are done to validate the sensor with the calibrated GC. The results will give answers to the question if this sensor is accurate enough for on-line measurements of ethylene.

With data on leak requirements and data from avocado ethylene production tests, it was calculated that in a 40 ft container loaded with avocado an ethylene sensor should be able to measure an ethylene concentration change of 0.5 ppm/h. If repetitive ethylene build-up can be used, measuring with an accuracy of 1 ppm is necessary. This depends on the dynamics of the sensitivity of the avocados for ethylene build-up during a few hours.

5. Control system

Together with product experts, possible quality improving control parameters for shipments with pineapple, banana and avocado were studied, by using the macroclimate model. A large number of simulations were done to determine the effect of QUEST Regular, ventilation rates and circulation rates on the container climate and energy usage. A number of the resulting temperature fluctuations were selected for product quality testing.

For QUEST Pro the ripening model has not been finished yet. The controller can be designed when the ripening model has been made.

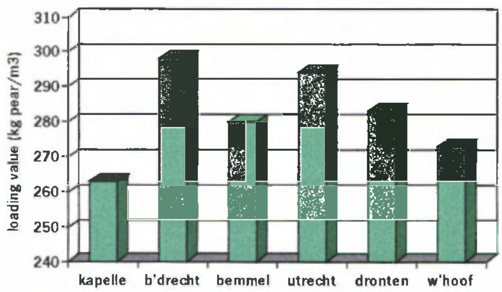
6. Practical guidelines

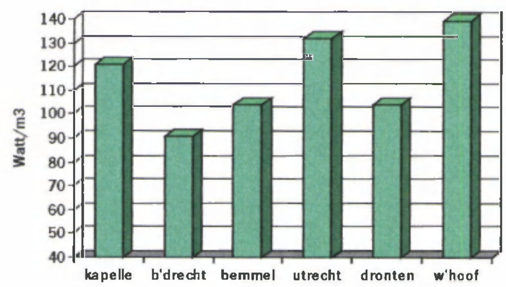
The discussion about the practical guidelines will be continued throughout the project. It will be a summary of all knowledge which is important to work successfully with reefer containers. It will proceed after one or more successful pilot-tests with QUEST Regular together with the market introduction work because these two are closely related.

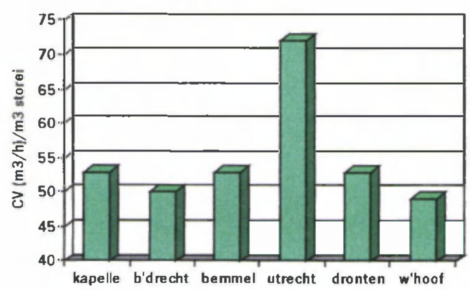
7. Chain information and technology transfer

The results of the technical inventory at the Greenery fruit-storage locations is evaluated and discussed at different meetings with the operators. The storage locations differ a lot, as well in capacity, technical set-up, as in quality result. These differences are seen at all the on-land facilities. The difference in technical set-up of the equipment is evaluated for the influence on energy use. One of the main differences is the used air-amount for circulation in the CA stores. For the coming months measurements in energy use of the specific circulation setting are being planned at each location. This will be combined with measurements of the air amount, the airspeed and the air distribution within the rooms. Lowering the air amount with specific regulation will perhaps influence the temperature difference within the storage room. By all the collected information, the storage managers are more interested in alternative settings. With their experience most operators are conservative to change their main settings, because of their fear for product damages. Especially for short storage of mostly imported product settings are changed. For the main settings with high influence on energy use, a basic checklist will be developed in the coming month.

8. Testing and integration







Preparations were made for the full-scale test a possible pilot in the summer. Due to reorganisation of the Fyffes department for pineapple import and low bell pepper and tomato prices in the U.S., the pilot has been postponed. Partners have decided to organize a land pilot if no sea transport can be arranged.

1.2 Cost in relation with planning last half year

The costs realized in the period from 1 April 2004 to 1 September 2004 are €393.341 and the requested subsidy is €210.826. This is exclusive of the costs made by Frugi Venta and Carrier Transicold Ltd. These expenses will be submitted in March 2005, after the next half-year period. R&R Mechatronics has not made costs in this period.
In total approximately 40% of the total costs of the project has been realized. A&F has realized approximately 71% of its total budget. It is expected that in the course of the project the relative contribution of the companies to the project will increase.

1.3 Milestones next half year

The milestones for the next half-year are:

1. Market introduction strategy
- will proceed after successful pilot tests

2. *Predictive models*
   - QUEST Regular
     - Extended research on set-points for pineapple, avocado and banana
     - Validation of models with pilot data
     - Testing of dynamic temperature distribution model
     - Microclimate stack model development & testing
     - Linking of models
     - Complete model simulations & conclusions
   - QUEST Pro:
     - Testing of Lab-scale setup and respiration estimator with avocado
     - Avocado ripening model
3. *Monitoring system*
   - Testing and improvement of lab-scale setup and respiration estimator with avocado
4. *Control system*
   - QUEST-regular control in the unit controller
   - Avocado ripening controller
5. *Chain information and technology transfer*
   - Detailed study on differences in air circulation and possible improvements
6. *Testing and integration*
   - Pilots with pineapple
   - Test QUEST-pro lab scale (at A&F)

2 Results

2.1 Main results

2.1.1 Product research

QUEST Regular

In this section the results for the second pineapple, a kiwifruit experiment and the banana experiment are reported.

The experimental set-up is as described in EETreport157: every product is subjected to at least the following treatments: i) normal storage temperature, ii) temperature below the normal storage temperature (coolest location), iii) temperature above the normal temperature (warmest location), iv) fluctuating temperature between certain boundaries) was expanded with a new cycling condition in which extra energy savings are to be expected. This was achieved by allowing fast cooling to even lower temperatures. In these treatments temperature refers to the temperature of the air around the product. After the storage period the product's quality was examined and repeated after a shelf life period. The temperatures in the experiments were based on expert knowledge and model simulations on container scale. The model predicts the climate in the load, headspace and T-bar floor, based on specific temperature ranges, package and product. From these values an estimate for the temperature fluctuations was made.

Pineapple

The second pineapple experiment was performed with the cultivar Smooth Cayenne, which is known for its sensitivity for quality problems. The product was airfreight and a 14 days transport simulation was performed, followed by 5 days of shelf life. Standard storage temperature was 7.8°C. Two cycling experiments were performed:

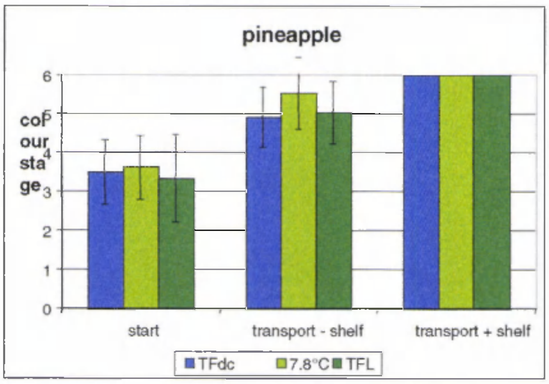
a) cycling between 9.0°C and 7.4°C, with 30 min(utes) cooling and 60 min heating (TFL);

b) cycling between 9.2°C and 4.0°C; with 2 min cooling, 8 min constant, and 50 min heating (TFdc).

