Simplified numerical modelling of infrared radiation effects in tomato dry peeling

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Abstract. In view of the increasing interest in developing sustainable systems for tomato peeling, the unsteady thermal field in a rotating tomato exposed to an array of infrared emitters was studied. First, a predictive 3D numerical model was developed to simulate heat transfer in a rotating tomato undergoing infrared heating. Since simulations required great computational efforts, it was considered appropriate to introduce a simplified model. To this purpose, the net radiative heat flux on the tomato surface was approximated by a suitable periodic function: the related angular velocity accounted for tomato rotation, while its amplitude was linked up with view factors between the tomato and the heating source. On such basis, a 1D axisymmetric model involving radiative heating from the source regarded as a periodic II-type boundary condition was set up. It was found that temperatures predicted by the simplified model agreed well with the 3D model output. Finally, a parametric analysis was performed to investigate the effect of the position and angular velocity of the tomato samples on the rate and uniformity of IR heating. Results were pursued both by the 3D and 1D model, in the latter case obtaining faster yet accurate responses.

1. Introduction
The main critical concerns about the sustainability of tomato processing industry regard energy consumptions and wastewater disposal problems associated with lye and steam peeling methods, [1-3]. The steam peeling does not use chemicals, yet, it results in higher peeling loss than lye peeling. Thus, tomato processors are seeking alternatives to replace traditional methods. In this connection, the development of sustainable tomato peeling technology seems to converge toward infrared (IR) dry-peeling: this process avoids using lye and water, meanwhile requiring almost the same time to heat samples. Moreover, it produces thinner thickness of peeled-off skin and slightly firmer texture of peeled, while a similar ease of peeling is achieved. Other attractive properties are claimed such as increased Young’s Modulus of tomato peels and reduced peel adhesiveness. These findings demonstrated the effectiveness of the novel IR dry-peeling process for tomatoes [4]. However, some critical aspects of peeling tomatoes using infrared radiation heating were outlined by [5].

Wishing to perform successful infrared peeling requires to realize both rapid and uniform heating on the tomato surface. A typical configuration for industrial peeling is realized by means of a plane matrix of infrared emitters, looking at tomatoes in relative motion; in fact, tomatoes are carried on by the conveyor belt which induces their rotation in order to improve heating uniformity. In order to achieve an optimal design of infrared heating systems, the irregular shape of tomatoes and their different expositions to the heating source when transported along by the conveyor belt are to be considered. Due to the complexity of the geometry at hand, a numerical approach is required to retrieve tomato thermal response to infrared
heating. However, a preliminary description based on an analytical model was previously attempted by the authors: by considering that the proper time scale of the process at hand is small, they considered a semi-infinite body subjected to a suitably chosen pulsating heat source [7;8]. With regard to the numerical approach, computational simulation of IR heating in peeling process has not yet been satisfactorily explored, probably because the IR dry-peeling technology is too recent. Pan et al. [9;10] proposed a numerical model with the tomato exposed to double sided infrared heating, yet no rotation was accounted for. Some authors considered volumetric absorption of infrared energy at food surface; consequently, they dealt with semi-empirical exponentially decaying models with a finite penetration depth [11-13]. In any case, tomato rotation was not considered although it is intuitively a critical operating parameter, since it strongly influences heating uniformity.

In this paper a three-dimensional geometric model for the unsteady temperature field in rotating tomatoes exposed to a matrix of infrared emitters was developed. The heating process duration was assumed to end when a specified temperature level was attained which turned out to be useful for peeling purposes. Having in mind to achieve the best heating uniformity, rotation speed and relative position with respect to the source are key parameters to feature; therefore, different geometrical configurations were considered when solving the problem by the 3D-numerical model. Finally, a careful characterization of the heating source intensity in terms of the view factors between the tomato and the source enabled an alternative 1D-model, independent of source geometrical details. Thus, a simplified equivalent model for the heat source was allowed which led to satisfyingly recover the description of the surface temperature field, whilst ensuring a sensible reduction of computational efforts.

