Post Harvest Cold Chain Optimization of Little Fruits

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Abstract: This paper presents heat transfer 3-D models of a passive refrigeration system, called Icepack, used to improve the shelf life and the quality of the perishable fruits. Passive refrigerator system uses the changing phase of a material to keep temperature close to the melting temperature.
A multi-step COMSOL Multiphysics (ver 4.2a) study was performed:

- a 3-D heat transfer model on the empty box;
- a 3-D heat transfer model on the box containing a slab with apparent thermal properties obtained from the air and the fruit;
- a 3-D heat transfer model on the box filled with randomized diameter spheres, simulating the fruits, created with an original MatLab® script and imported in COMSOL Multiphysics® (ver. 3.5a).

The temperature profile inside the box and the melting time of the ice slab were studied.
Results of the models agree with experimental data. The modeled melting time of the empty Icepack gives an error of about 7%. Modeled temperature profile inside the box filled with fruits reflects real temperature profile.

Keywords: heat transfer, phase change, perishable fruits, passive refrigerator.

1. Introduction

Little fruits like blueberries, raspberries and blackberries need to be refrigerated as soon as possible after the harvest, to preserve the structural integrity and the nutritional and organoleptic properties. In fact, removing the field-heat, the respiration of these fruits decreases and so the shelf life of the product improves.

Due to the fragility of these fruits means that the harvest must be done manually and the filling phase must be as gentle as possible. All the chain of transport from the field to the consumer should not cause further damages to the product and so the plastic case of sell that contain the fruits is the same that was used during the harvest.

These plastic cases, containing about 250 g of fruits (inconvenient transport them one by one), are placed inside another bigger box, normally a wooden box, that contain 8 plastic little cases.

The refrigeration can starts immediately after the harvesting with a passive refrigerator system, a special box, called Icepack.

The Icepack is a polystyrene box (external dimension: 42.5x33.5x12 cm) with a plastic hermetic bag filled of water (about 1.0 kg) placed on the bottom. Inside the Icepack is possible to place 8 little plastic cases as normal wood box. The wall thickness is 2 cm and the height of the plastic bag is about 1.8 cm. The bag is stored at -20 ° until the moment of the use. The heat flux from the outside is absorbed by the fusion of the ice keeping the temperature inside the Icepack almost constant, to 0°C, for a long period of time.

Another advantage of this transport system is in the stackability of the Icepack, that optimize the space occupied and the exchange surfaces with the external environment.

Experimental data were taken on blueberries taken in Ardenno (SO), Italy, in the Fojanini Foundation field.

2. Governing Equation

A mathematical model based on heat transfer in continuous media is used to model the cooling of blueberries. Temperature inside each material is considered uniform.

Respiration of fruits and inside convection was neglected because of the little internal height of the box (about 6 cm with the empty box) and presence of the cool slab of ice at the bottom of the Icepack. When the box is filled with plastic boxes with fruits, the space is occupied by these, so the free space for the air circulation, and then for the internal convection is further limited.

2.1 Energy conservation equation

Heat transfer occurs in three different form: conduction, convection (only external surface) and latent heat of fusion of water.

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \nabla(k\nabla T)$$

where ρ is the density, C_p is the specific heat and k is the thermal conductivity of the different material (see Table 1).

Icepack contains the plastic bag filled with water in the phase change, so a modified specific heat was used.

$$C_p = C_{p\,ice} + H(T)\left(C_{p\,w} - C_{p\,ice}\right) + G(T) \cdot lda$$

where the subscript w is water, lda is the latent heat of fusion, H is a smoothed step function of temperature from 0 to 1 and G is a Gaussian pulse centered in the fusion temperature. The pulse is necessary to simulate the latent heat of fusion (energy is absorbed while the temperature remains constant). The temperature range (defined by Gaussian pulse standard deviation) of the fusion is an approximation necessary because fusion at an exact temperature cannot be modeled numerically.

Also ρ and k of the water are modified density and thermal conductivity equations, that consider the two phases of water:

$$\rho = \rho_{ice} + H(T) \cdot (\rho_w - \rho_{ice})$$

$$k = k_{ice} + H(T) \cdot (k_w - k_{ice})$$

2.2 Boundaries conditions

The boundaries conditions on air/polystyrene interface are:

$$-\vec{n} \cdot \left(k\vec{\nabla}T\right) = h \cdot (T_{ext} - T)$$

where the subscript ext is external and h is the convective heat transfer coefficient

2.3 Initial values and input parameters

Initial temperatures are different for packaging material and fruits. Ice bags are put inside a polystyrene box to preserve their temperature.

