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Development of a model for simulating ambient conditions in fresh fruit and vegetable storage facility

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Abstract

A mathematical model simulating forced air cooling system for horticultural storage facility was developed. Governed by heat and mass transfer equations, the model describes both the storage process and the interaction between a produce and its environment, and takes into account the physiological behavior of the stored produce due to changes in the environmental conditions. The model was integrated in computer software to provide simulated environments. The software interface allows inputs of initial and incoming air conditions in a storage facility with specified dimensions and mass of produce, and predicts the resulting conditions over a specified period of time. The simulation software can be used as a research tool to test new systems or evaluate control strategies.

Key words: Research tool, simulation, control, storage, potato.

Introduction

After harvest, many agricultural produce, such as grain, fruit and vegetable, are stored in piles, silos or boxes. The most important factors in operating an economically successful storage are maintaining moisture content and quality of the produce while optimizing energy consumption and reducing diseases [1]. The complexity of managing a storage facility lies in the harvested commodities being alive and sustaining chemical and respiration processes [2]. Most producers today choose a programmable controller or a control software package to manage their storage facility [3]. These have demonstrated to be effective in controlling the desired environmental parameters, including temperature, relative humidity and gas composition (C_2H_4, CO_2, O_2). However, their capabilities are diminished due to the lack of sufficient information about the surrounding and storage environments, resulting in substantial losses of fresh produce through decay and shriveling during postharvest storage [4].

Heat and mass transfers in fruit and vegetable storage facility are not yet well understood or controlled [4]. The last thirty years have seen rapid developments in many areas of control theory in the industry, but relatively few developments have been translated into well established control practice [5]. There is a lack of confidence in new control methods and a belief that the traditional methods are adequate for most practical situations [5, 6].

Heat and mass transfer studies of agricultural produces have been performed by many authors [7, 8]. Various attempts have been made to model the complex interactions occurring in storage facility. These include one-dimensional models of heat and mass transfer[9], and two-dimensional models of air flows using finite difference methods [10, 11]. Baird and Gaffney [11] developed a finite difference model to predict the heat transfer occurring in bulk loads of horticultural produce. Their model assumed a negligible conduction between individual commodities and no mass transfer between commodities and cooling air. Their numerical and experimental data agreed well; however, their model cannot be used to determine the latent heat load generated by the stored bulk produce since transpiration was not considered. Yongfu and Burfoot [1] developed a transient three-dimensional CFD model for heat and mass transfer in porous bulk particulate foodstuffs. The model predicted temperature and moisture changes of potatoes during cooling with high accuracy. Becker *et al.* [12] developed a computer algorithm utilizing a porous media approach to estimate the latent and sensible heat loads of bulk refrigerated fruit or vegetable. The software was developed to assist designers and operators of refrigerated facilities and simulated a wide variety of commodities. The validation of the model was performed by comparing the output results to experimental data obtained from the literature which demonstrated a good agreement for both temperature and moisture loss data [13]. Alvarez and Trystram [3] developed a simple heat and mass transfer model using Fourier heat transfer equations for unidirectional flux for spherical produce cooling in bins and numerical techniques to compute the solution of the set of equations. While most of these models are valid, they are not adequate to dynamically test the performance of new control strategies.

Hence a tool is needed to investigate new control techniques or strategies to enhance the environmental control in postharvest storage facilities for horticultural crops. Although there are some computer models available to aid in the design and operation of storage facilities, there are no real time tools available to test new enhanced control strategies.

The objectives of this work were to develop a mathematical model that describes both the storage process and the produce interaction with its environment in a storage facility, and integrate this model into a computer algorithm to develop a research tool in which new control strategies can be evaluated.