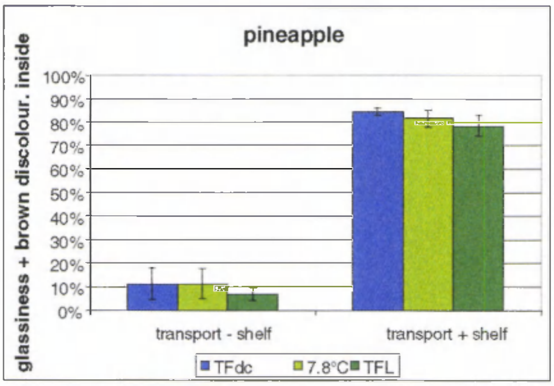
The following quality parameters were examined: colour stage (class 1 to 6); glassiness (watersoaked) inside and outside the product; brown discolouration (inside); weight loss, other deviations.

As an example two quality parameters are described in Figure 1. Figure 1a shows that at the start of the experiment the pineapples were at colour stage 3 to 4, and after transport simulation colour was developed to about stage 5. After shelf life simulation pineapples of all treatments had reached the maximum colour stage.

In all treatments glassiness and brown discolouration inside the pineapple (Fig. 1b) was at average 10%, but after shelf life simulation the problem had increased largely. However, this problem occurred in the control treatment as well, which indicates that applying cycling conditions in transport simulation is not the cause of this problem.



1a. Colour stage (outside appearance of the pineapple)



1b. Glassiness and brown discolouration inside the pineapple as observed by computer image analysis

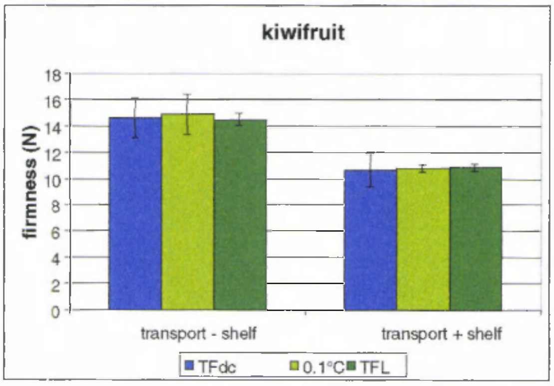
Figure 1 Changes in two quality characteristics as observed in transport and shelf life simulation using pineapple as a test product. Values are means ± SD.

In all the described conditions low temperature problems (such as black spot, black rot, pink disease) were not observed and the chosen transport simulation conditions had no effect on the analysed quality parameters, which indicates the possibility for using the cycling regimes.

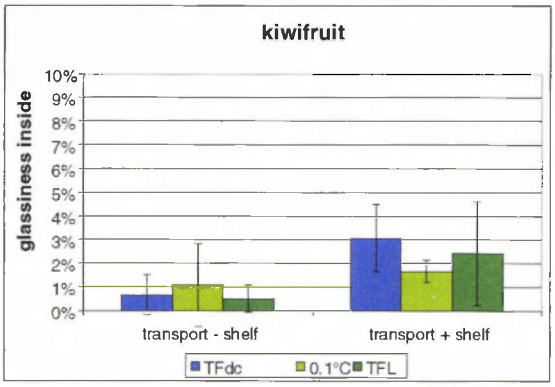
Kiwifruit

The kiwifruit experiment was performed with the cultivar Hayward. The product was shipped and a 28 days transport simulation was performed, followed by 4 days of shelf life. Standard storage temperature was 0.1°C. For kiwifruit two cycling experiments were performed as well:
a) cycling between 0.8°C and –0.8°C, with 27 min cooling and 45 min heating (TFL);
b) cycling between 1.2°C and –2.8°C; with 2 min cooling, 8 min constant, and 50 min heating (TFdc).
The following quality parameters were examined: firmness (using a penetrometer); glassiness (watersoaked) inside the product; soluble solids (°Brix); stem end rot; weight loss, other deviations.

Figure 2 shows as an example the firmness of the kiwifruits as well as the occurrence of glassiness inside the kiwifruits after transport simulation followed whether or not by shelf life simulation. During shelf life the firmness of kiwifruits decreased (as expected) from 15 to 11 N (Figure 2a), but no differences were observed in kiwifruits from different treatments.
After transport simulation and after shelf life the incidence of glassiness inside the kiwifruits (Figure 2b) was low and comparable between treatments.



2a. Firmness of the kiwifruits



2b. Glassiness inside the kiwifruits as visually judged

Figure 2 Changes in two quality characteristics as observed in transport and shelf life simulation using kiwifruits as a test product. Values are means ± SD.

Using the described conditions no chilling injury occurred in the kiwifruits and the chosen transport simulation conditions had no effect on the analysed quality parameters

Plans

A third pineapple experiment (cultivar MD2) and an avocado experiment (cultivar Hass) are being performed at the moment. These experiments are aimed at optimisation of the deep cooling cycling regime leading to potential quality improvement of the product, with respect to longer storageability.

QUEST Pro

The research for QUEST Pro in the past half year focused on the formulation of a model capable of describing the ripening of avocado. The ripening is defined as the influence of the ethylene production on the loss of firmness. The data obtained from the November 2003 experiment showed a wide scattering of ethylene production of loss of firmness for the different individual avocados, see Figure 4. The data showed a relation between ethylene production and ripening, the avocados that did not show a climacteric phase, also showed no ripening (colour or firmness development), see Figure 4 for an example of this phenomena. The differences in ripening are due to differences in maturity at harvest and lead to different features (level of maximal ethylene production, start time and duration of climacteric phase, final level of ethylene production, rate of firmness loss) in the data.

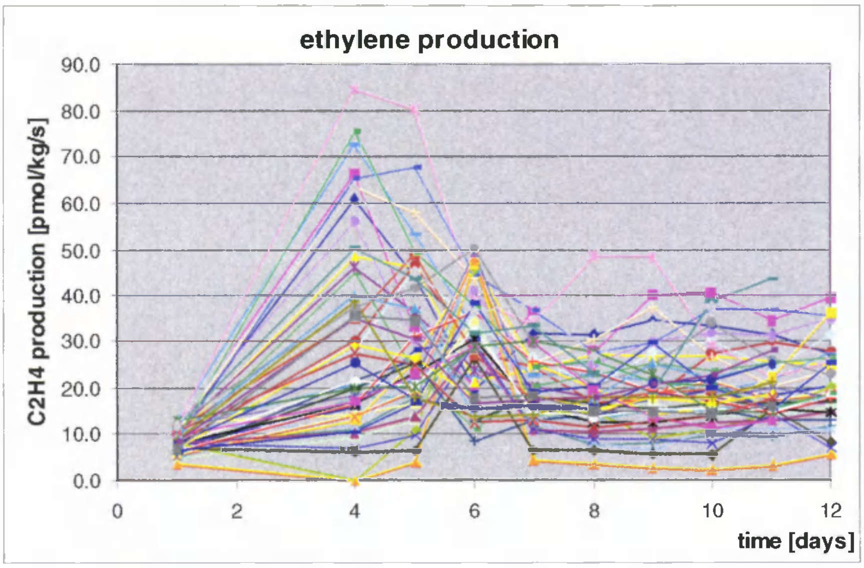


Figure 3 Ethylene production in time for 47 different avocado, cv. Hass, from the November 2003 experiment. The avocados were stored at 10°C, ethylene production and firmness (by hand scale 0 (hard) to 5 (soft)) were measured.