Input parameters and initial temperature are listed in Table 2.

	blueberries	air	polystyrene	ice	water
ρ - Density (kg/m^3)	990	1.248	25	917	1000
C_p - Specific heat (J/kg K)	3786	1013	1200	2260	4186
k - Thermal conductivity (W/m K)	0.539	0.024	0.033	2.208	0.6

Table 1: characteristics of materials

Parameters	Value	units
Blueberries initial temperature	302.25	K
Polystyrene initial temperature	295.15	K
Air initial temperature	297.15	K
Ice initial temperature	253.15	K
lda - Latent heat of fusion	333	kJ/kg
h - Convective heat transfer coefficient	8	$W/m^2 K$
T_{ext} - Ambient temperature	300.15	K
Ice fusion temperature	273.15	K
Percentage of blueberries in mixed slab	75 %	

Table 2: initial temperatures and input parameters

3. Methods

Two different type of experiment were performed, the first one in laboratory, on an empty Icepack, to study the passive refrigerator system in a controlled environment, the other one on field, to carry out operators manually harvest and the following trip to the collecting centre.

Laboratory experiments were performed using T-thermocouples to monitor the temperature inside the Icepack in 5 different point: they were all put to detect the defrosting time of the ice slab. Icepack rests at monitored ambient temperature 20 hours on a table with inside the charge of ice.

On field experiments were performed with 5 stand alone temperature data logger, put under the ice slab, under the cover of the Icepack, inside the plastic case with blueberries at three different height: top, bottom and in the middle. Ice slab at 253.15K was put inside an Icepack in the collecting center, after about 30 minutes trip, on field, Icepack was filled with 8 plastic cases with manually harvesting fruits and then about 2 hours trip to return to laboratory, where the box rests 15 hours.

4. Numerical Model

Three different numerical model was performed with COMSOL Multiphysics® (ver 3.5a and 4.2a):

- a 3D model of the empty Icepack to simulate the passive refrigerator system.

The partial differential equations for heat transfer were solved using the *Heat Transfer module*, with a free time step by the solver MUMPS. The cooling simulation is 20 hours with a collecting time of 60 seconds. The mesh is automatically created with a normal refinement and is formed by 34568 elements.

- a 3D symmetrical model of the Icepack filled with a 5 cm height slab with apparent thermal characteristics obtained from air and fruit.

The partial differential equations for heat transfer were solved using the *Heat Transfer module*, with a free time step by the solver GMRES. The cooling simulation is 15 hours with a collecting time of 60 seconds. The mesh is automatically created with a normal refinement and it is formed by 14398 elements

- a 3D symmetrical model of icepack filled with a randomize dispersion of fruits, created with a original Matlab® script and then imported in COMSOL Multiphysics®.

The partial differential equations for heat transfer were solved using the *Heat Transfer module*, with a free time step by the solver GMRES. The cooling simulation is 15 hours with a collecting time of 60 seconds. The mesh is automatically created with a normal refinement and it is formed by 87271 elements

4.1 Geometry

The geometry of the first model consist of 3 blocks put in the right position, that describe the Icepack system, the air inside the icepack and the ice slab. All the real geometry was drawn.

The second geometry consist of 4 blocks put in the right position. These blocks describe the Icepack system, the air, the slab of blueberries and the ice. Only a quarter of the real geometry was drawn because of the symmetry of the system.

The third geometry is created like the first one, but the fruits are simulated and imported from Matlab®. The original script consist in a randomized Gaussian distribution diameter of the fruits (sphere) experimentally determined. It is hypothesized that the set sizes of the plastic case, that contains blueberries is the resulting of the intersection of 5 sphere with infinite diameter. Each fruit have to touch three points of the geometry to be in equilibrium. The sphere that must be positioning will be placed in the point with less absolute potential energy. No overlapping between spheres is allowed. The loop ends when all the spheres have been positioned. Also in this case only a quarter of the real geometry was drawn because of the symmetry of the system. The sequence of randomized distribution of fruits was repeated two times because in a quarter of Icepack there are 2 plastic cases.

