A 3 dimensional physical model to predict temperature dynamics within fruits in response to environment changes

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Introduction

Numerous biological processes involved in the development of fruits depend on temperature. Consequences on fruit quality such as size, taste, appearance are straightforward and well established (Tomes, 1963). Moreover, temperature gradients within fruits are of economic significance because of sunburn injury (Glenn & al, 2002), and of larval development (Kührt & al., 2005), with loss of yield. Fruit temperature is then a crucial parameter if one wants to investigate impacts of climate change or to develop strategies to control fruit or larval developments.
Models of organ temperatures have been already developed in the past but they do not predict both temporal and spatial temperature variations within fruits (Thorpe, 1974; Smart and Sinclair, 1976). Some models only estimate spatial average of organ temperature. However, in thick organs such as fruits, spatial distribution of temperature is not uniform and gradients of more than 10°C may occur in orchard. This raises the question of what the actual temperature of a fruit is. Other models give the thermal gradient within spherical fruits but they assume steady heat fluxes at fruit surface. The steady state assumption for boundary conditions leads to steady solutions but in orchard situation the microclimate fluctuates and a relevant model should take into account such temporal variations.
The model presented below is one solution to achieve this goal, namely to mimic temporal and spatial temperature dynamics within fruits in response to variations of atmospheric conditions.

Model description

Spatial and temporal variations of temperature in a fruit are governed by its heat budget. Considering an organ surrounded by moving air, factors involved in its heat budget are environmental factors as solar radiation, air temperature, air humidity, and wind intensity, as well as internal parameters as heat capacity, surface conductance to water vapour diffusion, metabolism activity, moisture content or heat transfer from the plant to the fruit.
This system is complex to model since numerous physical and physiological processes are coupled. Nevertheless, some *a priori* and fruit physiology based assumptions can be made to reduce this complexity. For example, the heat released from the metabolism activity within fruit and the energy exchange between fruit and plant are small enough in comparison to heat fluxes coming from the environment and were neglected. Also, fruits are known to exhibit diurnal diameter variations attributed to changes in hydration. However to simplify the system, the amount of water in fruit was, *a priori*, assumed to be constant in time. From these hypotheses the heat transport process within a fruit is only governed by heat conduction without any source term. Temperature dynamics were then modeled by Fourier's law (Eq. 1a):

$$\begin{cases} \dfrac{\partial}{\partial t}(\rho C_P.T) = \vec{\nabla}.(\vec{\vec{k}}\vec{\nabla}T) & \text{(1a)} \\ \left[-\vec{\vec{k}}\dfrac{\partial T}{\partial \vec{n}}\right]_{r\equiv R} = \Phi + \lambda_E + R & \text{(1b)} \end{cases}$$

where T (K) is the temperature, ρ (kg m^{-3}) is the density, C_p (J kg^{-1} K^{-1}) is the specific heat capacity and $\vec{\vec{k}}$ (W m^{-1} K^{-1}) is the thermal conductivity of the organ. $\vec{\vec{k}}$ was assumed to be nearly isotropic so the deviatoric part of $\vec{\vec{k}}$ was set to zero. Diagonal elements of $\vec{\vec{k}}$ can vary in space and over time to mimic moisture content variations or changes of tissue conductivity - the skin, the pit - within fruits.

Energy exchanges between the fruit and the surrounding air were modeled by specifying that the normal heat flux at any point of fruit surface was equal to the loss or gain of sensible energy by convection (Φ), the loss of energy by transpirational cooling (λ_E) and the energy exchange by radiation (R) (Eq. 1b). Beyond the modeling of Φ, λ_E and R, an important point is that these heat fluxes are function of space and time to mimic variations of the environment.

To solve the system composed from Eqs. 1a and 1b numerically, a finite volume formulation was chosen. Ellipsoidal fruits were divided into n_r radial elements, n_θ azimuthal elements and n_φ polar elements. From this mesh, spatial derivatives were evaluated following Patankar's previous work (Patankar, 1980), and time integration was based on an implicit formulation. The sparse linear system obtained was solved by a biconjugate gradient stabilized method (BICGSTAB, Van der Vorst, 1992). The resulting implicit scheme was first-order accurate in time and second-order accurate in space.

Model predictions

To assess the ability of the model to handle realistic fruit and microclimate conditions, experimental data collected during June 2005 on isolated fruits (3 apples cv. Golden, 3 apples cv. Redchief and 3 peaches cv. Alexis) were used. Inputs of the model were fruit properties measured or collected from literature, and microclimate variables measured such as air temperature, air humidity, wind velocity, solar and atmospheric radiation. The comparison between measured and simulated fruit temperature (at fruit surface and fruit core during one day) was very good (Figs. 1 and 2). Statistical analyses from all fruits, led to determination coefficients R^2 ranging from 0.971 to 0.977 and RMSE ranging from 0.7°C to 0.8°C (Fig. 1). Daily temperature dynamics at fruit surface and within fruits were very well captured by the model (Fig. 2).

