Analytical solutions for tomato peeling with combined heat flux and convective boundary conditions

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Abstract. Peeling of tomatoes by radiative heating is a valid alternative to steam or lye, which are expensive and pollutant methods. Suitable energy densities are required in order to realize short time operations, thus involving only a thin layer under the tomato surface. This paper aims to predict the temperature field in rotating tomatoes exposed to the source irradiation. Therefore, a 1D unsteady analytical model is presented, which involves a semi-infinite slab subjected to time dependent heating while convective heat transfer takes place on the exposed surface. In order to account for the tomato rotation, the heat source is described as the positive half-wave of a sinusoidal function. The problem being linear, the solution is derived following the Laplace Transform Method. In addition, an easy-to-handle solution for the problem at hand is presented, which assumes a differentiable function for approximating the source while neglecting convective cooling, the latter contribution turning out to be negligible for the context at hand. A satisfying agreement between the two analytical solutions is found, therefore, an easy procedure for a proper design of the dry heating system can be set up avoiding the use of numerical simulations.

1. Introduction
Food safety reasons induce to remove the skin from vegetables, where a lot of bacteria, yeasts and moulds are housed which are difficult to remove. Since a suitable warming up ensures the skins to come off easily, radiative heating appears to be a sustainable means for peel removal as opposed to the ones traditionally used for peeling [1-6]. In facts, peeling is usually realized by using steam or lye, both techniques being recognized to be expensive and/or polluting. Consider that one of the most important advantages of the radiative peeling is that it is mostly waterless. The technique could not only cut the cost of bringing water into the cannery, but may also reduce the expense of recycling or properly disposing of it. Moreover, it is claimed that infrared peeling helps to reduce the wasteful "overpeeling" because the technique primarily affects only the peel and few thin layers beneath it. Reduced overpeeling improves sensorial quality as well, because deeper layers are typically paler than surface deep-red upper layers.

A typical scheme for realizing industrial plants based on radiative heating adopts a plane matrix of infrared emitters placed alongside the conveyor belts. These “illuminate” tomatoes traveling on belts which ensure their rotation in order to improve heating uniformity all over the surface, [8]. Predicting the thermal response of the tomato during the radiative dry peeling process can lead to good peeling
performance and, in addition, it can be of help in designing a suitable radiative heating system, ensuring high quality of peeled tomatoes and energy saving. To this purpose, numerical simulations are usually adopted [1-4,7] or models are selected which are based on semi-empirical exponentially decaying curves with a finite penetration depth [9-11,12-13].

In this context, the analytical solutions herein presented aim to be easy to handle yet accurate models in order to predict the tomato thermal response when subjected to both radiative and convective heat transfer at the surface. Both the analytical models consider a semi-infinite slab, since warming up involves only a few thin surface layers. With reference to the boundary conditions, tomato rotation exposes a point on the surface to a time variable heat flux even considering a radiative source featured by a constant and uniform heat flux; such effect is taken into account by introducing a suitable time varying source at boundary, which radiates oscillating sinusoidally in the first half-period, while is switched off in the following half. Of course, the source angular velocity corresponds to the tomato rotating speed. Most previous works considered pulsed heat flux or sudden temperature changes at the exposed surface [14-15]; however, as far as authors know, none are found in the literature of such kind as that above described. The solution is presented and discussed as depending on the main dimensionless parameters. Its poor sensitivity to the Biot numbers in the range of interest for tomato peeling allows to introduce a simplified yet accurate set of equations for predicting the onset of the peeling conditions.

2. Basic equations

In order to realize successful peeling, surface temperatures are to be raised to values as high as 100°C in a very short warming up period, typically no more than 60 s. Assuming water thermophysical properties apply for tomato, it can be easily checked that in such a short period, the thermal penetration depth is confined to really few millimetres under the tomato skin thus enabling to employ the semi-infinite body model [16]. At the boundary, a cycling radiative heating extended to the first half period of a sinusoidal source is allowed while convective heat transfer takes place as well.

2.1 Analytical solution with combined second and third kind boundary conditions

The present investigation concerns a semi-infinite medium with combined second and third kind boundary conditions, accounting for both heating by a periodic heat source and convective heat transfer at the solid-fluid interface, Figure 1. One-dimensional heat conduction and constant thermal properties are considered. The medium is assumed initially in equilibrium with the ambient temperature $T_i$.