Material and Methods

Description of the model

Sensible heat transfer: The mathematical model is based on the first law of thermodynamics. This law states that the total energy change in a closed system is equal to the heat added to the system minus the work done by the system (Eq. 1). This law may also be simplified for a heating process under constant pressure (Eq. 2). Applying heat balance to Eq. 2 results in the Eq.3.

$$\Delta E = q_{tot}\,\text{Work} \tag{1}$$

$$\frac{dh}{dt} = q_{tot} \tag{2}$$

$$\frac{dh}{dt} = q_p + q_s + q_r + q_v + q_b \tag{3}$$

The rate of heat flow between the potatoes and the air was determined by the temperature difference between the storage air temperature (T_{store}) and the temperature at the centre of potatoes and the sum of the conductive and convective heat transfer resistances (Eq. 4) [14].

$$q = \frac{\Delta T}{R} = \frac{T_p - T_{store}}{R_a + R_c} \tag{4}$$

The resistance to conductive heat flow (R_a) depends on the thermal conductivity of the material (λ) and the thickness of the material layer in the direction of the heat flow (Eq. 5). For potato, $\lambda = 0.55\ W\ m^{-1}\ K^{-1}$, which is an average for various potato cultivars[14].

$$R_a = c\,\frac{d}{\lambda} \tag{5}$$

The resistance to convective heat transfer (R_c) taking place between the tuber surface and the air can be computed using Eq. 6 and the resulting heat transfer can be determined based on the Nusselt number (Eq. 7). The heat produced by the produce resulting from the temperature difference was then calculated using Eq. 8 (The denominator was used to convert units).

$$R_c = \frac{1}{\alpha} \tag{6}$$

$$N_u = \frac{\alpha d}{\lambda} = 0.92\ Re^{0.59}\ Pr^{0.33} \tag{7}$$

$$q_p = \frac{q\,A_{surface}}{1000} \tag{8}$$

Heat of respiration: The heat generated by the respiration process (Eq. 9) tends to increase produce temperature. Given that the CO_2 production rate can be related to the heat generation due to respiration, Becker *et al.* [12] developed a correlation (Eq. 10) relating the CO_2 production rate to the produce temperature. The f and g respiration coefficients for potatoes are 0.01709 and 1.769 respectively [15]. According to the oxidation of glucose during respiration (Eq. 11), 10.7 J are generated for each mg of CO_2 produced [15] and the heat generated by the respiration process is presented in Eq. 12

$$q_r = m_p q_r \tag{9}$$

$$\dot{m}_{CO_2} = f\left(\frac{9T_p}{5} + 32\right)^g \tag{10}$$

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + 2667J \tag{11}$$

$$q_r = 0.297 \times 10^{-5}\ m\ co_2 \tag{12}$$

Sensible heat lost by ventilation: Sensible heat lost is actually heat lost by air removal. The amount of heat brought into or removed from the store by ventilation (Eq. 13) was calculated by methods suggested in ASHRAE [16].

$$q_v = \dot{M}_a\ Cp_a\,(T_{store} - T_{in}) \tag{13}$$

Heat loss through the structure: Heat loss through the building surfaces was evaluated as a summation of distinct heat losses through homogenous partitions (Eq. 14).

$$q_b = \sum_{p=1}^{n} A_p U_p (T_{store} - T_{outside}) \tag{14}$$

Moisture balance in a storage facility: The change in moisture content with time in a storage facility was expressed as the mass balance of the generated, condensed and ventilated moisture (Eq. 15).

$$\frac{dW}{dt} = \frac{(R_{trans} + R_{spray} - R_{cond} + R_{vent})}{m_a} \tag{15}$$

Transpiration of produce: Transpiration of fruit or vegetable constitutes of a mass-transfer process in which water vapor migrates from the surface of the commodity to the surrounding air process driven by their difference in water vapor pressure. The basic transpiration model is given by the Eq. 16, which considers a constant transpiration coefficient k_t, which may not represent reality because of the variability of skin permeability and airflow influences. For this reason, the porous media transpiration model [12] was implemented (Eq. 17) and the transpiration coefficient modification [17] was used to model skin permeability. The convective mass transfer coefficient occurring at the surface of the produce was described by the air film mass transfer coefficient (k_a). The skin diffusion resistance to moisture migration was described by the skin mass transfer coefficient (k_s).

