THE DYNAMIC BURNT-STRIPE EFFECT IN MICROWAVE HEATING

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A diametrical overheating of the central region of thin puck-shaped food items may occur in 2450 MHz microwave drying applications and then typically limits the processing speed. A primary cause is the diffractive co-called cold rim effect. But an additional set of microwave phenomena also occurs when moisture is transported outwards from the central area, then maintaining the moisture content in an outer zone. The burnt-stripe effect will thus not occur if there is only drying-out of the central zone.

1. Introduction

An overheating of the central region of thin puck-shaped food items such as potato chips, apple and banana slices occurs quite often in 2450 MHz microwave drying applications. The phenomenon is typically the factor that limits the speed of non-destructive drying. In so-called multimode systems, the overheated spot becomes symmetrical and the result is due to the cold rim effect [1;2] – see Figure 1, which shows the effect in diameter 30 mm banana "pucks".

But the overheated part may instead become a narrow diametrical zone; see Figure 2. This "additional" phenomenon occurs when liquid water is transported away from the centre region.

This presentation deals with investigations on what actually happens, by multiphysics modelling.

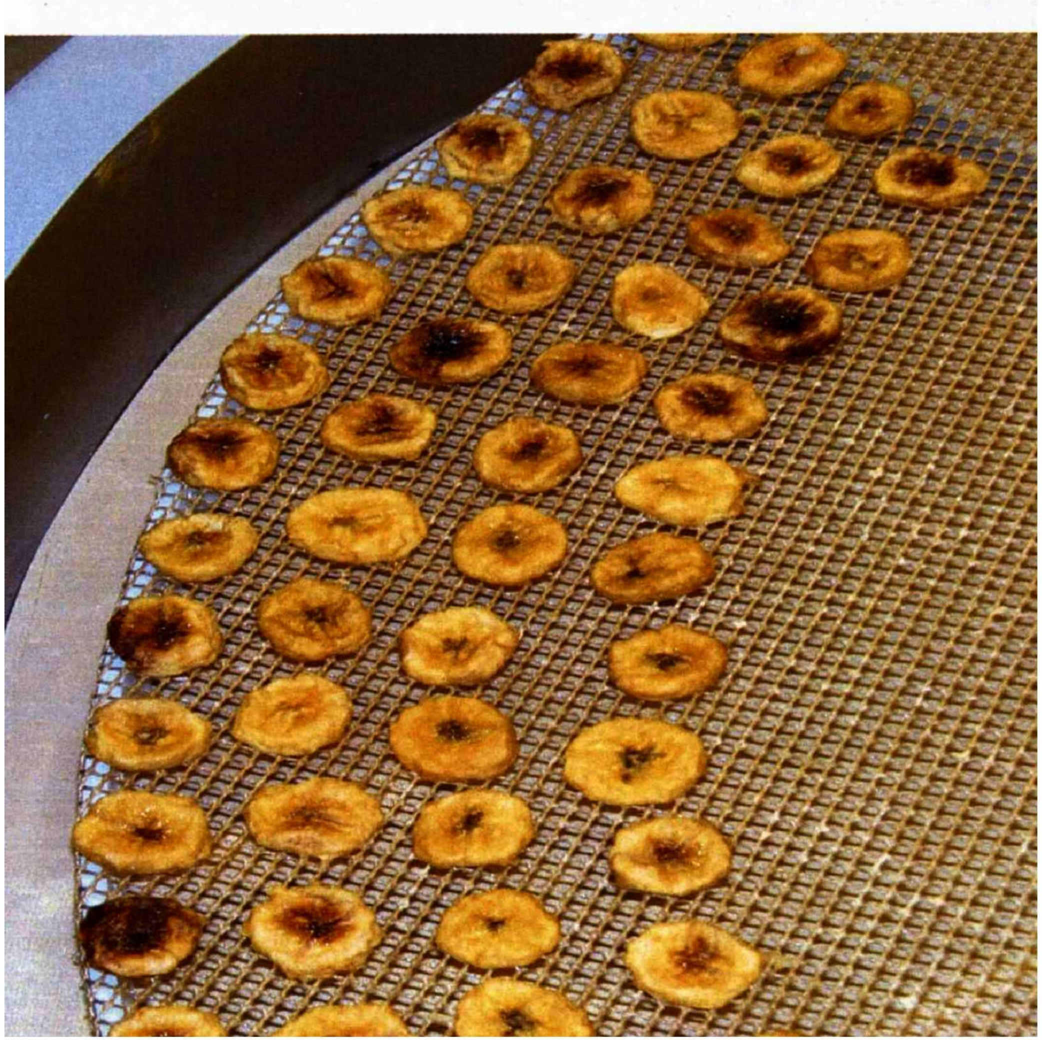


Figure 1