In order to describe the heating felt by the rotating tomatoes, the surface at $x = 0$ is assumed to be exposed to a periodic on/off heat flux with $\frac{1}{2}$ duty cycle; when the source is on, i.e. in the first half period, the heating intensity is assumed to vary sinusoidally with time, while it is zero in the second half, Figure 2. Then, a periodic non-homogenous boundary condition is established, which is featured by the semi-amplitude $\dot{q}_0$ and characteristic angular velocity $\Omega$ related to the tomato rotation speed around its main
axis. The semi-infinite slab model is justified because small heating times are required by the peeling process; it is easy to check that the temperature penetration depth is confined to the very first layers of the tomato skin [16]. By considering constant properties and internal conduction heat transfer for the tomato, while neglecting water evaporation effect, the dimensionless energy balance equation and the related boundary conditions lead to a non-homogeneous linear problem:

\[
\frac{\partial^2 \theta}{\partial \xi^2} = 2\frac{\partial \theta}{\partial \tau}
\]

\[-\frac{\partial \theta}{\partial \xi} \bigg|_{\xi=0,\tau} = \hat{q}(\tau) - Bi \cdot (\theta - \theta_1)
\]

\[\theta(\xi \to \infty, \tau) = 0\]

\[\theta(\xi, \tau = 0) = 0\]

where the following dimensionless parameters have been introduced: \(\theta= (T-T)/\Delta T_{ref}\) is the temperature; the group \(\Delta T_{ref} = \hat{q}_{ref} x_{ref}/k\) is a reference temperature difference related to the maximum wall heat flux, \(\hat{q}_{ref}\), and to a reference length \(x_{ref} = (2\alpha t_{ref})^{1/2}\), \(k\) and \(\alpha\) being the tomato thermal conductivity and diffusivity; the reference time, \(t_{ref} = \Omega^{-1}\), was chosen such as the dimensionless time resulted \(\tau = \Omega t\), \(\Omega\) being the angular velocity of the source; the dimensionless space variable was defined such as \(\xi = x / x_{ref}\)

and, finally, \(Bi = h x_{ref} / k\) is the Biot number, \(\hat{q}(\tau) = \sin(\tau) \cdot \left[1 + \text{sign}(\sin(\tau))\right] / 2\) is the normalized wall heat flux.

Since the problem is linear, the solution can be sought as the sum of two partial solutions, \(\theta_1\) and \(\theta_2\), each one affected by a single non-homogeneity arising from the boundary condition at the wall; the former is due to the heating source and the latter by the convective heat transfer to the surroundings. Then, the two partial solutions have to satisfy two distinct problems derived from the basic one:

\[
\frac{\partial^2 \theta_1}{\partial \xi^2} = 2\frac{\partial \theta_1}{\partial \tau}
\]

\[-\frac{\partial \theta_1}{\partial \xi} \bigg|_{\xi=0,\tau} = \hat{q}(\tau) - Bi \cdot (\theta - \theta_1)
\]

\[\theta_1(\xi \to \infty, \tau) = 0\]

\[\theta_1(\xi, \tau = 0) = 0\]

\[
\frac{\partial^2 \theta_2}{\partial \xi^2} = 2\frac{\partial \theta_2}{\partial \tau}
\]

\[-\frac{\partial \theta_2}{\partial \xi} \bigg|_{\xi=0,\tau} = Bi \cdot (\theta_1 - \theta_1 - \theta_2)
\]

\[\theta_2(\xi \to \infty, \tau) = 0\]

\[\theta_2(\xi, \tau = 0) = 0\]