2. The three-dimensional numerical model

2.1 Geometrical configuration

A three-dimensional FEM model was developed by employing the commercial code COMSOL Multiphysics [14]. The unsteady temperature field for the rotating tomato subjected to the irradiation coming from an array of IR emitters was obtained. A schematic representation of the geometry under study is reported in figure 1: three IR plane emitters, 72 cm x 9.2 cm, were supposed to heat the tomato; a reference position was chosen so that the tomato was placed in front of the central emitter, midway along the emitter longitudinal axis, at a distance \( w = 0 \). Of course, the reference position was such as the tomato experienced the maximum heating intensity. The tomato sample was placed orthogonally with respect to emitters longitudinal axis.

The computational domain of the tomato was generated based on the two-dimensional axisymmetric parametric profile introduced by Li et al., [15]; the related dimensionless shape coefficients were sought as: \( a = 31 \text{ mm}, b = 24 \text{ mm}, c_1 = 0.24, c_2 = 0.38 \), that identifying a realistic shape for medium size tomato. The tomato computational domain was discretized using unstructured tetrahedral grid elements. A mesh convergence study was formerly performed until results turned out to be independent of the mesh size during the warming up period, [7]. In practice, the warming up period is assumed to end when the
surface average temperature recovers a threshold value of 90°C; the latter temperature is known to be useful for peeling purposes.

The net radiative heat flux on the tomato surface was numerically evaluated for several distances \( w \) in figure 1 between the tomato and the emitters. The distance \( w \) varied between 0 and 2 cm, this range allowing heat rates to be as high as to ensure heating was fast enough for the addressed purposes.

2.2 Basic equations

The energy balance equation applied to the tomato undergoing transient conduction heat transfer is expressed by the fundamental equation of conduction, which, assuming constant properties, turns out to be:

\[
\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T)
\]  

where \( T \) is the tomato temperature, \( t \) is the time, \( \rho \), \( c \) and \( k \) are the density, the specific heat and the thermal conductivity of tomato, respectively.

On the tomato surface, the total heat flux is the sum of the radiative and convective heat transfer contributions. Hence, the first boundary condition is given by:

\[
\mathbf{n} \cdot (\mathbf{v} \cdot \nabla T) = \varepsilon (E_b(T) - G) + h(T - T_{\text{ex}})
\]

where \( \mathbf{n} \) is the outward normal vector of the boundary, \( G \) \([\text{W/m}^2]\) is the surface irradiation, \( E_b \) is the blackbody emissive power, \( \varepsilon \) is the tomato emissivity, \( h \) is the average surface heat transfer coefficient, \( T_{\text{ex}} \) is the air temperature. In particular, the view factor is automatically determined by the numerical code for each of the facets of the discretized geometry using a “hemicube” or “direct area integration” approach. The surface irradiation is mainly due to the infrared emitters. The average surface temperature of the emitters was assumed to be 650 °C, meanwhile the surrounding temperature was set to 20 °C. The tomato sample was assumed to be a grey body with a surface emissivity equal to 0.95, while air was assumed as a non-participating medium.

At the tomato centre, the symmetry boundary condition was imposed:

\[
\mathbf{n} \cdot (k \nabla T) = 0
\]

The initial temperature of the tomato was assumed to be uniform:

\[
T(x,y,z,t=0)=T_i
\]

where \( T_i \) represents the initial temperature of tomato.

The 3D model accounts for tomato rotation around its main axis by assigning the angular velocity \( \Omega \) and then calculating the local velocity components as in figure 2:
\[ v_x = -\Omega R \sin(\Omega t) = -\Omega x; \quad v_y = \Omega R \cos(\Omega t) = \Omega y \]  

Note that the angle \( \Omega t \) can be related to the path \( s = \Omega t R_0 \) described by a point moving along the circumference with peripheral velocity \( v = \Omega R_0 \).

