DYNAMIC SIMULATION OF CONTROLLED ATMOSPHERE (CA) COOL STORAGE SYSTEMS FOR PIP FRUITS

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ABSTRACT

Simulation of dynamic processes in controlled atmosphere cool room storage systems is presented. The model consists of three interacting sub-models, for the prediction of the transient behavior of the processes in the three units, namely, the cool room, the refrigeration system and the gas-handling unit. Several modules representing each of the components in these units were developed based on energy and mass balances. The modules were then arranged to form the sub-models and in turn, the global CA cool storage system model was formulated by interconnecting these sub-models. The modules are implemented in a computational environment, (EcosimPro) which can handle continuous and discrete events.

Due to the modular and object-oriented approach greater flexibility with respect to model modification and reusability is achieved. Simulation of several cool rooms (CA) loaded with different products is possible by using the model. Further, tuning of controller parameters can be carried out to improve performance of the cool rooms. In this work, the model predictions were compared with experimental results. In general, good agreement between model predictions and measured values was obtained. Moreover, the provided product respiration model enables easy coupling to product quality models to predict the quality deterioration of the stored products during storage.

INTRODUCTION

To meet the ever-increasing consumer demand for quality of fresh fruits and vegetables the whole year round, CA cool storage systems are widely used to increase the storage life of the produce. Once the optimal storage conditions for a specific product are known, the environment under which the produce is stored should carefully and appropriately be controlled to prevent possible storage disorders due to sub-optimal conditions. Thus, effective design and optimization with respect to plant performance as well as product quality should be ensured. In this regard, predictive modeling and computer simulation is considered as an essential tool.

Several models of complete cool room installations have been developed by various researchers (Cleland, 1983; Lovatt, 1992; Hasse et al., 1996). These models apply for conventional cool room installations where a refrigeration unit is coupled to one or more applications in which only the temperature and humidity are controlled. Moreover, the emphasis of these works was on performance of the plant operation. With the advent of CA storage the evolution of the gas concentrations involved in product respiration as well as the dynamics of the corresponding gas handling unit became important. This requires the inclusion of elaborate product respiration models to account not only for the evolution of the gas concentrations but also the heat of respiration generated as a result of the on going physiological processes of the stored produce. Since the underlying mechanisms of respiration and quality deterioration (at least that of firmness loss) are believed to be similar, this in turn can give an idea on the quality degradation of the produce during storage. With such an approach, optimization of the CA installation with respect to plant performance and ultimate product quality is possible.

The objective of the paper is to simulate the dynamics of heat, moisture and gas exchange in the cooled space as well as the dynamics of the involved mechanical plants of a controlled atmosphere storage systems using hierarchical modular approach implemented in an environment, EcosimPro (EA International, Madrid, Spain), which can handle discrete and continuous time events.

1 MODEL DESCRIPTION

The model consists of three interacting units namely the cooled space, the refrigeration system and the gas-handling unit. Hereunder, a short description of each of these sub-models and their components is outlineded.

1.1 Cooled space (room) model

Individual modules that describe the components in the room were developed and arranged to formulate the sub-model. The components of the cooled space can be classified as product and non-product components. The non-product components are the cooler, the surfaces, and the medium, air. Here, lumped parameter approach was pursued where the transient response of the system is formulated by an overall energy and mass balance. This results in a set of ODE's describing the system. Often the zoning approach is pursued to deal with spatial variability in the room when using lumped approach (Amos, 1995; Hasse et al., 1996; Tanner, 2002). In relatively smaller compartments such as a CA cooled spaces, the use of single or a couple of zones can be justified. The modules representing the main components of the cooled space model are mentioned below.

1.1.1 Room air: Heat and mass is transferred between the cool store components (cooler, building envelopes, product) through a medium usually air. The energy and mass balance of the well-mixed mass of air results in the characterisation of the room air by temperature, moisture content and O_2 & CO_2 concentrations. With regards to temperature two zones were identified, the air that comes out of the cooler and interacts with the product and the one that interacts with the cooler. The structure of the ODE's used to describe the time evolution of temperature, humidity and gas concentrations (O_2 & CO_2) are shown in Eqs. (1)-(4).