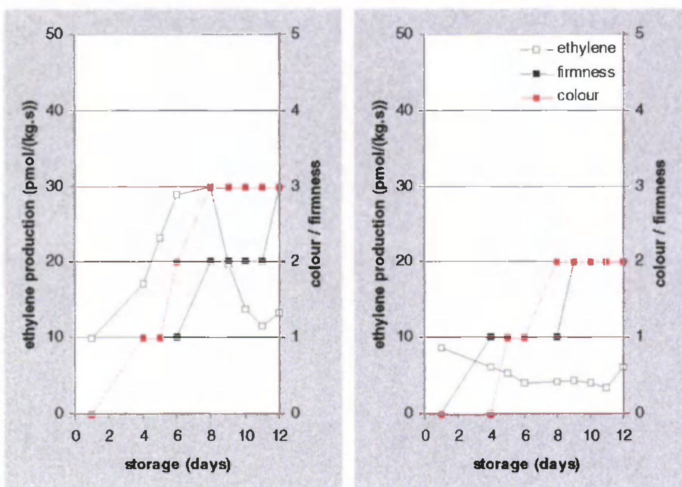


Figure 4 Ethylene production, colour (0 (green) to 5 (brown)) and firmness (0 (hard to 5 (soft)) for two different avocados, cv. Hass, from the November 2003 experiment. Ready-to-eat corresponds to a firmness of 3.5.

The model is formulated as a process-oriented description. There are different descriptions possible to describe the ethylene forming and firmness loss processes. Based on the shape of the obtained curves the formation of ethylene is described as being the result from an autocatalytic process, based on two precursors. The precursors represent chemical components involved in the formation of ethylene. The loss of firmness is directly related to the stage of the ethylene production. The resulting model consists of a set of maturity indices and a set of process rates combined with ethylene and firmness curve shape related equations. The maturity indices are individual avocado-specific initial levels of the two precursors, the initial ethylene production and the initial firmness. The process rates describe the formation of one of the precursors, of ethylene and of the loss of firmness. These rates are constant for all avocados.

Plans

The next avocado experiment will focus on the idea to use temperature a control mechanism to slow down or speed up the ripening process. Until which moment can the ripening process be influenced by a change in storage temperature? For this, batches of avocados are subjected to a temperature shift during their ripening and ethylene production, firmness and colour change are monitored. The results from this experiment will also be used to validate the developed ripening model. Values for the maturity indices and the process rates are not known when starting with the controlled ripening of a certain batch of avocado. Therefore, procedures to obtain these need to be developed. Together with the monitoring and control task work will be done to make the respiration set up (70 litres vessel, full temperature and gas controlled) suitable to perform ripening experiments on avocado. Furthermore, the model needs to be tested for applicability on batch scale and will be implemented in a controller environment.

2.1.2 Macro climate model validation

Background

The macro climate model is developed to predict the temperature distribution of a container with fresh products during transport. Different control strategies can be chosen from the simulation results with the macro climate model, hence it is important that the model has been validated and that there is knowledge about the accuracy of the model.

2.1.2.1 Experiment 1: Container filled with water tanks

Container

To validate the model the container has been filled with water tanks. Each water tank was filled with water and a heater (see figure 5). Further the container was filled with temperature and humidity sensors to measure the temperature distribution in the container, the water temperature and the humidity in the container.

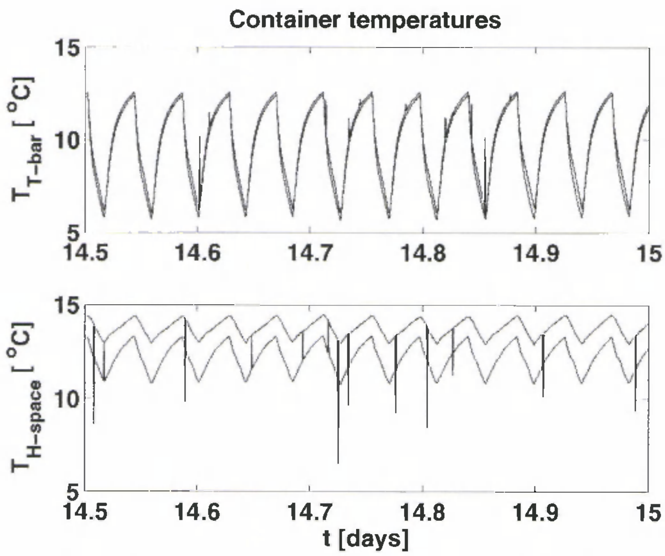
Figure 5 Left: container filled with water tanks, Right: heater in water tank

The mass of the water was around 18000 kg, the total power of the heaters was 1400W, these numbers are close to real fresh product transport.

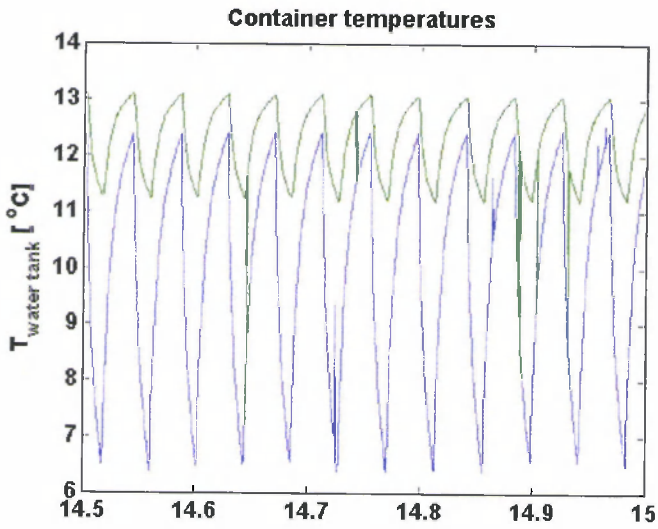
Controller

The container was controlled with the A&F designed QUEST Regular controller, which means that that the return temperature is between a high and low boundary while the inlet temperature is bounded during the cooling period. The high boundary temperature was set on 13°C, the low boundary temperature on 10°C, while the inlet temperature was set on 2°C.

