MICRO-WAVE COOKING OF FOOD AND ITS SAFETY IMPLICATIONS

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1 Introduction

Micro-wave heating is a common means of cooking and preparing a foodstuff [3], [8] [2] [9] as being an important industrial process for heating materials such as ceramics. Whereas the physics of the latter process is well established (see [5]) and that of heating water easy to understand, the processes of heating foodstuffs by micro-wave radiation are as yet rather poorly understood and difficult to control. This is because the response of a foodstuff to the energy in a microwave field depends upon many factors such as its temperature, moisture content and salt content which depend critically on the heating process [2]. As a result the literature on micro-waving food is rather confused with poor agreement between theory and experiment. The micro-wave cooking process if not adequately controlled can easily result in a non-uniform heating of the foodstuff with a low core temperature, high surface temperature and a reduced energy transfer efficiency. As a consequence there are important safety implications with evidence for the survival of *Salmonella* and *Listeria* in food heated in a micro-wave oven [10], [1]. In this article we will very briefly describe the micro-wave heating process, consider the effect of a variable moisture and salt distribution and discuss the resulting safety issues.

2 Basic mechanisms

Consider a typical foodstuff. In a microwave oven this is irradiated with microwaves at a frequency of 2.5 GHz (wavelength of 12cm). The micro-waves penetrate the food, becoming attenuated as they do so. Heat is generated in the foodstuff by two mechanisms, ohmic heating and the excitation of dipoles. For foodstuffs such as potatoes or beef at normal cooking temperatures these two effects are roughly comparable. Heat is lost in the foodstuff through conduction, moisture transport and radiation at the surface.

3 A model for heating without moisture

A simple model for micro-wave heating which ignores the effects of moisture. is given in Marchant and Smythe [7]. Consider a simple one-dimensional material with an electro-magnetic field

$$E(x,t) = E_0 e^{i\omega t} f(x) \tag{3.1}$$

incident from the left. Such a field satisfies

$$E_{tt} + (\sigma E)_t = c^2 E_{xx} \quad \text{if} \quad x \geqslant 0, \tag{3.2}$$

where c is the speed of light in the foodstuff and $\sigma(x,T)$ is the conductivity which depends upon position x and temperature T. Provided that σ/ω is small then to a very good approximation

$$|E| = E_0 e^{-\int_0^x \sigma dx/2c}, \tag{3.3}$$

so that that the energy of the electro-magnetic wave is attenuated as it penetrates the foodstuff.

If σ is constant then

$$|E|^2 = |E_0|^2 e^{-x\sigma/c} = |E_0|^2 e^{-x/\delta} \tag{3.4}$$

where $\delta \equiv c/\sigma$ is the *penetration depth* of the foodstuff. This parameter plays a vital role in the effectiveness of the cooking process. However its value is known very imprecisely and depends upon the foodstuff. For mashed potato and beef, values given by Dolande and Datta [3] and Nykvist and Decareau [9] give $\delta \approx$ 7mm at a temperature of 80^oC which implies that most of the heating occurs at the surface, whereas the penetration depth for water is $\delta \approx$ 3cm giving much more uniform heating. Thus δ depends significantly upon the moisture content of the food. Note further that as the saline content of the food increases so does σ and hence δ decreases in this case. In contrast δ is relatively insensitive to the sugar content of the foodstuff.

In the absence of moisture the microwaves heat the foodstuff with heat loss due to conduction so that

$$c_T \rho T_t = (kT_x)_x + Q(x,t) \tag{3.5}$$

where ρ is density, c_T specific heat, k the thermal conductivity and Q the heating effect of the microwaves. The form of Q is given by

$$Q = (\alpha\sigma + \beta\varepsilon'')|E|^2 \tag{3.6}$$

where ε'' is the dielectric loss factor and α, β are constants. The two contributions to Q are due to ohmic heating and dipole polarisation respectively. Simple estimates of c_T, ρ and k combined with some experiments on baking potatoes in an oven, indicate that a typical diffusion time-scale for a potato is about one hour. Given that the time to microwave heat a potato is about 10 minutes, it is reasonable to first approximation to ignore diffusion in our models. In the absence of a varying moisture content the values of α, β, σ and ε'' are roughly independent of temperature for a typical foodstuff. Thus we have simply that

$$\frac{dT}{dt} = (c_T\rho)^{-1}(\alpha\sigma + \beta\varepsilon'')E_0^2\, e^{-\int_0^x \sigma dx/c}. \tag{3.7}$$

Thus

$$T = T_0 + t(c_T\rho)^{-1}(\alpha\sigma + \beta\varepsilon'')E_0^2\, e^{-\int_0^x \sigma dx/c}, \tag{3.8}$$

where T_0 is the initial temperature.