$$\dot{m} = k_t (P_s - P_a) \tag{16}$$

$$k_t = \frac{1}{\frac{1}{k_a} + \frac{1}{k_s}} \tag{17}$$

The air film mass transfer coefficient depicts the convective mass transfer taking place at the surface of a commodity. This was estimated using the Sherwood-Reynold-Schmidt correlations (Eq. 18) [18] and the Sherwood number (Eq 19) [19]. The conversion of the driving force of concentration k'_a to the vapor pressure k_a was performed using Eq. 20 [12]. The skin mass transfer coefficient k_s used to calculate the transpiration rate of a commodity (Eq. 21) describes the resistance to moisture migration through the skin of a commodity and is based on the fraction of the produce surface covered by pores. The k_s value for potatoes was 0.6349 g $m^{-2}s^{-1}MPa$ [18].

$$Sh = 2.0 + 0.552\ Re^{0.53}\ Sc^{0.33} \tag{18}$$

$$Sh = \frac{k'_a d}{\delta} \tag{19}$$

$$k_a = \frac{1}{R_{H_2O} T} k'_a \tag{20}$$

$$\dot{m} = \frac{P_s \quad P_a}{\frac{1}{k_a} + \frac{1}{k_s}} \tag{21}$$

Moisture introduced by ventilation air: The rate of moisture introduced by ventilation air was calculated using the Eq. 22.

$$R_{vent} = Q_{in}\ \rho_{air}\ (W_{in} - W_{store}) \tag{22}$$

Produce temperature: The produce temperature varies with respect to changes in environmental conditions of the storage facility. A simple model was used for predicting the temperature of the produce based on the energy balance of the produce (Eq. 23). Solving Eq. 23 for T resulted in the predicted potato temperature.

$$m_p Cp_a \frac{T_{previous} - T_{simulated}}{dt} = q_p + q_r + q_e \tag{23}$$

Latent heat of evaporation of water from the stored commodity: The latent heat of evaporation is the heat required for evaporating water from the commodity surface. This was calculated using Eq. 24.

$$q_e = \quad (2502.5 - 2.3858 T_p) \tag{24}$$

Characteristics of moist air: The specific heat (Eq. 25) and density (Eqs 26, 27, 28) of moist air were calculated from ASHRAE recommendations [16]. The diffusion coefficient was computed according to Sastry and Buffinton [19] (Eq. 29). The air circulation Reynolds number was computed using Eq. 30 where the estimated value of L was based on Eq. 31 [20].

$$Cp_a = 1 + 1.88\ W_{store} \tag{25}$$

$$\rho_a = \frac{28.9645 P_{air}}{R_u T_{air}} (x_a + 0.62198 x_w) \tag{26}$$

$$x_a = \frac{0.62198}{0.62198 + W_{store}} \tag{27}$$

$$x_w = \frac{W_{store}}{0.62198 + W_{store}} \tag{28}$$

$$\delta = \delta_o \left(\frac{T_{air}}{273.15}\right)^{1.75} \left(\frac{P_{air}}{101.325}\right) \tag{29}$$

$$Re = \frac{V\ L}{\nu} \tag{30}$$

$$L = 0.41 d_m \tag{31}$$

The saturated water vapour pressure, the water vapour pressure of air and the moisture content (W) were calculated using the Eqs 32-33, 34 and 35, respectively [16].

$$P_{ws} = 22105.6\ e^S \tag{32}$$

$$S = \frac{-27405.5 + 97.5413 T_{air} - 0.146244 T_{air}^2 + 0.12558 \times 10^{-3} T_{air}^3 - 0.48502 \times 10^{-7} T_{air}^4)}{4.34903 T_{air} - 0.39381 \times 10^{-2} T_{air}^2} \tag{33}$$

$$P_w = P_{ws} \times \frac{RH}{100} \tag{34}$$

$$W = \frac{0.6219 \times P_w}{(P_{atm} - P_w)} \tag{35}$$

The enthalpy of the air was calculated using the Eqs. 36 and 37 [16]:

$$h = h_{dry\ air} + h_{water} \tag{36}$$

$$h = 1.00692540 T_{air} + 4.1868 W(T_{dp}) + h_{fg} W + 1.8756864 W(T_{air} - T_{dp}) \tag{37}$$

Water vapor pressure deficit between the air and the potato surface: Moisture loss trough a produce is governed by the water vapor deficit between the potato surface and the surrounding air (Eq. 38). The potato water vapor was considered at 100% or equal to P_{wp}.

$$MPV = P_{Wp} - P_{Wstore} \tag{38}$$

Model integration

The algorithm including all the previously discussed equations was developed using Visual Basic 6.0, while a user friendly interface allowed user input. The model simulates an actual experimental bulk type storage facility (Fig. 1). Information on this structure and instrumentation were presented by Markarian [21].