2.3 Modelling the pulsating heat source

Numerical simulations allowed to determine the net radiative heat flux crossing the widest tomato circumference. The addressed circumference is the more critical because it experiences the highest temperature increases. The points A and B of figure 2 belong to such a circumference. The former point is the first to experience heating from the rising source, while the latter is the one experiencing the maximum heating along the selected circumference. Due to the marked difference of temperature between the emitters and the tomato, the flux crossing the selected circumference essentially coincides with the irradiation due to the emitters; it was determined for several configurations, i.e. for selected distances \( w \), namely 0, 0.5, 1 and 2 cm. The following normalized function was found to satisfyingly describe the pulsating heat source:

\[
\frac{\dot{q}(\phi,t)}{\dot{q}_b} = \frac{1}{2} \left( \sin(\Omega t) + \sin(\Omega t)^2 + \phi \cos(2 \Omega t) + \phi \right)
\]

where \( \dot{q}_b = \dot{q}(\phi,t = \pi / 2 / \Omega) \) is the radiative heat flux experienced by point B, and \( \phi \) is a parameter which is determined by imposing that, for each distance \( w \), the average value along the circumference for the function at hand recovers the corresponding one given by the numerical 3D model. Since \( \dot{q}_A = \dot{q}(\phi,t = 0) \), the parameter \( \phi \) can be regarded as the ratio of the minimum to maximum net radiative heat flux: \( \phi = \dot{q}_A / \dot{q}_b \). As an example, in figure 3 the net radiative heat flux along the selected circumference as calculated by the numerical model and the one obtained through eq. 6 are compared for an arbitrarily selected distance. Apart from this specific case, the goodness of the fit is shown in Table 1 as a function of the distance \( w \).

| Table 1. RMSE and \( \phi \) as a function of \( w \) |
|-----------------|-----------------|-----------------|-----------------|
| \( w \) [cm]    | \( \phi = \dot{q}_A / \dot{q}_b \) | RMSE            | \( F_{1/2} / F_{1/3} \) |
|-----------------|-----------------|-----------------|-----------------|
| 0               | 0.42            | 0.019           | 0.430           |
| 0.5             | 0.41            | 0.018           | 0.418           |
| 1               | 0.39            | 0.017           | 0.403           |
| 2               | 0.37            | 0.015           | 0.381           |
In order to figure out the relationship between the distance \( w \) and the parameter \( \phi \), consider that the latter can be further interpreted as the view factor between the point \( A \) and the emitters, normalized with respect to the view factor related to the point \( B \), see figure 4. Therefore:

\[
\frac{\dot{q}_A}{\dot{q}_B} = \frac{F_{12}^\perp}{F_{12}^{||}}
\]

Equation (7)

By invoking the view factors definitions shown in figure 4, the right-hand side of the previous equation turns out to be a known function of the distance \( w \), [16, 17]. The last column in table 1, shows the ratio of the view factors appearing in eq. 7 evaluated by means of the corresponding analytical expressions whereas the left-hand side is given up in the second column of the same table in accordance with eq. 6. A relative error of about 2.5\% is achieved. Hence, equation (7) establishes a relationship of the kind \( \phi = \phi(w) \), accounting for the shape of the heat flux along the heated circumference as depending on the distance \( w \).

The knowledge of the view factor \( F_{12}^{||} \) allows to determine the radiative flow that crosses the point \( B \) when the distance \( w \) changes. In fact, if the maximum heat flux in the reference configuration is assumed to be known, the definition of the view factor between the emitter and the point \( B \) yields:

\[
\dot{q}_B(w) = \dot{q}_B(0) \frac{F_{12}^{||}(w)}{F_{12}^{||}(0)}
\]

Equation (8)

Thus, determining the maximum heat flux as a function of the distance \( w \) requires a single simulation for featuring the maximum heat flux at the reference distance, i.e. \( \dot{q}_B(0) \); the latter calculation can be conveniently carried out in the stationary regime in order to minimize time for computation, since it only depends on the geometry. Of course, such a simulation was performed by imposing a convective coefficient sufficiently large, in order to keep the tomato surface temperature lower than the peeling threshold: in this way, the net radiative heat flux turned out to be almost constant and independent of the tomato temperature.