For σ constant and a penetration depth of $\delta=$ 7mm this predicts that for a potato of radius 5cm, there is a factor of $e^{-50/7} = 7.9 \times 10^{-4}$ difference between the rate of heating at the surface and at the interior. In particular this predicts that core temperature of the foodstuff will be significantly lower than the surface temperature. (Note that due to radiation loss at the surface, the hottest part of the foodstuff is, in general, slightly beneath the surface). Furthermore, the core temperature will drop rapidly if the penetration depth is reduced, say by the addition of NaCl. Experimental results reported in [2] and [9], in which the core temperature was measured using a thermocouple wire probe, confirm these conclusions. To see this, in Figure 3.1 we see a cross section of the temperature determined in [9] of a sample of roast beef cooked using micro-waves. In Figure 3.2 which is given in [2] we see the drastic reduction in the core temperature of a sample of mashed potato heated by micro-waves when salt is added in varying concentrations. Clearly the effect of conduction will be to produce a more uniform temperature distribution, but this will not be in general achieved in the times generally allowed for micro-wave cooking. (This is why it is often recommended that food cooked using micro-waves should be allowed to stand for a while before consumption).

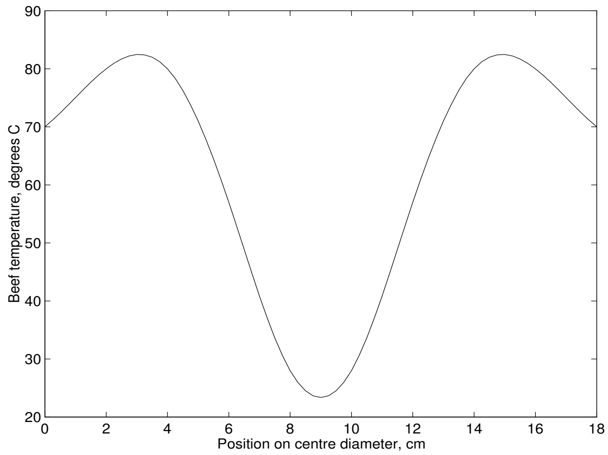

Figure 3.1: Cross section of the temperature of a sample of beef reported in [9] showing the reduction in core temperature.

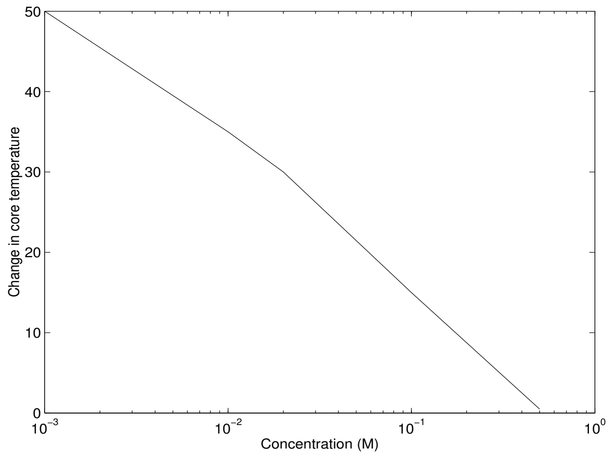

Figure 3.2: The reduction in the core temperature of a sample of mashed potato when salt is added, as reported in [2].

In [2] it was concluded that for foods with a high salt content *recommended heating times must be sufficiently increased to ensure that the core temperatures produced assure safety.*

4 Models which include moisture

In practice the core temperature also depends upon the moisture content of the foodstuff and heat transfer through convective processes. This gives a more even temperature distribution. Furthermore, as a material dries out during heating, its electrical conductivity reduces and hence the penetration depth of the microwaves increases. This process also acts to even out the temperature. A report on the effects of moisture on micro-wave heating is given in [11] with further modelling described in [4]. However, there is still a need for further modelling work to accurately couple the effects of moisture transport with heating.

In the model described in [4] the surface heating of the foodstuff rapidly raises the temperature of the moisture. This causes the foodstuff to dry out close to the surface and hence allows the micro-waves to 0 further. This in turn dries out the food at a greater allowing further penetration. The effect of this is to form a moisture front which moves into the foodstuff at a rate which could be estimated in terms of the thermo-physical and electrical properties (although the estimates were necessarily rather crude). In particular for moist foods (such as dough) the motion of the moisture acted to considerably enhance the heating process. In a carefully regulated dough product [11] the effect of moisture could be assessed relatively accurately, but in general the increase in temperature due to moisture transport is still very 0 to predict - with inherent safety implications

5 Conclusions

In the absence of moisture, the use of micro-waves over a short period of time to cook a foodstuff can result in wide temperature variations and, in particular, low core temperatures. These variations are much more significant if the foodstuff has a high salt content. As a consequence, bacteria may not be eliminated from the core of the foodstuff with a resulting safety risk. The inclusion of moisture transport predicts a more even distribution of heat, but the basic process of micro-wave heating is still very hard to predict. Much work still needs to be done in developing good predictive models for micro-wave cooking which will allow safe cooking times to be estimated accurately.

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