Diameter 30 mm banana cuts after microwave drying at 2450 MHz

Figure 2

Diameter 35 mm potato cuts after microwave drying at 2450 MHz

2. The cold rim effect

The cold rim effect is strong for thin semidry loads with radii less than about 35 mm (at 2450 MHz), which thus get a centre heating that cannot be modified much by the design of the microwave heating system. Qualitatively, the effect is caused by two phenomena [1;2]. The first occurs where the electric field component is parallel with the rim. Since this is curved, a depletion of the coupled horizontal electric field occurs at the rim, as the induced currents will follow the shortest paths. The second phenomenon occurs where the electric field is perpendicular to the rim. Due to the propagation slow-down, this external field will remain perpendicular around the rim surface in this region, and thus become weakened by approximately a factor ε' inside the object.

Numerical modelling has been used to compute the power density patterns in four pucks, each 30 mm in diameter and 10 mm in height, irradiated by a free space TM-polarised plane wave from the right; see Figure 3.

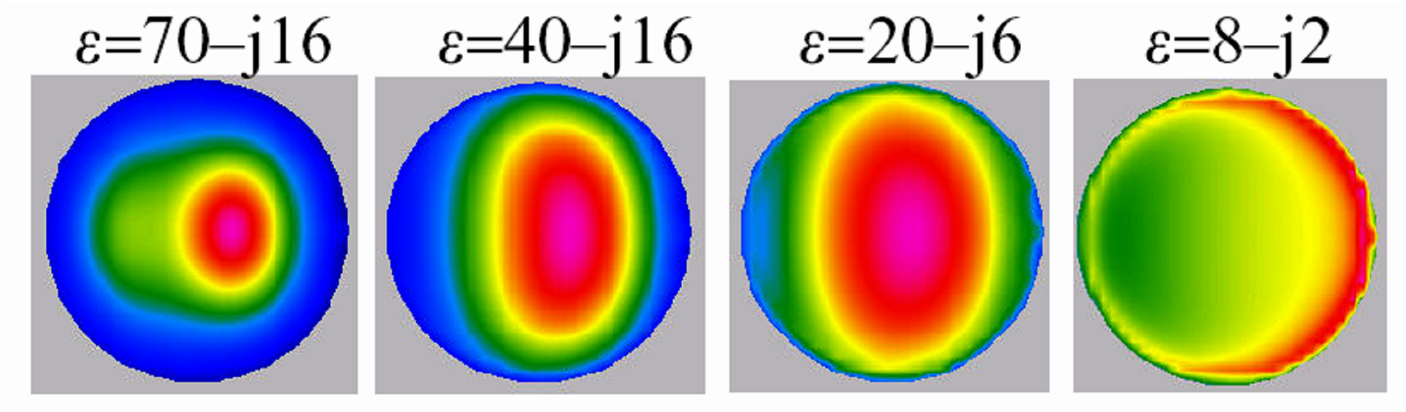


Figure 3. Modelled power density pattern near the top surface of diameter 30 mm height 10 mm pucks (ε given above), irradiated by TM-polarised 82° incidence angle free space plane waves from the left. Instantaneous energy pulse.