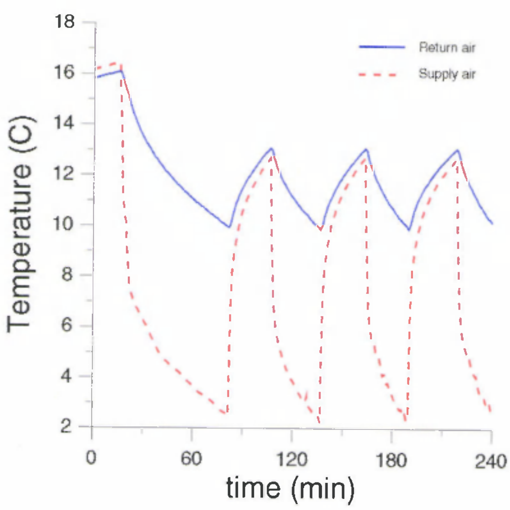
Results of the container experiments:



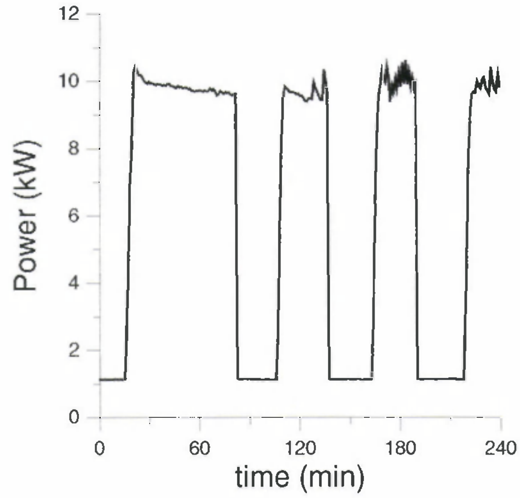
The above figure shows the temperature of the T-bar and headspace in the middle of the container. The fluctuation between the high and low temperature boundaries is good visible. The inlet temperature of 2°C is not reached during the experiment



The above figure shows the temperature of the wall on the outside of the water tank at 2 different heights, namely 0.3m and 0.7m from the bottom of the water tank.



The above figure shows the temperatures of the return and supply air at the refrigerant unit and are measured by the refrigerant unit it self.
Again it is clear to see the working method of the controller with the different boundaries.



This figure shows the consumed power during the control stage measured in the same time window as the previous figure. Clear to see that the power consumption is at maximum (10 kW) during the cooling phase.

Before a validation can be done simulations of the experiment have to be made. For simulations is the heat transfer coefficient of the water tank filled with water and a heater needed. To determine the heat transfer coefficient, a second experiment with the water tank was performed.

2.1.2.2 Experiment 2: heat transfer coefficient of a water tank

A water tank (same as used in experiment 1, dimension 1.12m x 0.915m x 0.92m) filled with water (800liter) and a heater (350W) was put in a isolated air temperature controlled cell. The temperature of the cell was set on 10°C and the initial temperature of the water was 18°C. Temperature sensors are placed at different heights in the water (see figure 6).

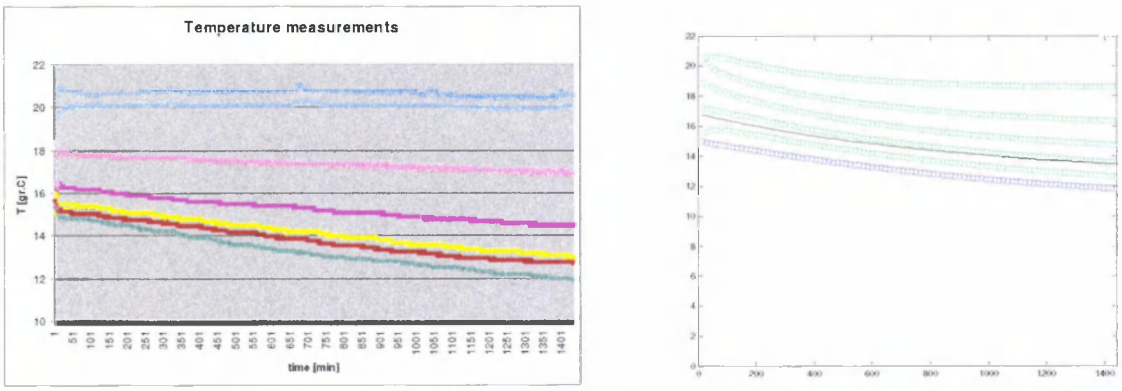


Figure 6 Left: Stratification in water tank during heating, Right: Modeled stratification in water tank

At the end of the steady state experiment the water was mixed so that the average temperature of the water tank could be validated, it was 12.3°C

From analysis of the Rayleigh number it seemed that the Ra number is around 10^{11}. This is highly turbulent, and difficult to model. In this regime differential heated cavities show horizontal thermal stratification and a thin vertical boundary layer. Let's assume that this is also the case for the water tank. It is probable that the heat resistance of the wall is much higher than the packaging material.

Experiments with water tanks have shown that in steady state there is stratification in the upper part of the tank. The bottom half of the tank is little above room temperature. We build upon the assumption of stratification a simple model. Convection is that strong that there is always stratification in the upper part, which gives a linear temperature profile along the height. In the middle of the water tank, and along the walls, there is a strong upward or downward current due to natural convection, as shown in figure below. This flow will determine what the temperature at the top will be. As natural convection is the driving force, we assume that the current velocity is proportional with the difference between average water temperature and the room temperature. Based on this we make a simple 1-D model, with heat flows shown in the figure below:

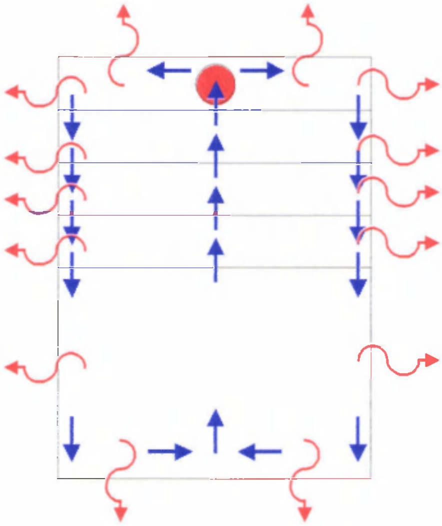


Figure 7 Schematic diagram of the model, with convective heat flows (driven by natural convection) indicated with straight arrow, and conductive heat flows indicated with wavy arrows.

We define the following variables: the area of the top of the water tank is A_{top}, the total area of the side walls is A_{wall}, the mass flux due to natural convection is $J = k.(T_{avg} - T_0)$, with T_{avg} the average temperature and T_0 the room temperature; h_{wall} is the effective the heat transfer coefficient of the wall (including the boundary layers in water and air). The power dissipated by the heater is P_{heat}.

Each shell in indicated by index n, with n=1 the bottom and n=N the top. In the graph above N=5. The side wall areas of the shell are then $A_{wall,1} = ½\, A_{wall}$, $A_{wall,n} = A_{wall}/2/(N\text{-}1)$ for n>1.

