Multi-Physics Modeling of Radio-Frequency Cooking

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Abstract: A radio frequency cooking process for a meat product was modeled using the heat transfer module with an internal heat generation term by joule heating caused by the applied electric field. The dielectric and thermal properties were implemented as function of temperature. The resulting simulation had good agreement with experimental end point temperature data from the literature, with a mean relative error of 2.6%. Using this model, the effect of centering the food in the holding cell was simulated. This simulated case had higher mean end point temperature and a smaller temperature difference in the sample than the case with the meat product sitting at the bottom of the holding cell.

Keywords: RF cooking, thermal processing, food, dielectric properties

1. Introduction

Thermal processing of food has gained an ever growing importance as food manufactures strive after increasing the number and quality of value-added products on the market. These products must have high microbiological safety in order maintain a shelf life conducive to a profitable distribution chain. At the same time there is an increasing trend towards minimally processes products – those which have had just enough heat treatment for adequate preservation yet maintain maximum “freshness” and avoiding over-cooking. Many of these products consist of solid food such as meat and vegetables as the main ingredient. Solid food is more difficult to heat efficiently since it cannot be pumped or stirred. In conventional thermal processing of solid food items, the product is heated externally via conduction, convection, or radiation. The main drawback with these types of heating processes is that they either cause over-cooking of food surfaces or require long cooking times as the heating needs to extend through entire food item. One way to reduce cooking times is to employ some form of volumetric electromagnetic heating such as ohmic, RF or microwave heating. These methods are similar in that they all use electromagnetic fields to internally generate heat through molecular friction.

Some examples of RF technology deriving benefit from volumetric heating include: the industrial drying of cookies and crackers which, have demonstrated a seven fold increase in efficiency, when using RF compared to conventional drying (Annon, 1996 and McCormick, 1988); the cooking time of large meat products (1kg) can be decreased by 10 to 30 fold, (Laycock et al. 2003); large blocks of frozen meat and fish conventionally are thawed a period of several days but by using RF heating this process can be accelerated to achieve defrosting times of 1 to 2 hours, whilst still maintaining control of the temperature distribution within the product (Rowley, 2001).

RF-heating technology is by no means new, studies dating back to the 1940’s can be found in the literature. However there have been some serious drawbacks which have prevented it from reaching its full potential such as inadequate understanding of electromagnetic wave propagation in complex materials and geometries. This is directly related to the physics of RF heating, causing practical problems such as arching and thermal run away heating. Furthermore, in the past, empirical experience, trial and error, and good fortune played a major role in designing RF-systems for industry. This resulted in the construction and re-working of many prototypes before a suitable solution was found. However, today’s current computer technology allows one to model, simulate, and design RF heating systems on a PC (Metaxas 2000).

Finite Element calculation packages such as COMSOL-Multi-physics are now widely available. This allows one to consider complex geometries, in-homogeneous food materials, and dynamic coupled effects, in order to predict how the electromagnetic will interact with both the food and the surrounding equipment. Other recent publications on modeling RF heating of foods include Marra et al. (2007) and Birla et al. (2007).

Previously to obtain a working RF heating system one might build ten or so prototypes over the period of one year, computer simulations could achieve the same result in a matter of weeks (Marchand and Meunier, 1990). Hence the objective of this work is to demonstrate the potential of modeling in COMSOL to describe an RF heating with the intention of improving the evenness of the heating in food product.

2. Description of the Problem

Despite the volumetric nature of RF heating processes there still remains cases where un-even heating still occurs. One such case published in the literature, was that of heating a large diameter cased luncheon roll described by Zhang et al. (2004a). This example was used as they provide details on the geometry and dielectric properties of their system as well as end point temperature data quantifying the unevenness of heating. In their work Zhang et al. (2004a) optimized an RF cooking protocol for a 1kg encased pork luncheon roll (PLR) meat product. This entailed RF heating for 30 minutes at 500 W in a Capenhurst RF oven. The PLR was contained inside a high density polyethylene holding cell filled with circulating water at 80ºC. After the 30 minutes the RF power is turned off and the water is allowed to circulate for an additional 2 minutes (holding time) after which the PLR is immediately removed from the holding cell and end point temperatures (EPTs) are measured at defined positions using a thermocouple jig. The EPTs showed that there was a cooler region near the bottom of the PLR. The aim of this modeling work was it to see if this cold spot was a result of the electric filed distribution and if altering the geometry could improve the evenness of the heating.