Beyond temperature dynamics within fruits, the model can provide also useful information about heat transfer within fruits. At each point of fruit surface the heat balance dynamics can be computed. This is an important point since heat fluxes are related to the temperature at fruit surface which is not known. Therefore their values can not be calculated *a priori*. Heat flux simulation performed with our experimental conditions showed that the amount of heat released by evaporation was negligible. Thus, temperature dynamics only resulted from a balance between radiation and convection processes.

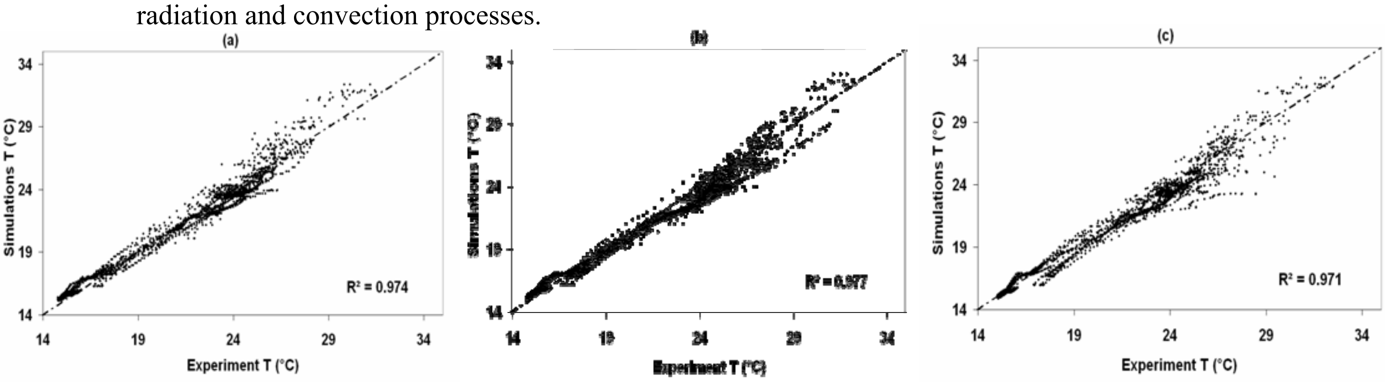

Figure 1: Measured *vs.* simulated temperature for apple cv. Golden (a), apple cv. Redchief (b) and peach (c). The long-dashed lines represent 1:1 relationships.

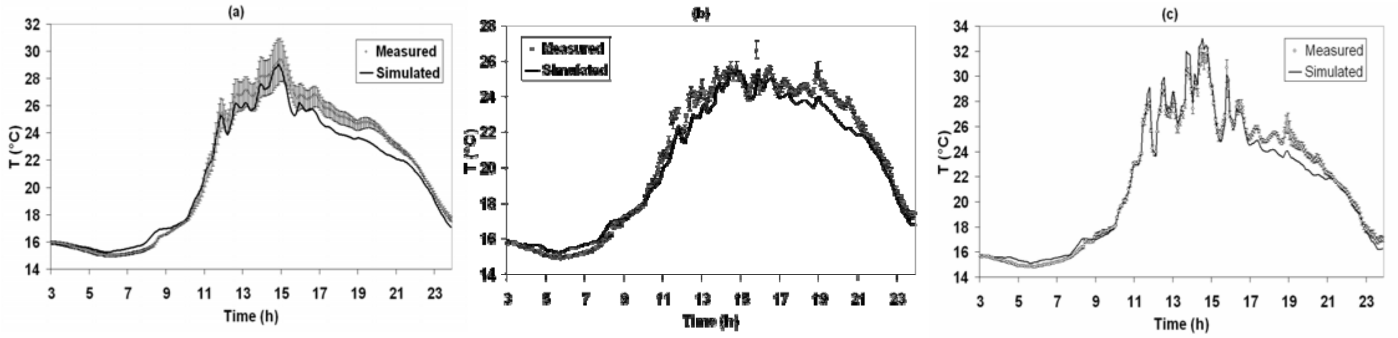

Figure 2: Daily variation of measured and simulated temperature of "Redchief" apple. At fruit center, (a). On the shaded face (bottom) (b). On the sunlit face (top) (c). Error bars represent the variations of measured temperature between 3 fruits.

From this study and from our point of view, the conduction process within fruits is not the main problem in modeling effects of microclimate on temperature of fruits. Finally, the proposed model enables a satisfying estimation of the within-fruit temperature distribution, if boundary conditions (surface irradiance, surrounding air temperature, humidity and speed) are known. Thus, using this model for attached fruits in orchard condition would require the characterization or modeling of the radiation transfer and air circulation within the tree canopy, which is a highly challenging task. Specialized models are now available to handle microclimate components within a tree canopy (Willaume & al, 2004, Finnigan, 2000). Therefore these models should be combined with our fruit temperature model in order to study temperature dynamics within fruits in orchards submitted to new training systems or global climate change scenarii.

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