3. Introducing the changes of complex permittivity with water content (enthalpy)

If the variations of complex permittivity with dryness is known, one may also calculate the enthalpy steps between permittivity steps, and construct a table – see Figure 4 below.
The basic permittivity data are from SIK in Sweden, and refinements were made by me.

banana.pmo

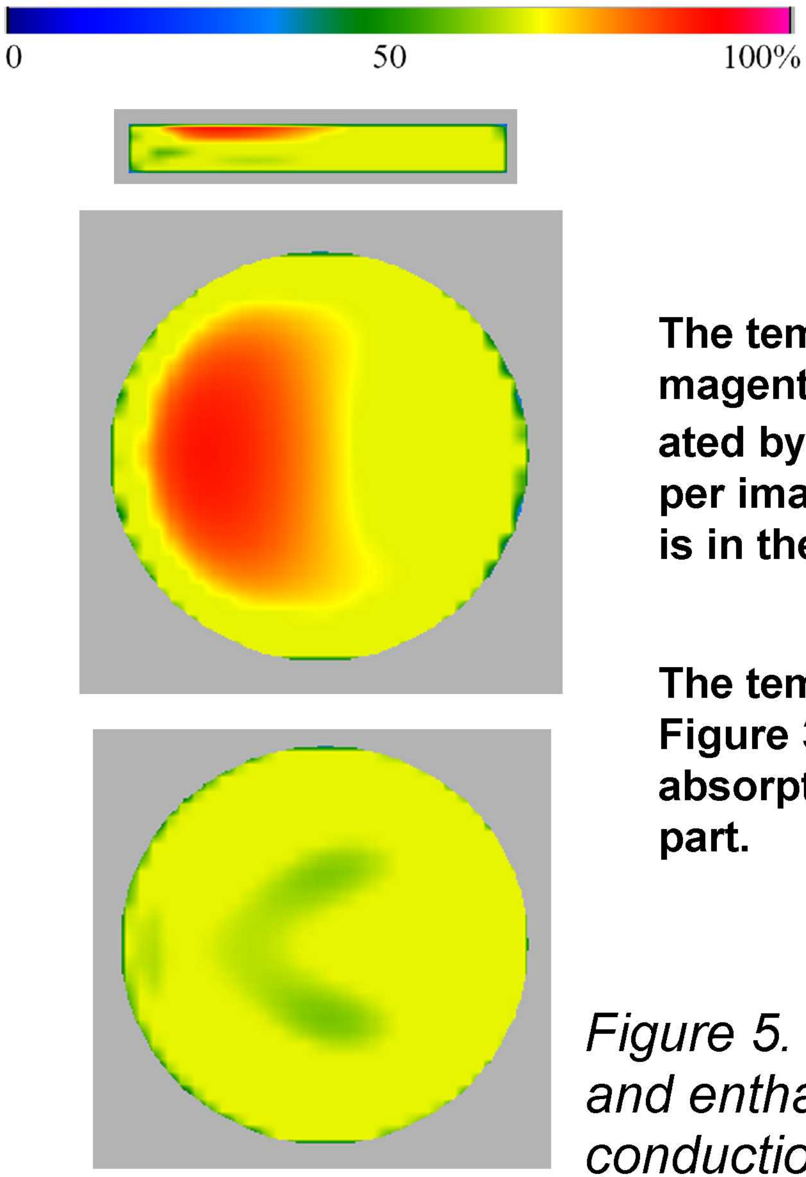
```
# Banana draft media file for QW-BHM module 071125 POR;
# Measurements & data by SIK/PF & POR 070914 & 071127
# DATA FROM 20 C to thermal destruction, dH/dV in J/cm3, no specheat&density
# columns,| reversedEnth/Temp column
!Temperature    Enthalpy        EPa             SIGa
# Data deg C    J/cm3                           S/m
20              0               59.3            3.57
50              99              55              3.41
60              243             52.5            3.20
60              467             41              2.86
60              691             30              2.04
60              803             26.3            1.66
60              915             21.9            1.23
65              1033            17.4            0.76
70              1151            13.8            0.41
75              1268            12.1            0.28
80              1385            10.4            0.14
85              1501            8.8             0.06
90              1617            7.5             0.03
90              1733            6.8             0.02
90              1755            6.3             0.02
90              1778            5.7             0.014
100             1894            4.5             0.014
110             2014            3.7             0.02
120             2068            3.7             0.04
130             2180            4               0.14
200             6               6               0.41
```

Figure 4. Measured and calculated dielectric data for banana, at 2450 MHz

Since the relaxation and ionic behaviour is not known, and the modelling is at a fixed frequency, SIGa (conductivity σ) is used instead of the loss factor ε''.