5. Results and discussions

The model of the empty Icepack was focused on the melting time of the ice slab. After a fast decrease of the inside temperature from ambient temperature due to the insertion of the ice slab in the box, there is an increase until it reaches the fusion temperature of the ice, with a constant value of about 273.15. The total thawing time of the ice slab is after 15.8 hours, and then the temperature rises again. The model gives about 17 hours as thawing time, with a relative percentage error, calculated as

$$\boldsymbol{e} = \frac{|\boldsymbol{t}_{exp} - \boldsymbol{t}_{mod}| * \mathbf{100}}{\boldsymbol{t}_{exp}}$$

where the subscript exp is experimental and mod modeled, equal to 7.6%.

Figure 1 is the graph of compared temperatures (modeled and experimental) of the ice slab.

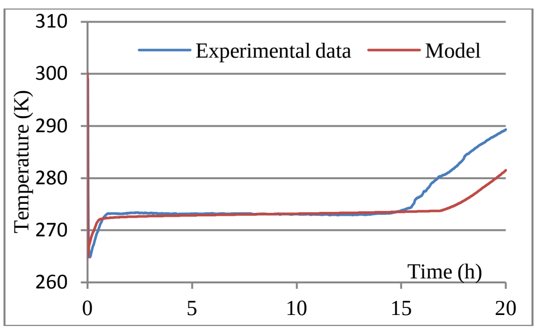

Figure 1: temperature of ice slab of empty Icepack

The model with the mixed air/blueberries slab was focused on thawing time of the ice slab and on the temperature in the warmer point inside the blueberries mass (the sensor in the middle). There is a quickly decrease of the measured temperature of the ice, followed by an increase until a plateau is reached at melting temperature of the ice. Total melting is about after 10.6 hours from the filling of the Icepack. The measured temperature between the blueberries presents a decreasing till about 283 K and after a slow increasing. The model simulate the total thawing of the ice at about 9.7 hours, with a relative percentage error (*e*) equal to 8.5%. The quality of the simulation is given by the mean relative error, which is defined as:

$$em(\%) = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{|T_{exp} - T_{mod}|}{T_{exp}}\right)_i$$

where n is the number of experimental observations. The calculated *em* of the central probe is 1.06%. Figure 2 shows the graph of temperatures (modeled and experimental) of the ice slab and of the blueberries

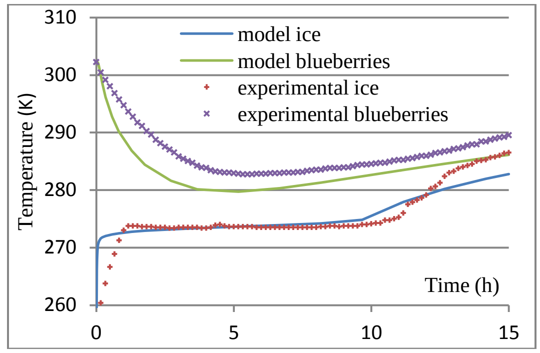

Figure 2: temperature profiles of ice and blueberries in the slab model

The model simulating fruits with sphere was focused on melting time of the ice slab and on the temperature distribution inside the blueberries mass, improving the slab model results.

The simulated melting time is very close to the real thawing time, with a relative percentage error close to 0. The mean relative error (*em*) of the central probe (blueberries mass) is 0.43%, about half of the error from the slab model. Figure 3 shows the temperature profiles of simulated fruits model and experimental data

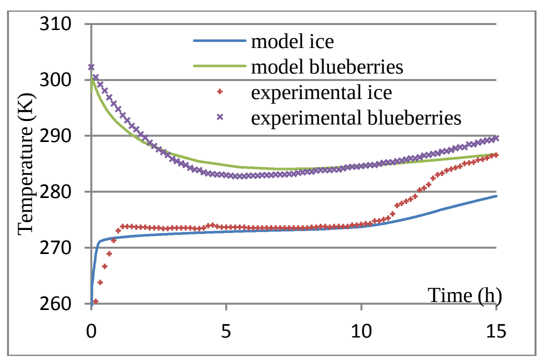

Figure 3:temperature profiles of ice and blueberries in the simulated fruits model

6. Conclusions

The finite element models were developed to investigate the temperature profile inside the Icepack and the cooling of blueberries from immediately after harvest to 15 hours later. The models predictions were validated with experimental measurements.

Future improvement of this models is under way, which will deal with the optimization of the geometry of the Icepack. The time from the harvest on field to the collecting center with the refrigerated rooms is about 6 hours, so it is possible to reduce the weight of the packaging reducing the ice slab height. Stackability of Icepack is also studied, to improve melting time of ice slab.

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