The analytical solution of both the above systems for \(\theta_1\) and \(\theta_2\) is obtained by the application of the Laplace transform technique; the transformation eliminates the time variable and reduces both the partial differential equations into ODEs in the space variable \(\xi\):

\[
\frac{\partial^2 \tilde{\theta}_1}{\partial \xi^2} = 2s \cdot \tilde{\theta}_1 - 2\theta_1(\xi, \tau = 0)
\]

\[-\frac{\partial \tilde{\theta}_1}{\partial \xi} \bigg|_{\xi=0,\tau} = \frac{1}{e^{-\tau s} - 1} \cdot (1 + s^2)
\]

\[\tilde{\theta}_1(\xi \to \infty) = 0\]

\[
\frac{\partial^2 \tilde{\theta}_2}{\partial \xi^2} = 2s \cdot \tilde{\theta}_2 - 2\theta_1(\xi, \tau = 0)
\]

\[-\frac{\partial \tilde{\theta}_2}{\partial \xi} \bigg|_{\xi=0,\tau} = Bi \cdot \left[\tilde{\theta}_1(\xi = 0) + \tilde{\theta}_2(\xi = 0) - \frac{\theta_1}{s}\right]
\]

\[\tilde{\theta}_2(\xi \to \infty) = 0\]
Here $s$ is the transformed variable, while $\theta_0(\xi, \tau = 0)$ and $\theta_0(\xi, \tau = 0)$ turn out to be zero for the respective initial conditions. The $\theta_0$-problem is coupled to the $\theta_1$-problem via the boundary condition at $\xi = 0$, that requiring the latter system to be formerly solved.

The complete solution in the transformed plane is:

$$\bar{\theta}(\xi) = \frac{Bi \cdot \theta_f}{s(Bi + \sqrt{2s})} \cdot e^{-\sqrt{2s} \xi} - \frac{e^{-\sqrt{2s} \xi}}{(Bi + \sqrt{2s})(e^{-s \cdot \xi} - 1)(1 + s^2)}$$

(4)

The former term of the above solution is easily inverted, turning out to be

$$\theta_n(\xi, \tau) = \mathcal{L}^{-1} \left[ \frac{Bi \cdot \theta_f}{s(Bi + \sqrt{2s})} \cdot e^{-\sqrt{2s} \xi} \right] = \theta_f \left( \text{erfc} \left[ \frac{\xi}{\sqrt{2\tau}} \right] - e^{Bi \cdot \sqrt{2s} \cdot \xi + Bi \cdot \sqrt{\xi}} \text{erfc} \left[ \frac{\xi}{\sqrt{2\tau}} + Bi \cdot \sqrt{\xi} \right] \right)$$

(5)

It represents the thermal response due to the convective heat transfer driven by the initial temperature excess $(T_i - T_0)$.

The latter term of eq. (4) is inverted by noting that it can be regarded as a product of two $s$-functions for which the inverse Laplace transform is well known:

$$F(\xi, \tau) = \mathcal{L}^{-1} \left[ \frac{e^{-\sqrt{2s} \xi}}{Bi + \sqrt{2s}} \right] = \frac{1}{\pi^{\frac{3}{2}}} \cdot e^{-\frac{\xi^2}{2\tau}} - Bi \cdot e^{Bi \cdot \sqrt{2s} \cdot \xi + Bi \cdot \sqrt{\xi}} \text{erfc} \left[ \frac{-\xi + Bi \cdot \sqrt{\xi}}{\sqrt{2\tau}} \right]$$

(6)

$$G(\tau) = \mathcal{L}^{-1} \left[ -\frac{1}{(e^{-s \cdot \tau} - 1)(1 + s^2)} \right] = \hat{q}(\tau)$$

(7)

Therefore, a convolution integral may be built:

$$\int_0^\tau F(\xi, \tau - \tau) \cdot G(\tau) d\tau = \mathcal{L}^{-1} \left[ -\frac{e^{-\sqrt{2s} \xi}}{Bi + \sqrt{2s}} \right] = \theta_n(\xi, \tau)$$

(8)

In order to perform the integration of the piecewise function $F(\xi, \tau - \tau) \cdot G(\tau)$, considering a fixed value for $\tau$, care is taken to break up the integral into $n$ intervals of amplitude $\pi$ over which $\hat{q}(\tau)$ remains continuous:

$$\int_0^\tau F(\xi, \tau - \tau) \cdot G(\tau) d\tau = \left(1 + (-1)^n\right) \cdot \bar{\theta}_t(\xi, \tau) - 2 \cdot \sum_{i=0}^{n} (-1)^{i+1} \bar{\theta}_m(\xi, \tau)$$

(9)

where

$$\bar{\theta}_t(\xi, \tau) = \int \left[ \frac{e^{\frac{3(t-\tau)}{4\pi}}}{\sqrt{4\pi} (\tau - \tau)} \cdot Bi \exp \left[ Bi \cdot \sqrt{2(\tau - \tau)} \right] \text{erfc} \left[ \frac{\xi}{\sqrt{2(\tau - \tau)}} + Bi \cdot \sqrt{\tau - \tau} \right] \right] \sin(\tilde{\tau}) d\tilde{\tau}$$

(10)

The above integral is expressed in explicit form in the Appendices.