Below we state the energy balances for each shell:

$$dQ_1/dt = J.c_{p,w}.(T_2 - T_1) - h_{wall}(A_{top}+A_{wall,1})\ (T_1 - T_0)$$
$$dQ_n/dt = - h_{wall}A_{wall,n}\ (T_n - T_0)+J.c_{p,w}.(T_{n-1}-2T_n+T_{n+1}) \qquad \text{for } 1<n<N$$
$$dQ_N/dt = J.c_{p,w}.(T_{N-1} - T_N) - h_{wall}(A_{top}+A_{wall,n})\ (T_N - T_0) + P_{heat} - r.J_{evap}$$

$$T_{avg} = \tfrac{1}{2}\,T_1 + \Sigma_2^{\,N}\,T_n/2/(N\text{-}1)$$
$$J = k.(T_{avg} - T_0)$$
$$Q_n=\rho_w.c_{p,w}.\Delta V_n.T_n$$
$$J_{evap} = \beta_{eff}.A_{hole}.(\ c_{sat}(T_{surf}) - c_{air}\ )$$

Via the Lewis relation it holds that $\beta_{air} = h_{air}/\rho_{air}.c_{p,air} = 0.01$ m/s. Evaporating surface is A_{top}. However, due to the presence of a lid, the ambient vapour concentration is not known. But, the amount of evaporated water is measured. In steady state, the weight loss $J_{evap} = \rho_w.A_{top}.dh_{water}/dt = J_{evap} = \beta_{air}.A_{hole}.(\ c_{sat}(T_{surf}) - c_{air}\ )$, and T_{surf}=20°C. c_{sat}=0.024 kg/m^3. With change in height of water dh_{water}/dt = 0.5 cm/day J_{evap}=58.1 10^{-6} kg/s. Hence, c_{air} = 18.2 g/m^3, and R.H. = 75% (based on T_{air}=20°C beneath the lid). Witht the latent heat of evaporation is r=2.45 10^6 J/kg, the evaporation does have a significant effect on temperature distribution. Compare the heat dissipation is P_{heat}=350W with r.J_{evap}=140W. Hence, evaporation is definitely not negligible.

k and h_{wall} are unknown parameters. h_{wall} might be estimated from the thickness of the water tank, given is λ_{wall}=0.4 W/m.K, and d_{wall}=4mm, and thus $h_{wall,1}$ =100 W/m^2.K. The thermal boundary layer in the water maybe of same order. However, there is also the heat resistance of the stagnant layer of air, for which holds h_{air}=6+4.u_{air} (with $u_{air}\approx$2 m/s) Hence, $h_{wall}\approx$13 W/m^2.K
In the first simulation, there is a non-uniform initial temperature distribution, copied from experimental data. Room temperature is kept at 10°C for 5 days and heater on 350W, after 5 days room temperature is set to 7°C and heater to 30W. h_{wall}=15 W/m^2.K (including effect of thermal boundary), and k=4 10^{-3} (kg/s.K).
As in experiment there remains a stratification in temperature in steady state, and the bottom cools to about 12°C in 1 day. Cooling experiment after 5 days shows that average temperature has an exponential decay. It is analysed whether such a decay can be modelled with a single equation. Via trial and error we have found good model predictions for the values h_{wall}=12 W/m^2.K and k=0.002 (kg/s.K). In figure 8, we have compared results with simulations, and have found they are quite comparable.
Change in temperature during cooling. Diagram on the left is numerical simulations, and on the right are experimental data (Temperature versus time is indicated). In the left diagram temperature is at different heights in the water tank (from top to bottom, with bottom in blue), and average temperature is the thin black line.
Subsequently, we have performed simulation (see figure 8). We compare the average temperature in steady state with T_{room}=10°C. Experimental value = 12.3°C: In figure 8, the average

temperature is indicated with a thin black line, showing a steady state value = 12.4°C, which is not significantly different from experimental value.

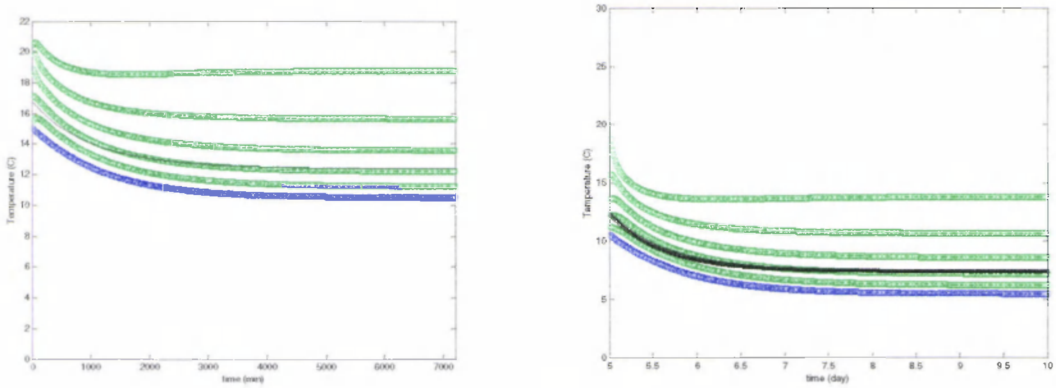


Figure 8 Left: Simulation with temperature at different heights in the water tank (from top to bottom, with bottom in blue). Average temperature is the thin black line. Right: Average temperature, estimated with simple model, is indicated with black crosses, which overlaps with the black line of the average temperature of the detailed model.

2.1.2.3 Simplified model

For comparison of macro model with container experiments with water tanks, it is demanded that the water tank can be described with a single equation. We investigate that analysing step responses with the detailed model, as described in the previous section. We compare the response of the average temperature with the following simple model:

$$C_{water}\, dT_{avg}/dt = h_{wall} \cdot A_{tot}\, (\, T_{avg} - T_{room}\,) + P_{heat,eff}$$

Analysis (see figure 8, right) shows that with $P_{heat,eff} = 0.75\,(P_{heat}\text{-}r\, J_{evap})$, the simple model will estimate the average temperature correctly.

Note, during container experiments there was no lid on the water tank (in contrast to single water tank experiments), and the evaporation might be quite different than above, where we assume a constant evaporation rate. In experiment J_{evap} depends on $(\, c_{sat}(T_{surf}) - c_{air}\,)$, as in the CEET-macro model. However, we need to estimate T_{surf}, which is probably a function of P_{heat}/C_{water} and $(T_{avg} - T_{room})$:

$$T_{surf} = T_{avg} + \alpha\, (\, P_{heat,eff} - k.c_{pw}(T_{surf} - T_{room}\,)\,)$$

Analysis (see figure 9) with detailed model shows that $\alpha = 0.07$ (K/W) this relation holds for $T_{room} < 7$°C.

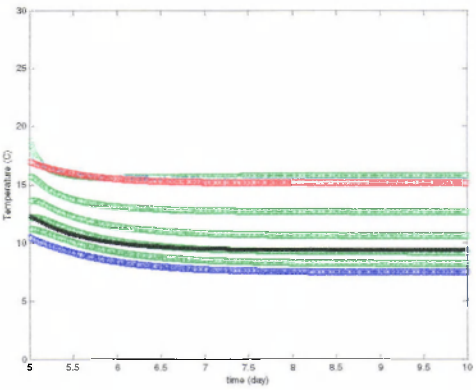


Figure 9 Estimated surface temperature is the red line, coinciding with the green line, obtained with the detailed natural convection model.