Energy:

$$(rVc)_a \frac{dT_a}{dt} = q_{(c,a)} + q_g \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Moisture:

$$(rV)_a \frac{dX}{dt} = m_{(c,a)} + m_g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Gas

$$V \frac{dC_{O_2}}{dt} = -M_{pr} V_{O_2} + k_{O_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$V \frac{dC_{CO_2}}{dt} = M_{pr} V_{CO_2} - k_{CO_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

1.1.2 Heat exchanger (cooling battery) model: The cooling battery (cross flow) is an indirect system where a secondary refrigerant, cooled by the evaporator of the chiller unit, is circulated. A two-zone model was employed to describe the dynamics of the refrigerant flowing inside the tubes and the stationary tubes, fins and structure, yielding two ODE's. Condensation on the surface of the cooler is an inevitable occurrence. Here, it is assumed that the condensed water is immediately removed from the system and thus no re-evaporation occurs. Moreover, since condensation does not occur in the whole surface of the cooler, a correction factor for the area is introduced to account for the equivalent water-covered surface of the cooler. A timer-based defrosting strategy is also modelled.

1.1.3 Surface model: The insulating walls and the ceiling are surfaces, which separate the cool store air from the outside. The mechanisms of the heat transfer through these surfaces may occur by convection (between air and boundary surfaces), by conduction (through the surface material) and radiation. Several approaches of modelling thermal behaviour of insulating surfaces are discussed in Flores et al. (2001). Here, a lumped resistance and capacity approach within a single zone is pursued. The surface is considered as a one-dimensional slab in which the thermal capacity is lumped and the change of temperature at one side is modelled. Since CA cells are constructed inside building envelopes, they are not directly exposed to the sun, and radiation can be ignored. The outside temperature (that is temperature inside the envelope) is assumed to be constant. However, when adjacent cells share a common wall, the dynamic room temperature of one cell is considered as a boundary condition to the other cell. With the exception of the floor, condensation on the surfaces is unlikely and thus no additional equation was needed. For the floor model conduction through the soil, concrete, floor slab and insulation was considered. Since insulation against moisture transfer from the soil to the room is often provided, penetration of moisture to the room through the floor can be ignored. However, condensation on the floor could occur depending on the temperature of the soil beneath.

1.1.4 Product: To represent the bulk of stored goods, a simple model based on lumped energy and mass balance was employed. For the energy balance Eqn. (5) is used to describe the cooling dynamics of the product, assuming the temperature of the packaging is the same as that of the product.

$$\left[(Mc)_{pr}+(Mc)_b+(M_{w,b}c_w)\right]\frac{dT_{pr}}{dt}=q_{(a,pr)}+q_{resp}+q_{p(a,pr)}+q_{(a,b)}-c_{pr}T_{pr}\frac{dM_{pr}}{dt}-c_wT_{pr}\frac{dM_{w,b}}{dt} \quad \ldots\ldots(5)$$

For the moisture balance, the partial pressure of vapour was determined by using moisture isotherms (Equilibrium Moisture Content curves) for the product as well as for the bin. Respiration is responsible for the majority of the heat generated by the product. The rate of respiration was modelled by using non-competitive inhibition given by Eqn. (6) and (7) (Peppelenbos and Van 't Leven, 1996).

$$V_{O_2}=V_{m,O_2}\frac{P_{O_2}}{\left(K_{m,O_2}+P_{O_2}\right)\left(1+\frac{P_{CO_2}}{K_{mCO_2}}\right)} \ldots\ldots\ldots(6) \qquad V_{CO_2}=RQ*V_{O_2}+\frac{V_{m,CO_2,f}}{\left(1+\frac{P_{O_2}}{K_{m,O_2,f}}\right)} \ldots\ldots\ldots\ldots(7)$$

Moreover, a control strategy based on selective control, which involves a set of PI and PID controllers, and phenomena related to the implementation of these controllers such as anti-reset windup are included in the model. The modules and their hierarchy in the model is shown in figure 1.