The model is based on a porous media approach. The control volume is made up of a block, which represents the bin in which the potatoes are stored. A centrifugal fan enables the vertical movement of the air through the pile of potatoes, from the slotted floor. A heater and sprayer add heat and/or moisture to the incoming air.

Fig. 2 shows the simplified flow diagram for the simulation

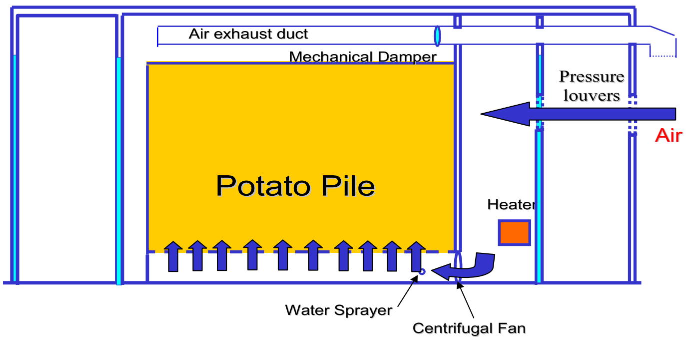

Figure 1. Schematic of storage system.

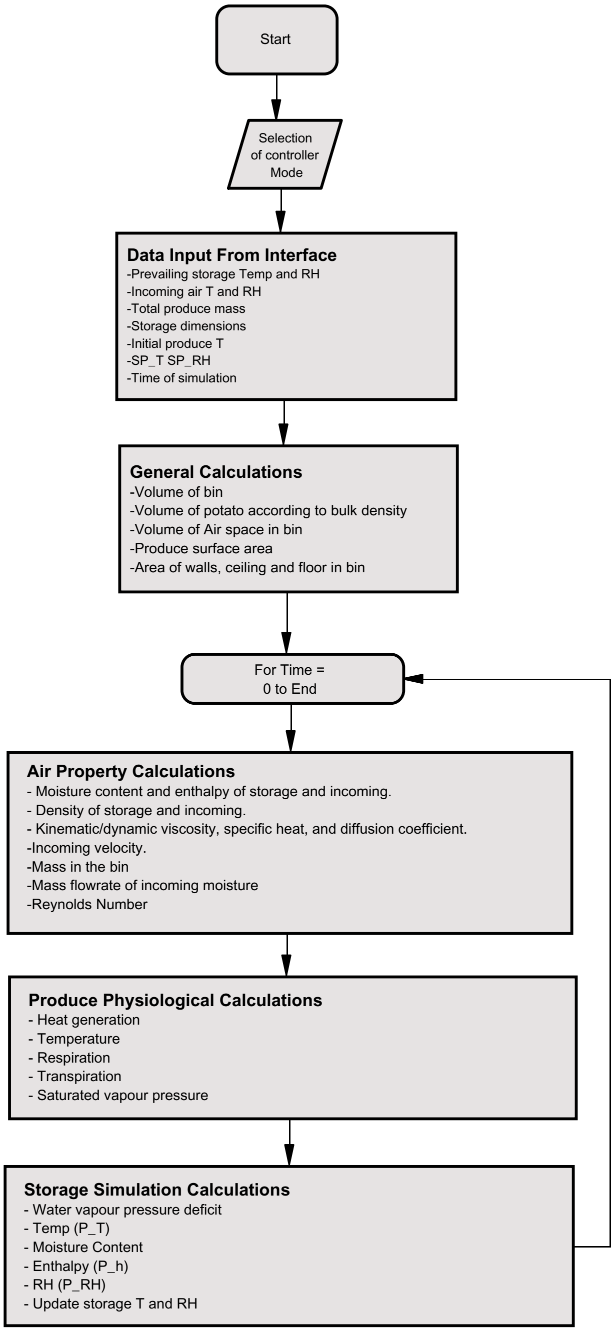

Figure 2. Flow chart of the simulation software algorithm.