3. Governing Equations

3.1 Electromagnetic model

The electromagnetic problem is modeled as a quasi-static case since the changes in the E-field are much faster than the dynamics of heat transfer. Furthermore, dimensional analysis based on comparing the processing frequency (in this case 27.12 MHz) and the critical frequency of the material was performed to estimate what kinds of electric losses are dominating the process.

$$\omega_{cr} = \frac{1}{\tau} = \frac{\varepsilon'}{\sigma_r}$$

τ is the dielectric relaxation time, i.e. the time needed for the material in an electric field to reach a new state of equilibrium after changing the excitation in an electric field (Takhistov 2007). ε' is the relative dielectric constant and σ_r the relative conductivity:

$$\sigma_r = 2\pi f \varepsilon''$$

where ε'' is the relative dielectric loss. If the ratio if the processing frequency to the critical frequency is small than the one can say that the processes dominated by ionic effects (i.e. drift of dissolved ion) and the conductivity of the food product dominates over the dielectric permittivity. If ratio is large, then the heating is dominated by di-pole rotation (e.g. water molecules) and a high frequency analysis should be used (Takhistov 2007).

$$\frac{\omega_p}{\omega_{crit}} = \begin{cases} << 1 \rightarrow ionic \\ \approx 1 \rightarrow mixed \\ >> 1 \rightarrow dielectric \end{cases}$$

In this problem the ratio was calculated to be less than 0.02 based on the dielectric property data for the pork luncheon roll from Zhang et al. (2004b) over the range of process temperatures (see section 4.1). In this case we can say that the conductivity dominates the heating and thus a joule heating model was used to couple the RF heating term to the heat transfer model:

$$Q = \frac{1}{2}\sigma\left|\overline{E}\right|^2$$

This can be accessed directly in the COMSOL variable for resistive heating: Qav_emqvw.

3.2 Heat transfer

The heat transfer in this problem, is based on the generalized heat equation which depends on the thermal physical properties of the product being heated:

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

Where T is the temperature, ρ is the density, C_p is the heat capacity at a constant pressure, k is thermal conductivity, Q is a heat source or a heat sink. In this case Q denotes an internal heat generation source term and is a result of the RF power being dissipated in the product. The boundary condition on the surface of the cased pork luncheon roll exposed to the flowing water from the heating bath was implemented as a convective flux:

$$-k\nabla T = h(T - T_{bath})$$

Where T_{bath} is the water bath temperature and *h* is a convective heat transfer coefficient set 200 W m-2 K-1. This value is a rough estimate and considered acceptable based experimental finding from Zhang et al. (2004a) which showed that there was no significant effect on the in final end point temperatures with changing the circulation water bath temperature over a 5ºC range. This assumption was further confirmed by considering what the minimum heat transfer coefficient would be to give a Biot number over 40, i.e. the case where internal resistance to heat transfer dominates.

$$N_{biot} = \frac{hD}{k} > 40$$

Given the diameter, D, of the PLR is 9 cm and k is in the range of 0.36 to 0.44 Wm^{-1} K^{-1} (Zhang et al., 2004b), the minimum *h* value giving a Biot number >40 would be less than 195 which is above the range for free convection in water, 20 to 100 W m^{-2} K^{-1}, but at the low end of forced convection, 50 to 10 000 W m^{-2} K^{-1} (Singh and Heldman, 1993). The forced circulation in the holding cell by the pumping water bath is assumed to have exceeded 200 W m^{-2} K^{-1}, thus the heat transfer is limited by the internal resistance, i.e. the conduction through the PLR.