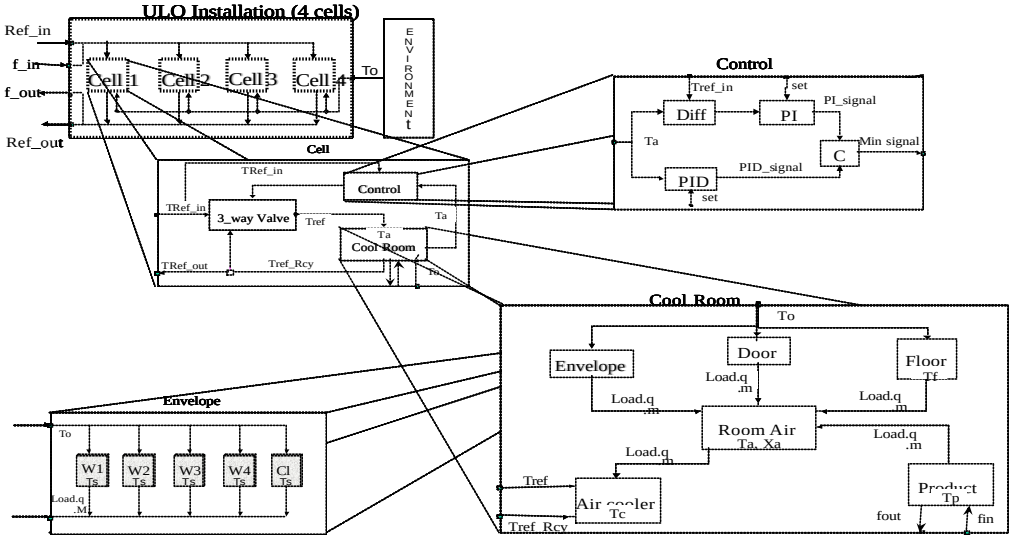

Figure 1: Hierarchical model structure of the cool room installation.

1.2 The refrigeration unit model

Based on the requirement for a simple model with limited number of parameters and the level of accuracy sought to predict the transient behavior of a refrigeration unit, a simple thermal model, which ignores the hydrodynamic effects, was considered. The models for the evaporator, condenser, compressor and the holding tank were developed by a zone approach using mass and energy balances around the components. It is established that the compressor behavior can be modeled algebraically assuming a constant compressor speed and thus constant volumetric flow rate (Cleland, 1990). For the structure of the model equations the reader is referred to, Eg., Cleland (1990), Darrow et al., (1991), Lopez and Lacarra (1999).

1.3 The Gas handling unit model

In modern CA cool storage systems, Pressure Swing Adsorption (PSA) or Vacuum Swing Adsorption (VSA) systems are commonly used to generate nitrogen for pull-down operation as well as scrubbing excess carbon dioxide from the cool rooms. In this system, a mixture of gas is fed to a column of bed packed with particles (adsorbent) and one component is preferentially adsorbed on the surface of the particles. The selectivity may depend on a difference in adsorption equilibrium (equilibrium driven) or in sorption rates (Diffusion driven). The latter is often used for CA purposes due to the short cycles and somewhat easier regeneration phase. Often, two columns are employed where

one undergoes the adsorption step while the other column is in regeneration step. As the two columns switch there is a short pressure equalization step.

Unlike many separation processes, PSA process is more complex in that it operates in transient conditions. Thus, a dynamic simulation model is more appropriate to obtain realistic results. In a kinetically controlled process where the mass transfer resistance is significantly greater than the axial dispersion the fluid phase flow can adequately be represented by a plug flow model (Eqn. (8)) (Ruthven et al., 1994).

$$\frac{\partial v c_i^g}{\partial z} + \frac{\partial c_i^g}{\partial t} + \frac{1-e}{e}\frac{\partial \overline{q}_i}{\partial t} = 0 \qquad (8)$$

Assuming that the column is operated at constant total pressure, the overall material balance yields:

$$C^g \frac{\partial v}{\partial z} + \frac{1-e}{e}\sum_{i=1}^{n}\frac{\partial \overline{q}_i}{\partial t}, \text{ where } C^g = \sum_{i=1}^{n} c_i^g \neq f(z) \qquad (9)$$

The solid phase mass transfer rates can be approximated by the linear driving force model (LDF) (Eq. (10)).

$$\frac{\partial \overline{q}_i}{\partial t} = k_i(q_i^* - \overline{q}_i) \qquad (10)$$

$$q_i^* = q_{is}\frac{b_i c_i^g}{1+\sum_{i=1}^{n} b_i c_i^g} \qquad (11)$$

The term q_i^* is the adsorption equilibrium isotherm and can be represented by the Extended Langmuir model for multi-component mixtures (Eqn.(11)) (Ruthven et al, 1994).