software algorithm. The developed software allows the user to input the initial prevailing conditions of the storage facility; temperature, relative humidity, mass of stored potatoes, initial potato temperature, outside air conditions, and the state of the fan, sprayer and heater. Calculations are performed according to these initial conditions. The time step begins with the first mass of air moving into the storage room. Heat loss, respiration, heat generation and transpiration are calculated. The storage temperature and humidity are then determined iteratively and are considered as the prevailing storage conditions for the next step. The algorithm essentially allows storage temperature and relative humidity prediction according to air exchange rate and stored produce metabolic activities. The modular architecture of the software allows further addition of routines. Hence, if control routines were to be integrated in the software, the simulation software will enable the dynamic testing of the performance of these controllers by estimating the resulting environmental conditions in the storage (temperature and relative humidity).

Parametric study

A parametric study was performed to determine the influence of various parameters on the simulated temperature and relative humidity of a storage facility. The study used a storage bin that was 2.44 m high, 0.85 m wide, 3.26 m long and holding 3500 kg of potatoes with a bulk density of 763 kg m^{-3}. The time of simulation was 1 hour. The effects of respiration, transpiration and air mixing were investigated.

Identical initial and incoming conditions: This test was performed to investigate the behavior of temperature and relative humidity during an adiabatic process. This test represents the case with no respiration and transpiration rates, i.e. when there is no produce in the storage. Additionally no heat lost trough the structure and no heat or moisture were added to the storage bin. Hence, the simulated environmental conditions are expected to be the same as the initial or incoming environmental conditions.

Decreasing environmental conditions: This test was used to evaluate the behavior of the environmental conditions inside the storage when the incoming air has a lower temperature and relative humidity than the initial storage conditions within an adiabatic process. The results were compared to results obtained using standard adiabatic mixing of moist air for the same environmental conditions. The latter was based on conservation of mass using the mixing of moist air at two different states to obtain a third state[16]. Table 4 presents the data used for simulating this test for a standard method [16] and the simulation model.

Increasing environmental conditions: This test was performed to investigate the environmental conditions inside the storage when the incoming air has a higher relative humidity and temperature than the initial conditions in the storage. Again, the process was adiabatic and the same procedure as for the previous test was followed to compare the results. Table of nomenclature presents the data used for simulating this test.

Results and Discussion

Results from some of the components were compared to values cited in literature and some others were used in parametric studies to validate the model.

Respiration and transpiration rate

Transpiration and respiration rates obtained with the simulation software were compared to experimental data obtained in literature. Heat of respiration values at different storage temperatures for mature potatoes were obtained from data provided by Buffington *et al*. [22]. Table 1 presents these values together with the respiration rate values obtained from the simulation at different storage temperatures. With exception of the 5°C, the simulated respiration rates corresponded within the lower and upper limits of respiration rates obtained from literature.

Simulated transpiration rates were compared to ones computed from the standard transpiration rate equation (Eq. 16) using transpiration coefficients 2 and 171 mg $kg^{-1}s^{-1}$ MPV^{-1} [22], for the lower and upper limit of various potato varieties. Both the model and literature transpiration rates computation were based on the same MPV obtained from the simulated environmental conditions for the same time. Fig. 3 provides a comparison between the transpiration rates computed using the coefficients obtained from literature and values obtained by from the proposed model. Transpiration rates obtained from the model were within the lower and upper limits of transpiration rates calculated using Eq. 16. In fact, results obtained from the model are much closer to the lower limit values computed. This can be explained by the fact that the coefficients obtained from literature were an average representing various varieties of potatoes.

Table 1. Comparison of respiration rates obtained from literature and calculated using the model for mature potatoes at different storage temperatures.