Finally, the full solution turns out to be:

$$\theta(\xi, \tau) = \theta_0(\xi, \tau) + \left(1 + (-1)^n\right) \cdot \bar{\theta}_t(\xi, \tau) - 2 \cdot \sum_{i=0}^{n} (-1)^{i+1} \bar{\theta}_m(\xi, \tau)$$

(11)
As expected, the solution depends not only on the values at time $\tau$, it also depends on the heating previously experienced at each revolution, i.e. at each $\bar{\tau} = i \pi$.

2.2 A simpler analytical solution

The solution obtained in previous paragraph appears rather involved, thus a further approximate approach to the same problem is attempted in order to obtain an easy-to-handle solution, which takes into account only radiative heating.

In fact, considering that tomato diameters are typically lower than 3 cm and anticipating that the rotational speed of the tomatoes has to be at least as high as 10 rpm for suitably reducing surface temperature fluctuations, the Biot number always turn out to be lower than 0.01. Therefore, the convective cooling contribution turns out to be negligible, as witnessed by the boundary condition $@ \xi = 0$ in the problem (1).

The simplification stems from considering a time-differentiable function for approximating the heat source distribution:

$$q_{\text{approx}}(\tau) = \frac{1}{2} \left( \sin(\tau) + \sin(\tau)^2 + \frac{4 - \pi}{\pi} \sin(2\tau)^2 \right)$$

The latter shape exhibits the same average value of the original source over a period, meanwhile it is such as the relative variation with respect to the original shape is always lower than 5%; its structure is clearly simpler than the previous one being expressed by a single, differentiable, term. Then, by making use of the Laplace Transform once again, the solution to the problem is readily obtained:

$$\theta_{\text{approx}}(\xi, \tau) = \int_0^\tau e^{-\frac{\xi^2}{4\pi (\tau - \bar{\tau})}} \left( \sin(\bar{\tau}) + \sin(\bar{\tau})^2 + \frac{4 - \pi}{\pi} \sin(2\bar{\tau})^2 \right) d\bar{\tau}$$

The explicit integral is reported in the Appendices.

It can be shown that the magnitude of temperature oscillations given by the previous equation differs from that given by the corresponding exact ones, eq. (11), no more than 2.6%.

It will be shown in the next paragraph that it is of interest to evaluate the average temperature on the surface during the last revolution at a given time $\tau$; it can be calculated as

$$\theta_{\text{ave,approx}}(\tau) = \int_{\tau}^{\tau + 2\pi} \theta_{\text{approx}}(0, \zeta) d\zeta / 2\pi$$

The explicit integral is given in the Appendices again. Such a function approximates the corresponding exact one by a maximum relative error less than 2%.

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**Figure 3.** The dimensionless surface temperature @ $\xi = 0$

**Figure 4.** The dimensionless inner temperature @ $\xi = 1$
3. Results and discussion

The solution given by eq. (11) is readily validated by considering the limiting case for $\tau < \pi$ when the initial temperature equals the fluid temperature, i.e. $\theta_i = 0$: for such conditions, the full temperature distribution should reduce to that well-known resulting from a simple sinusoidal heating source. That is the case at hand since it can be shown that the first term in the summation, i.e. $-2 \tilde{\theta}_0(\xi, \tau)$, fully recovers expected solution.