Given the evaporation rate, RH=69% in single tank experiment, with T_{room}=10°C, and hence c_{air}=6.2 g/m^3. $c_{sat}(T_{surf}$=20°C) = 16.2 g/m^3, we find $\beta_{eff}.A_{hole}$=6 10^{-3} m^3/s. This value is used in the simplified model.Analysis of container scale experiments with water tanks

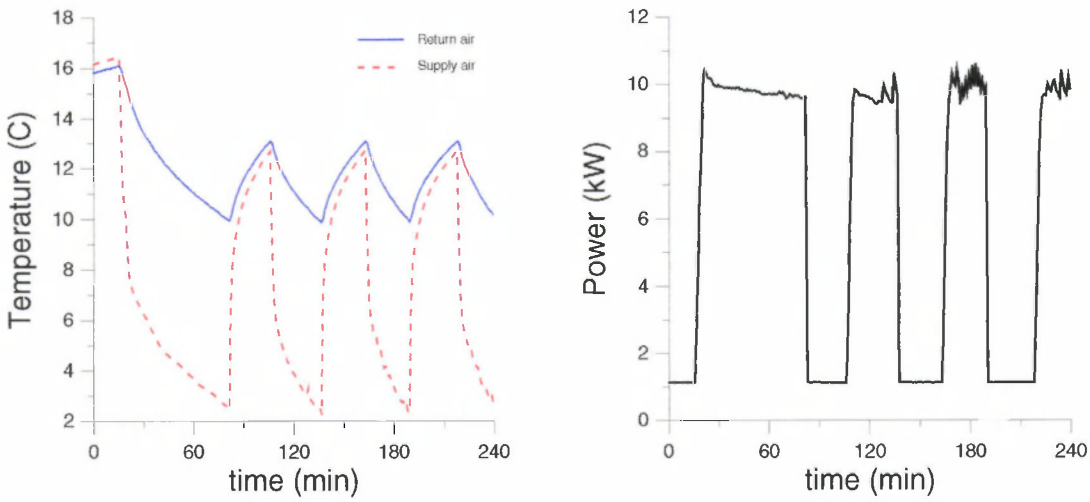


Figure 10 Experiment #3 with cycling: (started at 17.00h 13/11/2003).

The design of the above experiment is: Fan speed = 1 m^3/s (full speed), fresh air intake = 5 m^3/h, ambient temperature = 10°C-12°C, ambient RH = 100% (it was rainy outside). The power of the dissipated heat is: 350W, but it was cycled 1 minute on/4 minutes off, and hence on average: Dissipated heat is 70W. Control Algorithm applied cycling with return air temperature between 10 and 13°C, and supply air temperature T_{sup} = 2°C.

We have modified the existing macromodel, in order to simulate the above container experiments. The following modifications are done:

1) Above simple model of water tank is implemented,
2) Finite cooling capacity is implemented, and
3) Adjustment of geometrical parameters, such as AirVolume, are done.

Experiments has shown that the supply air does not reach the desired setpoint due to the finite cooling capacity. This is implemented in model in the following way: if difference between supply and return air is larger than 7^0C, we will stepwise increase T_{sup}, until cooling power is below the 10 kW limit. Furthermore, note that air volume in the load is now quite large, due to the presence of empty water tanks.

Simulation gives a good first approximation (see figure 11 and figure 12). The cooling power stays at maximal cooling power of 10 kW during cooling, and is 1 kW during warming as is measured during experiment. The dynamics in return air/supply air temperatures are also quite comparable. The number of cycles in the same time period is also the same. For the RH value during cooling there is some discrepancy. However, the final value is okay, and during warming the RH prediction is very good.

The ill prediction of RH during cooling is probably due to the fact that the cool unit model is not quite valid in the situation of Finite Cooling power. This is modelled via a shortcut (via raising the setpoint until the power is maximal), and thus not based on physical principles. A cooling experiment using standard controlling (figure 13) shows the effect more strongly.