Temperature (°C)	Literature RR (kW)	Simulation Model RR (kW)
5	0.028116 - 0.122157	0.126728
15	0.061079 - 0.318966	0.241266
20	0.084347 – 0.46536	0.310147

Table 2. Effect of adiabatic mixing on temperature and relative humidity for identical initial and incoming conditions after 3600 seconds.

	Initial conditions	Incoming conditions	Simulated conditions
T (°C)	10.00	10.00	10.09
RH (%)	90.00	90.00	89.45

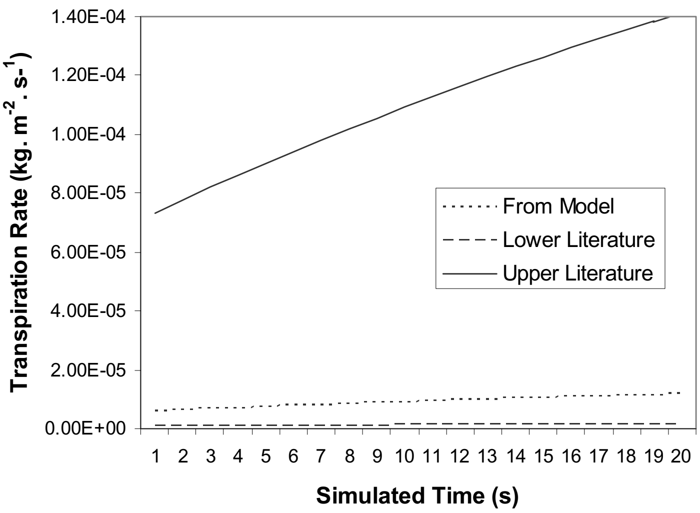

Figure 3. Comparison of transpiration rates obtained from literature and those calculated using the model for different varieties of potatoes.

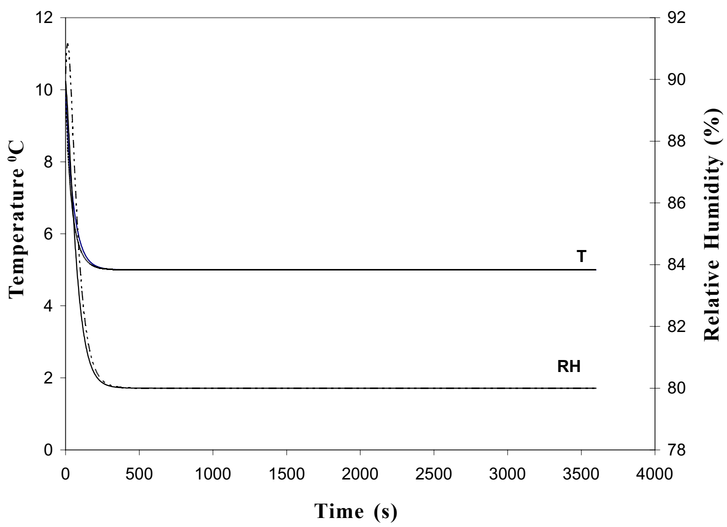

Figure 4. Temperature and relative humidity vs. time for decreasing environmental conditions during the adiabatic process computed using the model and standard adiabatic mixing methods. The dotted lines represent the results obtained from the model.

Table 3. Comparison of results obtained while using both model and standard mixing methods for a simulation duration of 3600s, during the adiabatic mixing for decreasing environmental conditions.

	Initial conditions	Incoming conditions	Result :Model	Result : Standard adiabatic mixing	Mean absolute difference	Mean absolute maximum difference
T (°C)	10.00	5.00	5.00	5.00	0.01	0.07
RH (%)	90.00	80.00	80.00	80.00	0.46	2.79

Table 4. Comparison of results obtained while using both model and standard mixing methods for a simulation duration of 3600s, during the adiabatic mixing for increasing environmental conditions.