3. One-dimensional axisymmetric numerical model

In order to predict the thermal response of the tomato subjected to radiative heat flux with lower computational efforts, a numerical 1D axisymmetric model was implemented in Comsol Multiphysics. Therefore, the rotating tomato was described as an infinite cylinder, whose radius \( R_0 \) was assumed to be equal to the segment connecting the points \( A \) and \( B \) of figure 2. The cylinder was subjected to periodic heat flux according to eq. 6. A combined II-type and III-type boundary condition was considered providing for both radiative infrared heating and convective cooling to an ambient at fixed temperature; the latter assumption is justified by considering that surface temperatures of infrared heaters are much higher than the surrounding ones during the warming-up period. This strong simplification allows to avoid the three-dimensional description of the emitters.
Under such assumptions, the dimensionless energy balance and the related boundary conditions led to the following linear problem:

\[ \rho c_p \frac{\partial T}{\partial t} = k \frac{\partial}{\partial R} \left( \frac{R \frac{\partial T}{\partial R}}{\partial} \right) \]

\[ -k \frac{\partial T}{\partial R} \bigg|_{R=R_0,t} = \dot{q}(\phi,t) - h \cdot (T - T_{\text{ext}}) \]

\[ k \frac{\partial T}{\partial R} \bigg|_{R=0,t} = 0 \]

\[ T(R,t = 0) = T_i \]

This approximate description allowed to numerically predict the thermal response of the tomato points lying on the more exposed circumference.

4. Results

4.1 Comparison between 3D and 1D numerical models

As expected, the 1D model was attractive because of its execution speed: only few seconds were required, whereas the 3D model required almost one hour in order to describe the tomato thermal transient until the threshold-time. On the other hand, a subsequent reduction in the related accuracy could be expected when using the simplified model. A measure of the achieved approximation is given in figure 5, where temperature evolution for a point moving along the circumference is shown for both 3D and 1D calculations. To two typical angular velocities, i.e. 5 and 20 rpm, are considered. For the sake of simplicity, calculations were performed by neglecting convective heat transfer. Results inherent the 1D model satisfyingly approach the corresponding 3D model calculations: the relative percentage error during the warming up period resulted to be contained within about 3.5% and 5.2% for the two rotational velocities. It is interesting to observe that the time interval needed to complete the warming up turns out to be independent of the angular velocity as shown in figure 6, where the average surface temperatures are represented.

4.2 Parametric analysis of thermal uniformity

Since heating uniformity all over the tomato surface is mandatory in order to realize good peeling performance while ensuring high quality of peeled tomatoes and energy saving, [18,19,20], a surface temperature uniformity analysis was carried out by the 3D model. In order to quantify the surface
temperature uniformity while varying the angular velocity of the sample under test and its position with respect to the matrix of emitters, the surface temperature uniformity index (STUI) was introduced [7]:

\[
STUI = \frac{1}{T_{objective}} \sqrt{\int_{A} (T - T_{average})^2 dA} \tag{13}
\]

the area \(A\) representing the whole tomato surface.

The STUI was evaluated at the end of the warming-up period for different tomato positions. In particular, for a selected distance between the tomato and the emitters, namely \(w = 0\), ten different tomato positions were considered, see figure 7: positions were identified by selecting five displacements with respect to the emitters longitudinal axis (\(\delta\)) and two distances, 5 and 36 cm, measured far away from the emitters leading edge, labelled “entrance” and “middle way” in the figure. Results for the STUI are represented in figure 8: for a fixed angular speed, the STUI exhibits a minimum on the symmetry longitudinal axis while higher values are attained in correspondence of the exterior emitters (\(\delta = -9.22\) cm e \(\delta = 9.22\) cm): unfavourable positions corresponding to the highest lateral displacements worsen noticeably temperature uniformity on the tomato surface. On the other hand, the STUI appears scarcely sensitive to the distance from the leading edge. Finally, with increasing the angular speed, the STUI significantly reduces.

5. Conclusions

A 3D numerical model was developed in order to predict the temperature field of a rotating tomato subjected to radiative heating for peeling purpose. The resulting net radiative heat flux on the tomato surface was modelled by a suitable periodic function, depending on the view factors between the tomato and the heating source. This function was used to introduce a II-type boundary condition for a 1D asymmetric numerical model, thus allowing a simplified description of the problem at hand since 3D description of the emitters was avoided. The simplified model was able to recover the thermal response of the tomato with considerably reduced computational efforts; yet, it was able to approximate the 3D model results with satisfying accuracy within the framework of interest.

Finally, in order to provide useful information to support innovative dry-peeling process, 3D simulation results showed how rotational velocity and position of the tomato influence the surface temperature uniformity.

6. References

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