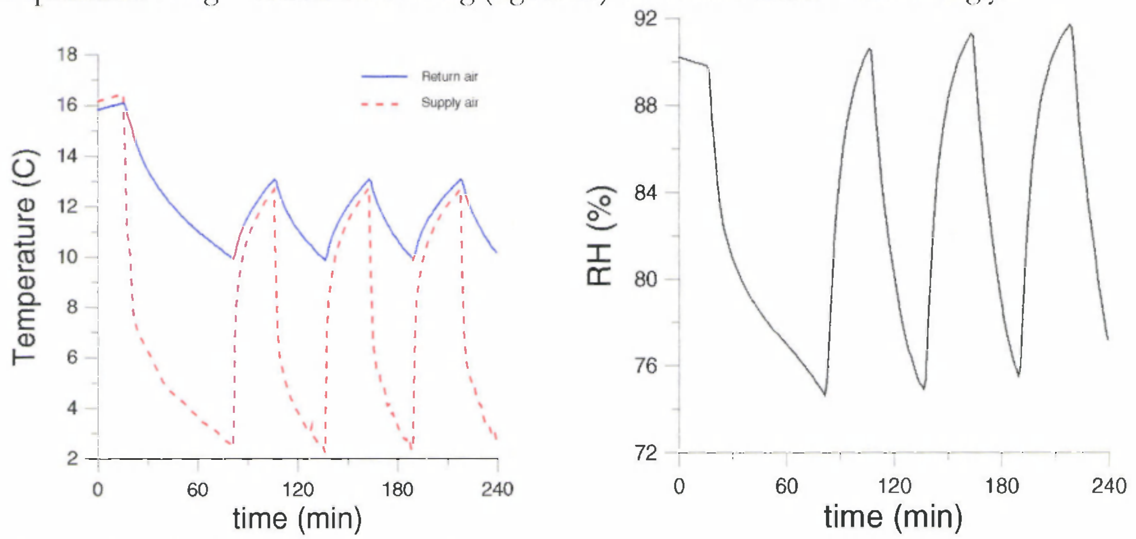


Figure 11 Readings from cool unit

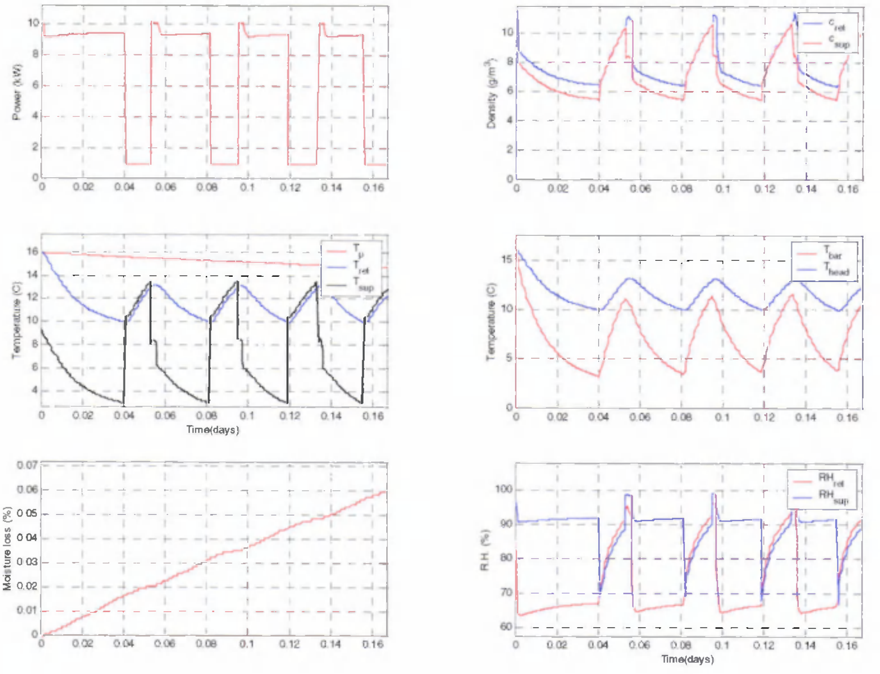


Figure 12 Simulation of container experiment

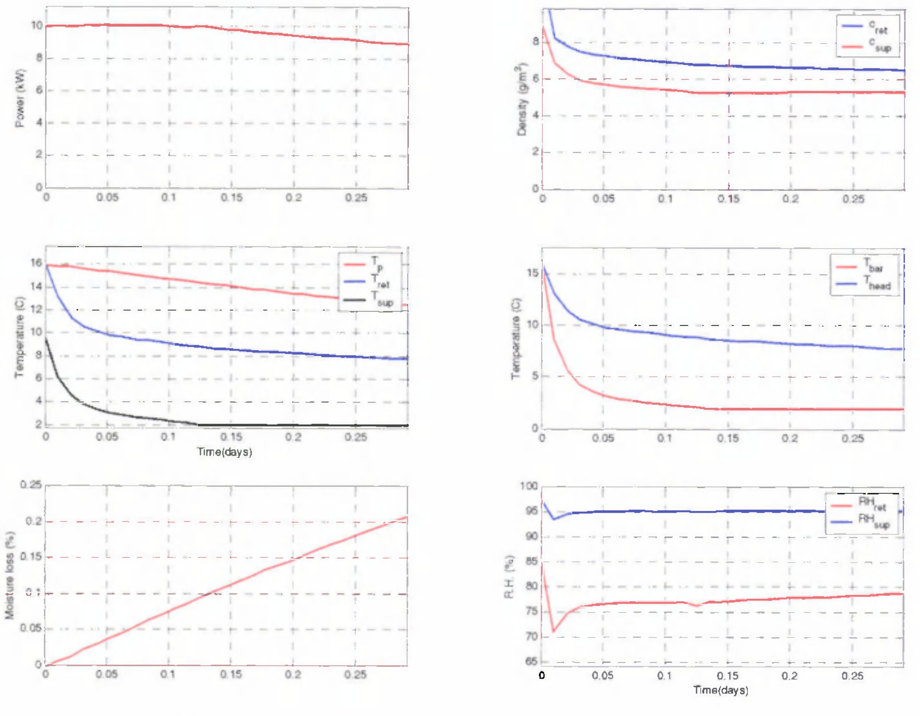


Figure 13 Container with water tanks, using standard controlling.

During the period of Finite Cooling power the RH of supply is quite low compared to later period, while the temperature of evaporator coil is higher than during the Finite Cooling power period. Furthermore the evaporator coil temperature is in the range of [2...4]°C, meaning that some part of it can be below freezing point, meaning that frost formation can occur during experiment, an effect that is not captured yet in the model.

2.1.3 Effect of temperature fluctuations on chilling injury during banana storage

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2.1.3.1 Introduction

Bananas are quite sensitive to storage at low temperature. If stored for too long at any temperature below 12°C, the peel first becomes grayish-black and then black. The advised temperature for long-term banana storage is therefore about 12°C, and often is about 14°C just to be on the safe side.

The banana trade centers around the Cavendish group, which is mainly grown in Meso-America and shipped to Northern America and Europe. Locally, however, many other bananas are grown, such as cooking bananas and dessert bananas. The latter are sweeter, and have much more aroma, than the Cavendish type. Since they are harvested at a relatively late stage of development, they cannot be transported by boat to their destinations in the Northern hemisphere. They would arrive too ripe. Dessert bananas are therefore now transported to the Northern markets by air, and in low volumes due to the high cost involved.

If dessert bananas such as cv. Sucrier, harvested in Thailand, are stored at 12°C, taken out of storage at color index 3 and evaluated for shelf life at room temperature in the tropics (30°C), their shelf life is 4-5 days. If displayed in the supermarket (at 20°C, or somewhat below) their shelf life is 7-8 days. Stage 3 means a bit yellow at the ends; it is the normal stage in which the fruit is removed from storage and taken to the supermarkets. Here they arrive at stage 3-4, which is about as green as yellow.

The aim of the present experiments, which were carried out in Thailand, is to find out if it is possible to extend the storage life of dessert banana. Our hypothesis is the following. Bananas can be stored at lower than recommended temperatures, and will therefore have a longer storage life, provided that they are intermittently warmed.

2.1.3.2 Methods

Sucrier and Gros Michel bananas (*Musa acuminata*) were harvested at commercial maturity (80% mature, based on their shape and color development) from a plantation in Petchaburi province in western Thailand. Bunches were dehanded, placed in corrugated cardboard boxes, and transported in a controlled-temperature truck (25°C) to the laboratory, within 2 h of harvest. Hands were then selected for uniformity of size and color, cleaned in a solution of 0.5% $MgSO_4$ to remove latex from the cut surface. Fruits were dipped for 2-3 min in 500 mg l^{-1} thiabendazole solution to control fruit rot and allowed to air dry before placing them in cardboard boxes. The boxes, each with 30 individually tagged fruit, were placed in cool rooms at 20, 12, 8, 6 en 4°C. At 12, 8, 6 en 4°C the temperature was regularly brought to 20°C , for 1 day, with a frequency of 2, 4, 6 and 8 days.

The following parameters were measured: at 20 en 12°C the time to ripening stage 3, the time to off-color or to 'off flavor'. At the other temperatures the time to peel blackening was assessed.

2.1.3.3 Results

In cv. Sucrier the intermittent warming resulted in a shorter time to stage 3 of ripening, compared to fruit that was not intermittently warmed. The more frequent the intermittent warming, the shorter the time to ripening stage 3 (Figure 14). This is to be expected in bananas that are held at temperatures where no chilling injury is found. In contrast, when stored at temperatures lower than 12°C chilling injury (peel blackening) was found. This injury occurred earlier and was more frequent when the produce was stored at lower constant temperature (Figure 14, white bars). Interestingly, at these temperatures, if provided with intermittent warming, the bananas had a longer storage life than those without such intermittent warming. The warming partially prevented chilling-injury. This effect was greatest at the most frequent intermittent warming (2 and 4 days). Even when compared to produce that was continuously stored at 12°C, some treatments had a longer storage life. This was true for 4 days intermittent warming every 4 days at 8°C and every 2 days at 6°C. No chilling injury was observed in the treatment at 8°C with intermittent warming every 2 days. Here the storage life was limited by normal ripening to stage 3.

Very similar results were obtained with cv. Gros Michel (Figure 15). In this cultivar no quick ripening to stage 3 was found at 8°C and 2 days intermittent warming every 2 days. This may explain why this cultivar had a very long storage life in this treatment. However, the Gros Michel bananas that were stored at 8°C and with intermittent warming every 2 or 4 days did not become black either. They ripened in a way that was different from normal. They had an off-color and they had off-flavor. This happened at about day 50.