From the point of view of the cool room, in a unit of two columns only the adsorption steps of the two columns is visible with short intermittent gaps as the columns undergo pressure equalization step. For this reason only the adsorption step of the two columns is modeled. Thus an initial condition of a clean bed ($c_i(z,0) = 0$ and $\overline{q}_i(z,0) = 0$) is considered after each cycle for the beds

2 VALIDATION METHOD

2.1 Experiments

The indirect system pilot cool room installation at the Laboratory of Postharvest Technology (Catholic University Leuven) was used. The system contains 4 CA rooms of 4.25x2.8x3.6 m³, 47.6KW chiller unit and 2 VSA units for N_2 generation and CO_2 scrubbing, respectively. A cool room was loaded with 8 bins (1.0x1.2x0.75m) each containing around +/- 380kg of conference pear. A total of 59 calibrated T-type Teflon-insulated thermocouples (Omega Engineering, Inc., Stanford, USA) were used to follow the dynamics of the temperature inside and outside the bins and the product temperature (a fruit situated at the centre of the bin was selected). The thermocouples were connected to an HP 34970A data acquisition system (Hewlett-Packard Company, USA), which was interfaced to a personal computer. An additional temperature sensor PT100 situated at the back of the room was used for control purposes. The accuracy of the temperature sensors was ±0.5°C. In order to obtain a representative temperature of the room for validation purposes the volume average of the measured temperatures was calculated. The relative humidity of the room was measured by an RH meter (Siemens, Building Technologies Inc., Illinois, USA) and a dew point meter (General Eastern Instruments, MA, USA) with accuracy of 5% and 3%, respectively. A set of capacitive type RH sensors (ESCORT junior, Tech Innovators, Oakland, Newzealand) were used to record the relative humidity inside 4 of the bins with an accuracy of 5%. The surface temperature of the cooler was measured at two positions, near the entrance of the secondary refrigerant and at 2/3 the pipe length. The loaded room measurement set up is shown in figure 2. The gas concentrations in the room were analysed by 1111D/000 (Servomex Group Ltd, USA) paramagnetic oxygen analyser and 2008SDH (Valtronics, CA, USA) non-depressive infrared analyser for oxygen and carbon dioxide, respectively. The cooling process was started from room conditions to a set point of -1°C. Seven days later the gas-handling unit was set into operation to pull down the O_2 concentration down to a set point of 2.5%. The CO_2 level was controlled to a set point of 0.7%.

2.2 Model Parameters

The vital and difficult step in the validation of such a model is the determination of the model parameters.

2.2.1 Cool room parameters: The thermal masses of the non-food components of the cool room were calculated from available material masses, manufacturer manuals and literature (Eg. ASHRAE). For those that are related to the product, approximate literature data were used (Eg. Sprenger -Institute (1980). The heat transfer coefficients for

the surfaces were estimated from heat flux measurements and were found to be comparable to estimations by using empirical correlations. The heat transfers coefficients for the cooler battery were obtained the from manufacturer and these values were compared with estimations from empirical correlation and found to be analogous. For heat transfer coefficients around the product correlations for flow in a packed bed of material were used. Moreover, the enzyme kinetics model parameters were taken from Lammertyn (2001).

2.2.2 Refrigeration unit: The thermal masses for the components were again estimated from material masses and literature data. Heat transfer coefficients were calculated from technical characteristics obtained from manufacturer manuals. The necessary refrigerant thermodynamic properties were calculated from empirical equations developed by Cleland (1986).

2.2.3 Gas handling unit: The flow rates were obtained from measurement devices built in the system. The equilibrium and kinetic parameters of the adsorbent were obtained from literature (Eg. Valenzuela and Myers, 1989, Ruthven et al., 1994).