	Initial conditions	Incoming conditions	Result : Model	Result : Standard adiabatic mixing	Mean absolute difference	Mean absolute maximum difference
T (°C)	10.00	15.00	15.00	15.00	0.00	0.01
RH (%)	90.00	95.00	95.00	95.00	0.08	0.46

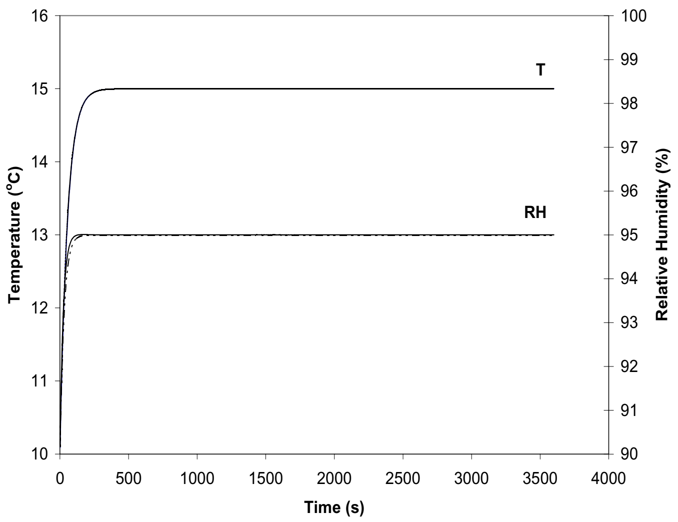

Figure 5. Temperature and relative humidity vs. time for increasing environmental conditions during the adiabatic process computed using the model and standard adiabatic mixing methods. The dotted lines represent the results obtained from the model.

Parametric study

Identical initial and incoming conditions: The conditions for an adiabatic process were met. There was no change in the environmental conditions with time (Table 2).

Decreasing environmental conditions: Table 3 shows the initial and incoming conditions along with the results obtained for both model and standard adiabatic mixing methods. Fig. 4 shows T and RH versus time for decreasing environmental conditions during the adiabatic process computed using the model and the standard adiabatic mixing methods. The overlapping curves of both methods for T and RH demonstrate the correspondence of both methods. The mean absolute difference for T and RH are 0.01°C and 0.07% respectively and the maximum absolute difference are 0.46°C and 2.79% respectively (Table 3).

Increasing environmental conditions: Table 4 shows the initial and incoming conditions along with the results obtained for both model and standard adiabatic mixing methods. Fig. 5 shows T and RH versus time for increasing environmental conditions during the adiabatic process computed using the model and the standard adiabatic mixing methods. The overlapping curves of both methods for T and RH demonstrate the correspondence of both methods. The mean absolute difference for T and RH are 0.00°C and 0.01% respectively and the maximum absolute difference are 0.08°C and 0.46% respectively (Table 4).

Conclusions

A mathematical model for the prediction of temperature and relative humidity in horticultural crop storage facilities was developed and integrated in simulation software. The software interface allows the input of initial and incoming environmental conditions in a storage facility with specified dimensions and mass of produce and predicts the resulting conditions over a specified time period.

The model considered the physiological properties of potatoes and was governed by heat and mass transfer processes normally encountered in a storage facility. The resulting respiration and transpiration rates correspond to rates specified in literature. However, due to the complexity involved in measuring respiration and transpiration rates, not all values obtained from the literature can be considered highly reliable.

Parametric studies were performed using standard methods to compare the results obtained using the simulation software. The effect of adiabatic mixing on temperature and relative humidity were tested. The results correlate with the results obtained by standard methods.

The simulation model successfully performed the prediction of temperature and relative humidity in a potato storage facility. Further investigation is required to fully validate the model in an actual horticultural storage facility.

The addition of control routines to this software will require very little effort due to its structural design. This supplement will allow comparison of different control strategies, which would be a great tool for a postharvest control engineer.