4. Methods

4.1 Material Properties

The relative dielectric constant values as a function of temperature for the pork luncheon roll was estimated from the data in Zhang et al. (2004b). A linear function was chosen since the significance of temperature effect was low.

$$\varepsilon'_{(T)} = 5.41 \times 10^{-2} T + 3.10 \times 10^{1}$$

Similarly the relative dielectric loss factor as a function of temperature was fit using a 2nd order polynomial since 3 values over the measured temperature range reported in Zhang et al. (2004b) were significantly different.

$$\varepsilon''_{(T)} = -7.70 \times 10^{-2} \cdot T^2 + 5.42 \times 10^{1} \cdot T - 8.61 \times 10^{3}$$

The COMSOL model uses relative permittivity, ε', and AC conductivity,σ thus we can include the temperature effects by:

$$\sigma_{(T)} = 2\pi \cdot f \varepsilon_0 \varepsilon''_{(T)}$$

The other temperature dependent material property is the thermal conductivity and a function was generated using thermal diffusivity data from Zhang et al. (2004b).

$$k_{(T)} = \rho \cdot C_p \left(6.30 \times 10^{-10} \cdot T - 6.64 \times 10^{-8}\right)$$

Table 1. Other Material Properties Used in Model

Property	Value	mode
ρ [kg m^{-3}] density PLR	1057	heat
C_p [J kg^{-1} K^{-1}] heat capacity PLR	3600	heat
ε' relative permittivity water	79.7	elect.
σ [S m^{-1}] conductivity water	1.3E-3	elect.
ε' relative permittivity polyethylene	2.3	elect.
σ [S m^{-1}] conductivity polyethylene	6.97E-7	elect.
ε' relative permittivity air	1	elect.
σ [S m^{-1}] conductivity air	0	elect.

4.2 Numerical Model

Simultaneous solution of the electric field distributions and conductive heat transfer with an internal power generation term (resistive heating) was solved using COMSOL Multi-physics 3.3a 3.3.0.511. The application modes and modules used in this model were:

- Geometry: Axial symmetry (2D)
- Meridional Electric Currents (AC/DC Module)
- General Heat Transfer (Heat Transfer Module)

The model was simplified by taking advantage of the axial symmetry, as the pork luncheon roll and polyethylene holding cell are both cylindrical in shape. However, the oven and electrodes are in reality rectangular so a mean radius based on the physical dimensions was used (see Zhang et al. 2004a for details). A sketch of the geometry is found in figure 1 and details of the sub-domains initial and boundary conditions in table 2.

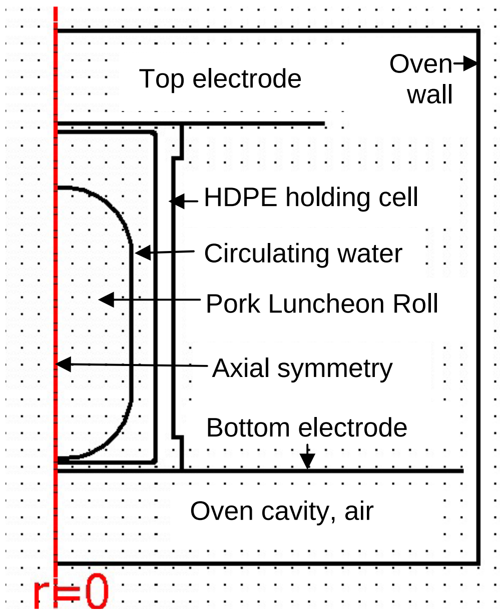

Figure 1. Model 2D axial symmetry

Table 2. Details of Comsol Model

Boundary Conditions, Electrical model
Oven wall: electric insulation
Top electrode: $V_{electrode}$-$V_{electrode}$*flc1hs(t-cook_time,0.1)
Bottom electrode: ground, V=0
Sub-domains (4) Oven Cavity (Air), holding cell (polyethylene), Circulating water, Pork Luncheon Roll
Initial Conditions: $V_{(t=0)} = 0$
Boundary conditions, Heat transfer model
Between the solid food and the circulating water: heat flux h=200W/m²K T_{inf} = 80ºC
Sub-domains (1) Pork Luncheon Roll
Initial Condition: $T_{(t=0)}$ = 20ºC

One boundary condition that should be noted is it that of the top electrode. In order to simulate the 2 minute holding time after the RF power has been shut off it is necessary to have a function that sets the electrode voltage to zero after 30 min, and allows the heat transfer calculation to continue. This was implemented using COMSOL's Heaviside function *flc1hs* which will be equal to one after a time delay. By using it in the following form:

$V_{electrode}$-$V_{electrode}$ × *flc1hs(t-cook_time,0.1)*

The voltage is initially at $V_{electrode}$ until *cook_time* has elapsed and the function goes to zero. The value of $V_{electrode}$ is determined by iteration until the appropriated power level is obtained (Marra et al. 2007).