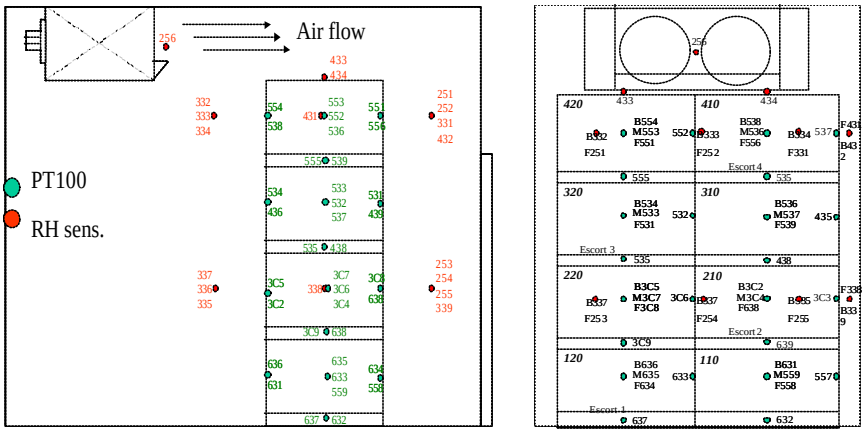

Figure 2: Loaded room measurement set up

3 RESULTS AND DISCUSSION

In figures 3-8 comparisons between simulation and experimental results are shown. Here, emphasis was given to the conditions in the room for one obvious reason. As the refrigeration unit and the gas-handling unit were not constructed to serve as experimental facilities no built in sensors were integrated to enable to measure their performance. However, for the refrigeration unit the model has been validated on an experimental set up constructed to imitate an indirect system layout (Nahor et al., 2002). Thus, in this work these models are validated indirectly by the variables that can be measured in the cool room such as the temperature of the refrigerant entering the cooler and gas concentrations.

In figure 3 the room air temperature for zone 1 is shown. A good fit between the predicted and measured values was found for both zones. The curves of cooler temperature prediction and measured values at two positions are depicted in figure 4. As might be expected, the model predicts the temperature of the cooler at 2/3 the pipe length than at the entrance. This is due to the obvious reason of lumping the cooler into one mass. The measured product temperature in figure 5 shows three curves Tprod1, Tprod2 and Tprod3. Tprod1 represents the bins marked 110, 120, 210, 220, Tprod2 the bins marked 310, 320, 420 and Tprod2 the bin 410 (figure 2). The difference between the two former curves can be attributed to spatial variability. It is expected that the lower bins cool faster given the flow of the cold air. The peculiar profile, Tprod3, was due to the construction of the bin, i.e., no air gaps were provided for the air to flow into the pack of fruit. The positive influence of this was on the moisture loss of the fruit after the storage period (38 days). It was observed that the value for this bin (0.4%) was much smaller as compared to the rest (1.9%). Thus, the design of bins can be a trade-off between fast cooling and moisture loss of the products. Under-cooling phenomenon was observed in both the predicted and experimental product temperatures due to evaporative cooling. Generally speaking, the model prediction represents the reality with acceptable accuracy. Figure 6 shows the room relative humidity measured at two positions and a simulation curve. The measurement from the RH meter is underestimated by about 5% as compared to the measurement from the dew point meter. This difference is rather ascribed to the calibration error than spatial variability, for the reason that at steady state the

measurements from both sensors are expected to give close values. The model prediction and the measurement from the dew point meter are in good agreement. The temperature of the secondary refrigerant entering the cooler is depicted in figure 7. Here, it is observed that during the defrosting phase the model predicts decrease in temperature while the measurement show an increase in temperature. This discrepancy arises from the way the defrosting phase was modeled in that a certain load is imposed on the cooler forcing the valve to open letting more cold refrigerant in to the cooler. While in reality warm refrigerant flow through the cooler, resulting in temperature increase.