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Nomenclature

λ	Thermal conductivity	W m^{-1}K^{-1}
α	Heat transfer coefficient	W m^{-2} K^{-1}
δ	Diffusion coefficient of water vapor in air	m^2 s^{-1}
ν	Kinematic viscosity of air	m^2 s^{-1}
ρ_a	Specific gravity of moist air	kg m^{-3}
ρ_{air}	Specific gravity of dry air	kg m^{-3}
δ_o	Diffusivity at the reference temperature of 273.15 K	21.9x10^{-6} m^2 s^{-1}
A_p	Surface area of the partition	m^2
A	Surface area of tuber	m^2
c	Factor of proportionality or sphericity, for potato c= 0.85.	
Cp_a	Specific heat of air	kJ kg^{-1} °C^{-1}
d	Equivalent diameter of the produce; for potato, d = average of the minor and major axis length	m
d_m	Major diameter of the tuber	m
E	Energy	kW
f, g	Respiration coefficients	
h	Enthalpy of air	kJ kg^{-1} dry air
$h_{dry\ air}$	Enthalpy of dry air	kJ kg^{-1} dry air
h_{fg}	$2502.535259 - 2.38576424T_{air}$	kJ kg^{-1} water
h_{water}	Enthalpy of water	kJ kg^{-1} dry air
k'_a, k_a	Air film mass transfer coefficients	m s^{-1}
k_s	Skin mass transfer coefficient	m s^{-1}
k_t	Transpiration coefficient	m s^{-1}
L	Characteristic length	M
$\dot{m}$	Transpiration rate per unit area of commodity surface	kg m^{-2} s^{-1}
m_a	Mass of air in the storage facility	kg
$\dot{M}_a$	Mass flow rate of incoming ventilation air	kg s^{-1}
$\dot{m}_{CO_2}$	CO_2 production	mg kg^{-1} h^{-1}
m_p	Mass of produce in storage	kg
MPV	Water vapor pressure deficit between surface of potato and surrounding air	kPa
N_u	Nusselt number	
P_a	Ambient vapor pressure	kPa
P_{air}	Air pressure	kPa
P_{atm}	Standard atmospheric pressure	103.325 kPa
P_r	Prandtl number	
P_s	Water vapor pressure at the surface of the commodity	kPa
P_w	Water vapor pressure	kPa
P_{Wp}	Water vapor pressure of potato	kPa
P_{ws}	Saturated water vapor pressure	kPa
P_{Wstore}	Water vapor pressure of storage	kPa
q	Heat transferred through produce surface	J m^{-2}
q_b	Heat loss through storage walls, ceiling and floor	kW
q_e	Latent heat of evaporation of water from the stored commodity	kW
Q_{in}	Ventilation flow rate	m^3 s^{-1}
q_p	Heat absorbed by the produce	kW
q_{resp}	Heat of respiration	kW or kW kg^{-1}
q_s	Supplemental heat from heating sources	kW
q_{tot}	Heat added to the system	kW
q_v	Sensible heat lost by ventilation air	kW or kW kg^{-1}
R	Total resistance to heat transfer	m^2 K W^{-1}
R_a	Resistance to conduction heat transfer	m^{2}K W^{-1}
R_{cond}	Moisture rate condensation on the evaporator to cooling systems	kg s^{-1}
R_c	Resistance to convective heat transfer	m^{2}K W^{-1}
Re	Reynolds number	
RH	Relative humidity	%
R_{H_2O}	Gas constant for water vapour	m^3 Pa kg^{-1} K^{-1}
R_{spray}	Moisture rate production by sprayers	kg s^{-1}
R_{trans}	Moisture rate production by transpiration	kg s^{-1}
R_{vent}	Moisture rate introduced by ventilation	kg s^{-1}
Sh	Sherwood number	
T	Mean temperature of the boundary layer	K
t	Time	S
ΔT	Produce to air temperature difference	°C
T_{air}	Storage air temperature	K or °C
T_{dp}	Dew point temperature	°C
T_{in}	Incoming air temperature	°C
$T_{outside}$	Outside air temperature	°C
T_p	Temperature at the center of the produce	°C
$T_{previous}$	Produce temperature before the period t	°C
$T_{simulated}$	Produce temperature resulting from the simulation after the period t	°C
T_{store}	Storage air temperature	°C
U_p	Overall heat transfer coefficient	kW m^{-2} °C
V	Air velocity perpendicular to potato pile	m s^{-1}
W	Humidity ratio of the air	kg water kg^{-1} dry air
W_{in}	Incoming air moisture content	kg water kg^{-1} dry air
Work	Work	kW
W_{store}	Storage air moisture content	kg water kg^{-1} dry air
x_a	Mole fraction of dry air	
x_w	Mole fraction of water vapour in air	