The unsteady temperature field turns out to depend on the spatial and time coordinates and on the Biot number. The oscillating temperature field behaviour is represented in Figures 3 and 4 by taking temperature profiles on the surface and at a distance $\xi = 1$ from it and for different values of the Biot number. The plots clearly show different thermal responses to different cooling rates: the greater the Biot number, the more both temperature levels and the amplitude of the oscillations decrease at each location. It can be further observed that, the phase shift with respect to the driving heating flux decreases with the Biot number. Attenuation and phase shift behaviour as a function of depth $\xi$ are qualitatively the same discussed before for the Biot number, however thermal diffusion deeper under the surface determines a smoothing effect with increasing $\xi$ so that the time-discontinuous shape of the source is scarcely resembled. Profiles still keep their asymmetric shapes since different heating and cooling rates are realized.

As noted before, it is of primary interest for proper dry tomato peeling design to characterize the surface temperature. For the present context, reduced machining times are to be considered, meanwhile $Bi \to 0$: therefore, a periodic sustained solution is not useful and the complete solution should be handled which requires high computational efforts. In the light of this consideration the magnitude of the oscillations and the phase shift are evaluated numerically at the surface after a reference time is elapsed while the Biot number varies. The reference time is chosen to correspond to the completion of 30 revolutions which, for usually accepted rotating rates, requires no more than a minute and is compliant with tomato peeling. Such results are then fitted with Hyperbolae equations, which are shown in Figure 5; hyperbolae fine adapt to the computed data, so that the corresponding coefficients of determination differ from one only in the fourth decimal place, both for the magnitude of the oscillations and the phase shift. Inspection of figures shows that the solution is basically insensitive to Biot numbers up to 0.01. Such a behaviour is of help wishing to answer the question of the frequency at which the tomato has to rotate so that the source appears to it almost as a continuous source. In fact, provided small Biot numbers are realized, the amplitude of the oscillations at the surface, $\Delta T_0$, can be estimated as:

$$\Delta T_0 = 0.8 \dot{q}_0 \frac{\sqrt{2a}/\Omega}{k}$$

(15)
from which the tomato angular speed can be obtained. The knowledge of \( \Omega \) allows the subsequent evaluation of the time at which the heating process is complete, \( t_{\text{proc}} \); the latter event is triggered when a target value, usually fixed at \( T_{\text{targ}} = 90^\circ \text{C} \), for the surface average temperature is attained. The above purpose is suitably fulfilled by invoking the approximate solution; then, making use of eq. (14) or equivalently of Figure 6, one can write:

\[
T_{\text{targ}} = T_i + \theta_{\text{ave,approx}} (\Omega, t_{\text{proc}}) \frac{\sqrt{2} \alpha / \Omega}{k}
\]

in order to derive \( t_{\text{proc}} \). A plot of the average temperature could be of help as well, see Figure 6.

4. Conclusions

Having in mind to study temperature patterns through tomatoes subjected to radiative heating during dry peeling process, an analytic solution of the Fourier heat conduction in a semi-infinite medium is obtained by making use of the Laplace transform technique. The thermal response fully recovers the temperature field due to a sinusoidal varying heat source as a limiting case. Simplified expressions for evaluating the surface phase shift and magnitude of temperature oscillations are given. Moreover, in order to facilitate the average temperature evaluation, a simplified model is introduced which properly recovers the average surface temperature. Since peeling takes place when the surface temperature attains a threshold value with contained magnitude of temperature fluctuations, an easy way to help the design of a proper radiative heating system is proposed, thus avoiding the use of numerical simulations.

5. Appendices

Performing the integration of eq. (10) gives:

\[
\theta_i(\xi, \tau) = \frac{1}{8 \sqrt{2} (1 + Bi^4)} \left( 2 \sqrt{2} + 2Bi + \sqrt{2}Bi^3 \right) \left( e^{-\xi} \cos(\xi - \tau) - e^{\xi} \cos(\xi + \tau) \right) +
\]

\[
+ 4Bi e^{i(\xi^2 + Bi^2(\tau - \xi))/2} \text{erfc} \left( \frac{\xi \sqrt{2} + 2Bi (\tau - \xi)}{2 \sqrt{\tau - \xi}} \right) \left( \cos(\tau) + Bi^2 \sin(\tau) \right) +
\]

\[
+ \left( \sqrt{2} - \sqrt{2}Bi^2 - 2Bi^3 \right) \left( \sin(\xi - \tau) + e^{2i} \sin(\xi + \tau) \right) + e^{2i} \left( \left( 2Bi - \sqrt{2} - \sqrt{2}Bi^3 \right) \left( \cos(\xi - \tau) a_i(\xi, \tau, \bar{\tau}) \right) +
\]