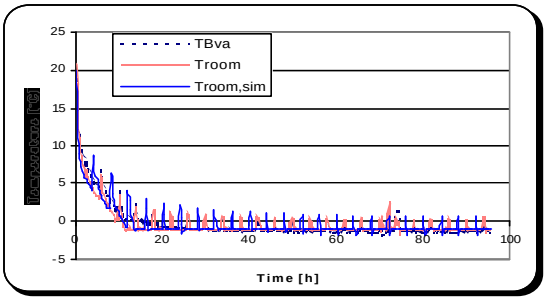

Figure 3 Room air temperature for zone 2

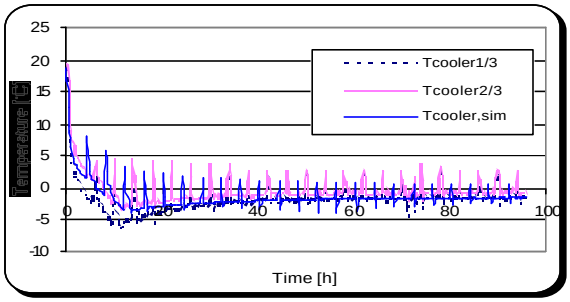

Figure 4 Cooler temperature

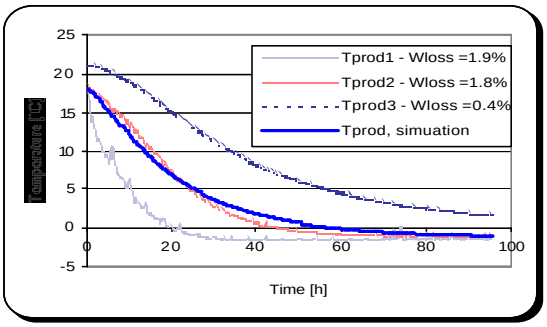

Figure 5 Product temperature

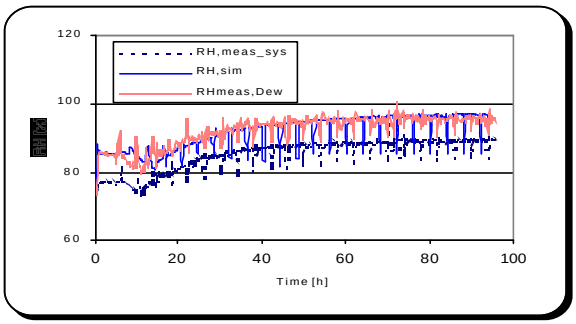

Figure 6 Room Relative humidity

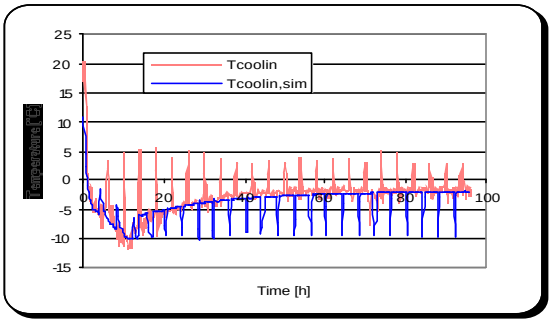

Figure 7 Refrigerant temperature entering cooler

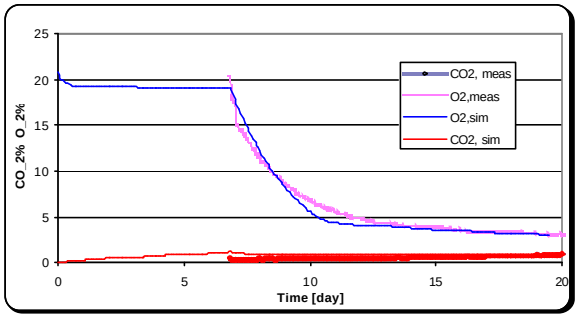

Figure 8 Room O_2 and CO_2concentration

However, the trend predicted by the model is in agreement with that of the measurement. Finally, in figure 8 the prediction of the evolution of CO_2 and O_2 concentrations in the room are compared with the measured values. The small decrease in O_2 concentration is due to respiration of the produce. Respiration is then hindered by reduced temperature and the rate of consumption of oxygen is equalized by leakages. The relatively good agreement between the measured and predicted values can be an indication for the good performance of both the product respiration model and the gas handling unit model.

4 CONCLUSION

A model for simulation of dynamic processes in controlled atmosphere cool room installations is presented. The model incorporates interacting sub-models for the cooled space, the refrigeration unit and the gas-handling unit.