In this calculation there were 4 sub-domains in the electrical model and but only the sub-domain, representing the PLR, was active in the heat transfer model. The mesh was refined until it had satisfactory spatial resolution and the solution was found to be independent of the mesh size. The time-dependent solver used was the direct (UMFPACK), solving for 2100s, relative tolerance 0.01 and absolute tolerance 0.001. The post processing data obtained include the temperature profiles in the PLR as well as ETP's calculated at positions corresponding to the thermocouple placements used by Zhang et al. (2004b). A sketch of their positions in the PLR is shown in figure 2.

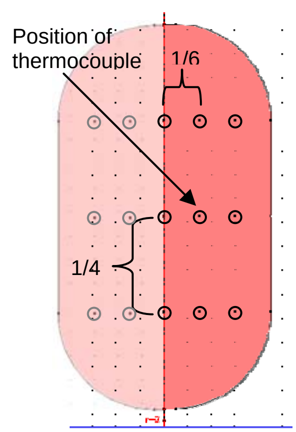

Figure 2. Positions of thermocouples for EPTs

6. Results and Discussion

Final temperature distributions in the simulated RF-cooking process are shown in figure 3 (top). The COMSOL simulation also finds that there is a cooler region in the lower half of the PLR (due to its higher density sinks to the bottom of the water filled holding tube) similar to that seen in EPT's from the experimental data from Zhang et al. (2004a). A contour plot generated from published data with a similar colour scale is shown in figure 3 (bottom).

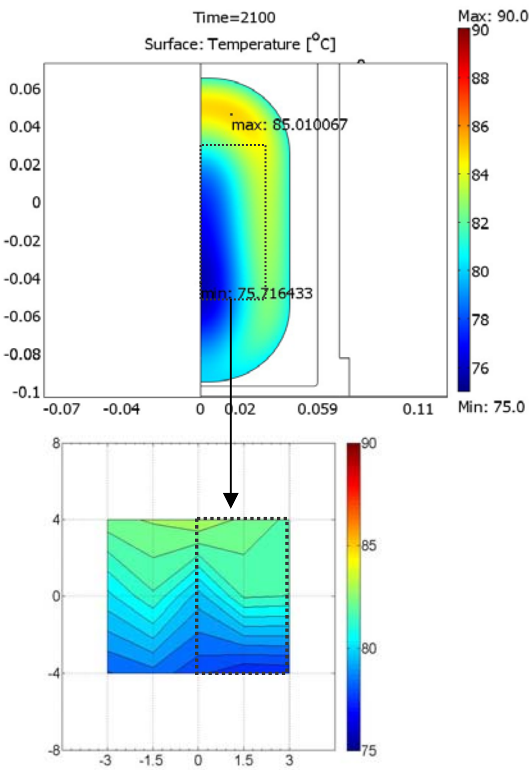

Figure 3. Final temperature distribution of simulated pork luncheon roll (top), and plotted end point temperatures. Dotted box shows equivalent regions of analysis.