The following conclusions are drawn. The two investigated cultivars can have a longer storage life than at 12°C, if they are stored at lower temperature and subjected to the right cycle of intermittent warming. It seems that 8°C is the best storage temperature, and 2-4 days the best cycle. It is possible, but not very likely, that an intermittent warming of 1 day was also a good treatment at 6 or 4°C.

It should be recalled that this test is preliminary. The time to the end of storage life means that there is no shelf life. So if a shelf life at 20°C is required, which is a reasonable requirement, the storage life is shorter. The effect on shelf of the best treatments need further investigation. Nonetheless, it seems that the QUEST regulation of containers may not only have no negative impact on some products, it may even mean that some products, especially those showing chilling injury, may have an improved quality. This suggestion is at present tentative only and needs rigorous testing.

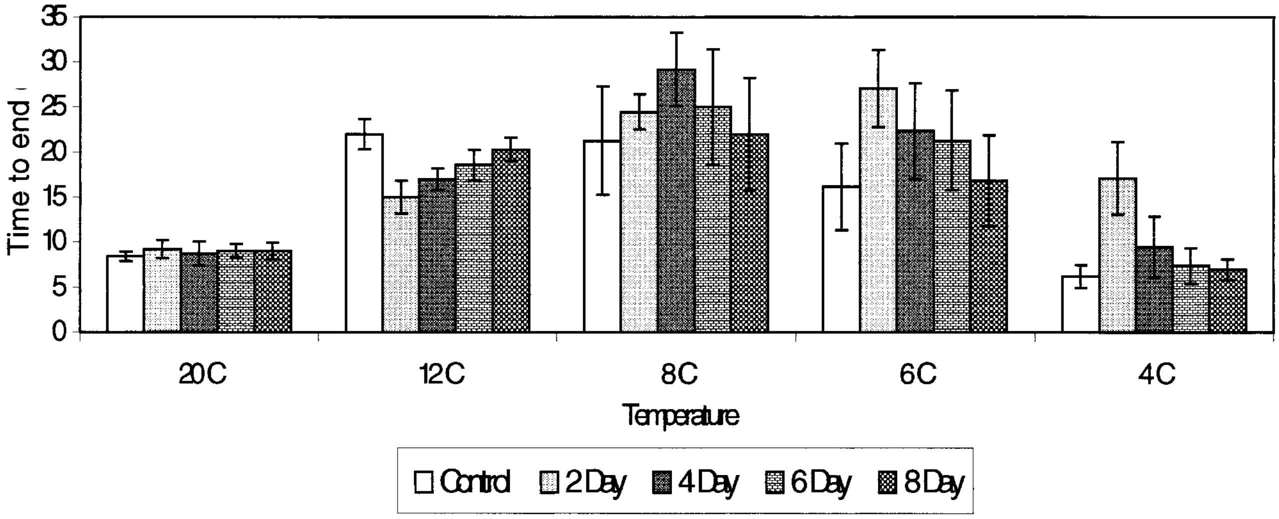

Figure 14 Time to end of storage life in cv. Sucrier. Fruit were stored at various constant temperatures. (20, 12, 8, 6, and 4°C). The control at each of these temperatures had no intermittent warming, the other treatments had intermittent warming (one day at 20°C) after 2 days, 4 days, 6 days, or 8 days. Thus the intervals between the warming periods were 2, 4, 6 and 8 days, respectively.

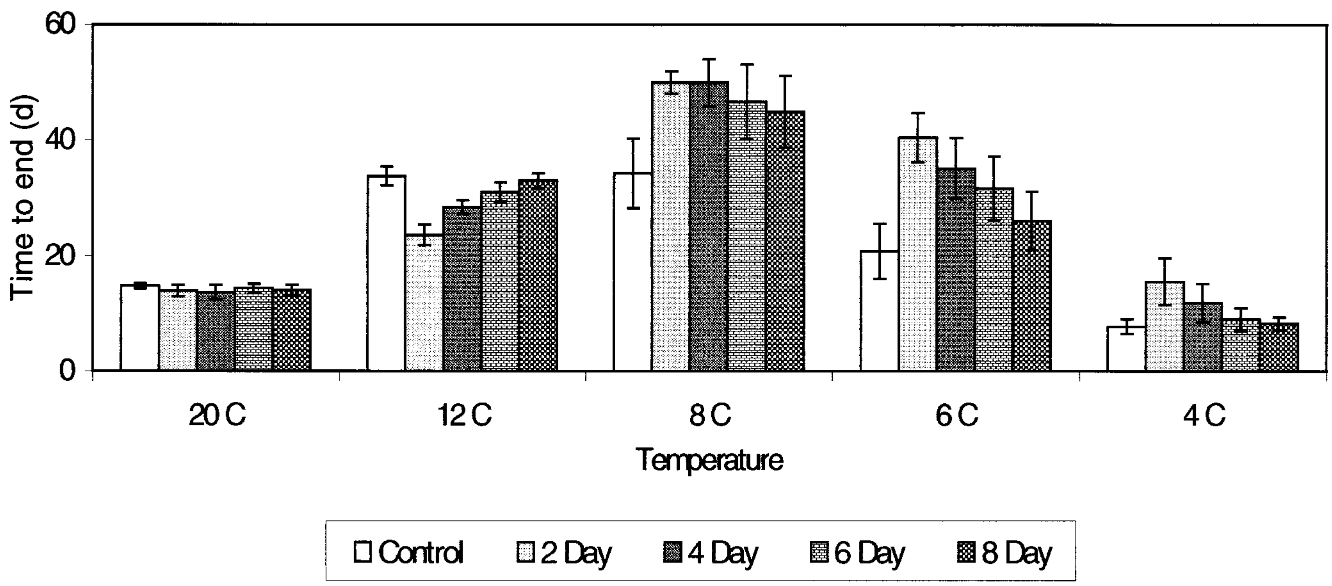

Figure 15 Time to end of storage life in cv. Gros Michel. Fruit were stored at various constant temperatures. (20, 12, 8, 6, and 4°C). The control at each of these temperatures had no intermittent warming, the other treatments had intermittent warming (one day at 20°C) after 2 days, 4 days, 6 days, or 8 days. Thus the intervals between the warming periods were 2, 4, 6 and 8 days, respectively.

2.2 Difficulties and solutions

Conducting a full-scale test with QUEST-regular was not possible due to reorganization at Fyffes and very low product prices and high production in the USA. Appointments have been made for inventory measurements during regular Fyffes transport of pineapple from Costa Rica to Europe. After these measurements a pilot with Fyffes could be organized. Also, it has been decided to organize a land pilot test in which the models can be validated.

A strategy meeting was held in June 2004, in which it was decided to focus the remaining part of the QUEST regular product research on banana, avocado and pineapple. To achieve market acceptance and application of QUEST technology in practice it is important to prove the advantage on product quality.

2.3 Internal reports

The internal reports and presentations are available on request submitted to the project manager G. van den Boogaard at A&F. For the participants of the projects some of these documents can be addressed via the web-site of the project: http://www.agrotechnologyandfood.wur.nl/quest.

Reports

- Feasibility of Mach Zehnder interferometer sensor for detection of ethylene. R Heideman & M Wehrmeyer, Lionix, 12 March 2004

2.4 External reports

None