\[
+ \sin(\xi - \tau) b_i(\xi, \tau - \bar{\tau}) + \left( \sqrt{2} + 2Bi^2 - 2Bi^3 \right) \left( - \cos(\xi - \tau) b_i(\xi, \tau - \bar{\tau}) + \sin(\xi - \tau) a_i(\xi, \tau - \bar{\tau}) \right) \right) +
\]

\[
+ e^{2i} \left( \left( \sqrt{2} + 2Bi \right) a_i(\xi, \tau - \bar{\tau}) + \sqrt{2} a_i(\xi, \tau - \bar{\tau}) \left( Bi^2 \cos(\xi + \tau) - \sin(\xi + \tau) \right) \right) +
\]

\[
+ \sqrt{2} a_i(\xi, \tau - \bar{\tau}) \left( \cos(\xi - \tau) + Bi^2 \sin(\xi + \tau) \right) \right)
\]

where \( a_i(\xi, z) \) and \( b_i(\xi, z) \) are the real and the imaginary coefficients of the following error functions:

\[
\text{erf}_i(\xi, z) = \text{erf} \left( \frac{\xi \sqrt{2} + (-1)^i \sqrt{2} z}{2 \sqrt{z}} + (-1)^i \frac{\sqrt{2} \sqrt{z} \xi}{\sqrt{2}} \right), \quad k = 1,2
\]

Performing the integration of eq. (13) gives:
\[ \vartheta_{\text{approx}}(\xi, \tau) = 2\left( \sqrt{2} I(\sqrt{2} \pi^{3/2}) \right) e^{-\xi^2/2\tau} - \xi/\pi + \left( 1/16 \pi^2 \right) \left( 2\sqrt{2} \left( -e^{-\xi^2/2\tau} \cos(\xi - \tau) + \sin(\xi - \tau) \right) + e^{-\xi^2/2\tau} \right) \]

\[ + \left( 4\pi / (\pi \sqrt{2}) \right) \left( e^{-\xi^2/2\tau} \left( -\cos(2\xi - 4\tau) + \sin(2\xi - 4\tau) \right) + e^{\xi^2/2\tau} \left( \cos(2\xi + 4\tau) + \sin(2\xi + 4\tau) \right) \right) + \]

where:

\[ c_i(\xi, \tau) \text{ and } d_i(\xi, \tau) \text{ are the real and the imaginary coefficients of the following error functions:} \]

\[ \text{erf}_k(\xi, \tau) = \text{erf}\left( \frac{\xi \sqrt{2} + (-1)^k 2\tau}{2\sqrt{\tau}} \right) - (-1)^k i \frac{\sqrt{\tau}}{\sqrt{\tau}}, k = 1, 2 \]

\[ m_k(\xi, \tau) \text{ and } n_k(\xi, \tau) \text{ are the real and the imaginary coefficients of the following error functions:} \]

\[ \text{erf}_k(\xi, \tau) = \text{erf}\left( \frac{\xi \sqrt{2} + (-1)^k \pi \sqrt{2}}{2\sqrt{\tau}} + (-1)^k i \frac{\sqrt{\tau}}{2}, k = 1, 2 \right) \]

\[ p_k(\xi, \tau) \text{ and } q_k(\xi, \tau) \text{ are the real and the imaginary coefficients of the following error functions:} \]

\[ \text{erf}_k(\xi, \tau) = \text{erf}\left( \frac{\xi \sqrt{2} + (-1)^k \pi \sqrt{2}}{2\sqrt{\tau}} + (-1)^k i \frac{\sqrt{\tau}}{2}, k = 1, 2 \right) \]

Performing the integration of eq (14) the approximate average temperature on the surface over a period is given by

\[ \vartheta_{\text{ave,approx}}(\tau) = \frac{-3\pi \sqrt{\tau - 4\tau^{3/2}} + 11\pi \sqrt{2\pi + \tau} + 4\tau \sqrt{2\pi + \tau}}{6\sqrt{2} \pi^{3/2}} \]

6. References

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