EPT's at the same positions in the simulated PLR as those from measured data were extracted using COMSOLs point evaluation function. These are compared in tables 3 and 4, and the relative error at each of the ETP points for the data versus the simulated values is given in table 5. The final simulated temperatures showed rather good agreement with the published data having a mean relative error or 2.6% and the mean temperature over all the positions was differed by 0.3ºC. There are several sources of error and uncertainties in the model which can account for some of the discrepancy. The conditions in water bath are not well know, or if there were and "dead zones" in the holding cell (low flow rate), there could also be significant heat losses through the tubing system. It is also not known exactly how long it takes to load/unload the PLR before and after treatment. This will affect the starting temperature distribution as well as the effective holding time after the RF power is turned off, but before it is removed and loaded into the thermocouple jig to measure EPTs. A rough estimation of this additional time could be on the order a minute. Thermocouple jigs can also be difficult to align in products, thereby reducing spatial accuracy in temperature measurements. Another aspect is the "auto-tuning" function of the oven's RF power system. In these simulations we assume a constant electrode voltage, but the apparatus tries to maintain a constant power output. This also complicates the picture. However, despite these details there was still rather good agreement between simulated results and published data. Since this model is considered to reflect reality it could then be used to test different geometries to see if the heating process could be improved.

Table 3. Data EPTs

78.4	78.8	78.0	77.4	77.5
80.4	81.6	79.8	81.8	81.7
82.6	82.8	83.3	82.6	82.1

Mean: 80.6
CV%: 2.6%

Table 4. Simulated EPTs, PLR at bottom

82.2	78.5	76.1	78.5	82.2
83.0	79.2	76.7	79.2	83.0
84.1	82.1	80.4	82.1	84.1

Mean: 80.3
CV%: 3.3%

Table 5. Relative Error Data vs. Simulation

4.9%	0.3%	2.5%	1.5%	6.1%
3.2%	3.0%	3.9%	3.2%	1.6%
1.9%	0.9%	3.5%	0.6%	2.5%

Mean: 2.6%

It was hypothesized that the cold region was caused by the non-symmetric vertical position of the PLR in the holding cell. To test this hypothesis, the simulation was re-calculated but this time with the PLR positioned in the centre of the holding cell (see figure 4, and table 6). This simulation result had a higher mean temperature (83.4ºC vs. 80.3ºC for the bottom case), a lower coefficient of variation between the EPT points (2.5% vs. 3.3% for the bottom case) and had a lower span between the maximum and minimum temperatures in the PRL (6.0ºC vs. 9.3ºC for the bottom case).

Table 6. Simulated EPTs, PLR in centre

78.4	78.8	78.0	77.4	77.5
80.4	81.6	79.8	81.8	81.7
82.6	82.8	83.3	82.6	82.1

Mean: 83.4
CV%: 2.5%

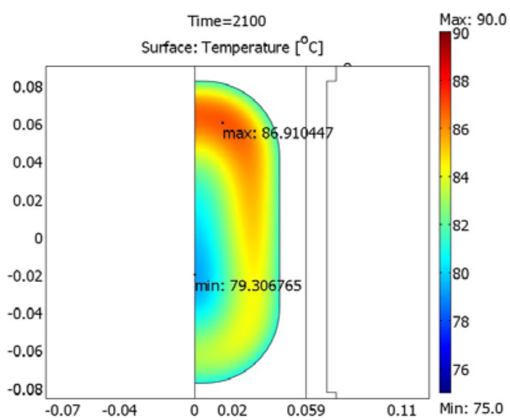

Figure 4. Final temperature distribution of simulated pork luncheon roll for the case when it is positioned in the centre of the holding cell.

In terms of sensitivity, the model output is of course affected by the level of the initial and boundary conditions, but the parameter which had the highest effect on the heating rate was the electrode voltage. This is of course no surprise since the electric filed is raised to the power two in the joule heating equation in heat generation term in the PLR. With more experimental data to verify the model, a more in-depth parametric study could be made to compare the effects of the various model inputs.

7. Conclusions

A radio frequency cooking process for a large meat product was modeled using the heat transfer module with a heat generation term describing the joule heating caused by the applied electric field. The dielectric and thermal properties were implemented as function of temperature to include the couple effects. The resulting simulation had good agreement with experimental end point temperature data from the literature, with a mean relative error of 2.6%. This model could be used to improve the process by testing different geometries and placement position of the food product within the RF oven. One example of a geometric improvement is centering the food in the holding cell. This simulated case had higher mean end point temperature and a smaller temperature difference in the sample. This type of modeling could be used to test different designs and holding cell geometries efficiently to reduce the amount of time consuming physical prototyping.

8. References

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9. Acknowledgements

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