Product respiration model was also included in the cooled space sub-model to account for the evolution of the O2 and CO2 concentrations as well as respiration heat generation. The model was implemented in a computational environment, which can handle discrete and continuous simulation. The global model performance was tested using experimental results obtained by performing a loaded room experiment. In general, the model predictions were found to be in good agreement with the experimental results.

Due to modular and object-oriented approach greater flexibility with respect to model modification and reusability was achieved. Using the model, simultaneous simulation of several cool rooms loaded with different products is possible. Moreover, the model is suitable for tuning of controller parameters as well as improving the control strategy to achieve better performance. Finally, the included product respiration model can easily be hooked up with product quality models to predict the quality deterioration of the produce after the storage period.

NOMENCLATURE

Symbol	Description	Unit
b	: Langmuir constant	[-]
c	: heat capacity	[J kg^{-1} °C^{-1}]
c^g	: gas phase concentration	[mol m^{-3}]
C	: concentration	[mol m^{-3}]
C^g	: total gas phase concentration	[mol m^{-3}]
k	: effective mass transfer coefficient	[s^{-1}]
k_{CO2}	: rate of carbon dioxide removed	[mol s^{-1}]
k_{O2}	: rate of oxygen removed or added	[mol s^{-1}]
K_m	: Michaelis constant	[KPa]
m	: mass transfer rate	[kg s^{-1}]
M	: mass	[kg]
P	: partial pressure	[KPa]
q	: heat transfer rate	[W]
q^*	: value of $\bar{q}$ in equilibrium with c^g	[mol m^{-3}]
$\bar{q}$	: solid phase concentration	[mol m^{-3}]
q_s	: saturation solid phase concentration	[mol m^{-3}]
RQ	: respiration quotient	[-]
t	: time	[s]
T	: temperature	[°C], [°K]
v	: velocity	[m s^{-1}]
V	: volume	[m³]
V	: rate of accumulation	[mol kg^{-1} s^{-1}]
V_m	: maximum rate of accumulation	[mol kg^{-1} s^{-1}]
X	: moisture content	[kg kg^{-1}]
z	: axial distance	[m]
e	: bed void ratio	[-]
r	: density	[kg m^{-3}]

Subscripts	Descripion
a	: air
b	: packaging (carton, bin, etc)
c	: room components (surfaces, air, cooler, product)
CO_2	: carbon dioxide
f	: fermentative
g	: generation term
i	: component
O_2	: oxygen
p	: phase change
pr	: product
$resp$	: respiration
w	: water

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SIMULATION DYNAMIQUE DU STOCHAGE EN CHAMBRE FROIDE SOUS ATMOSPHERE CONTROLEE

On présente une simulation des processus dynamiques concernant le stokage en chambre froide sous atmosphère controlée. Le modèle utilisé pour cette simulation est constitué de trois entités (sous-modèles) en mutuel interaction. On souhaite prédire le comportement transitoire des processus dans les trois entités, à savoir, la chambre froide, le système de réfrigération et le "traitement et contrôle de gaz". Plusieurs modules, représentant chacune des composantes de ces unités sont developpés, basés sur les équilibres d'énergie et de masse. Les modules sont alors arrangés pour former les sous-modèles. Le modèle global du système de stokage en chambre froide est alors formulé en interconnectant les sous-modèles. Les modules sont implémentés dans l'environnement de simulation EcosimPro qui peut traiter les évènements discrets et continues.

Grâce à l'approche modulaire et orienté objet, on peut atteindre une plus grande flexibilité en ce qui concerne la modification du modèle et sa réutilisation. Il est possible, en utilisant le modèle, de simuler plusieurs chambres froides abritant différents produits (on parle alors de chambres chargées). De plus, le modèle permet de régler les paramètres du contrôleur. Dans ce travail, les prédictions du modèle sont analysées avec les résultats expérimentaux dans le cas d'une chambre froide vide et chargée. En général, on obtient une bonne corrélation entre la simulation et les résultats expérimentaux. De plus, on peut lier facilement le modèle de respiration du produit à son modèle de qualité afin de prédire la déterioration de la qualité des produits emmagazinés durant le stokage.