Investigative measurement results have been used to estimate the properties above 100 °C: ε' does not change much initially but in-creases due to charring; ε'' then increases sharply. The enthalpy entry at 200 °C is just for practical viewing of the resulting modelled data.

4. Modelling results (using the Quickwave™ BHM module)

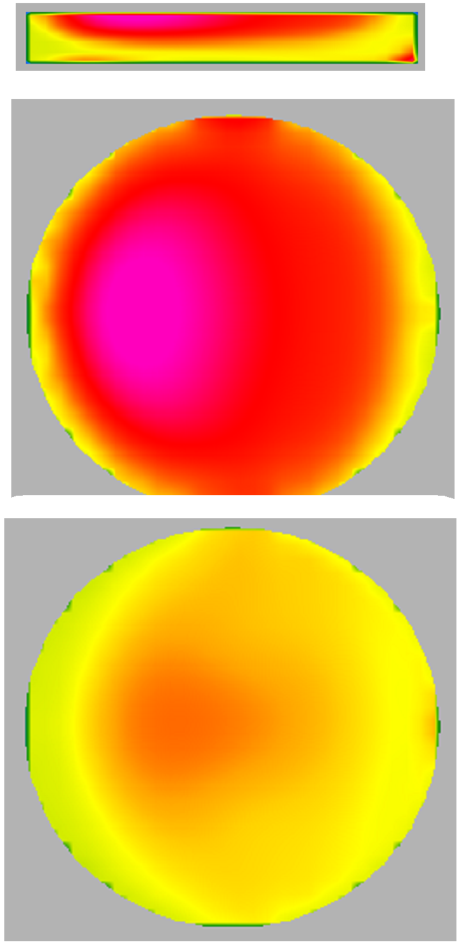


The temperature scale is: about 20 °C = dark blue; about 80 °C = magenta. The diameter 30 mm and 4 mm thick “puck” is irradiated by a plane wave (θ = 82°) from the left, in free space. The upper image is in the central cross section, the image just below that is in the top region, and the lowest image is in the centreplane.

The temperature becomes much more even than what is shown in Figure 3. The reason is of course the negative feedback by less absorption capability in an already drier part, to a still more moist part.

Figure 5. Modelled final temperature, with the permittivity (ε) and enthalpy (H) variations. 20 energy pulses; no heat conduction.

5. Modelling results (using the Quickwave™ BHM module AND heat conduction (HFE) module)



The heat conductivity is set to 0,007 W/(cm,K), with no heat exchange with ambient. The temperature scale is the same as in Figure 5: about 20 °C = dark blue; about 80 °C = magenta. The total heating time is set to about 40 seconds.

It is seen that the final temperature is now higher than in Figure 5. Reasons are that the hottest regions will be cooled down by surrounding colder areas, leading to an overall higher microwave absorption in a “middle time interval”. An additional explanation may be that the total (integrated) microwave absorption capability is reduced if any part gets a low ε' – by an effectively smaller electric diameter – which occurs to a lesser extent with heat conduction from the hottest regions.

Figure 6. Modelled heating pattern, with the ε and H variations, plus heat conduction. 20 energy pulses during 40 seconds; same impinging total energy as in Fig. 5.

6. Water transport in microwave drying

The left Figure 7 below shows the main phases of drying, as function of increasing mean moisture content (from [3]). – The right figure shows the same, but now with time in the +*x* direction, showing the actual process behaviour, in order to assist in the qualitative understanding.

It seems to be commonly agreed that the first phase is one of liquid movement, followed by a phase characterised by evaporation being the dominant phenomenon. Of course, the boundary in time and moisture content varies greatly among different materials. The water mobility is crucial.

This principle of successive phenomena has been applied here – see the next section.

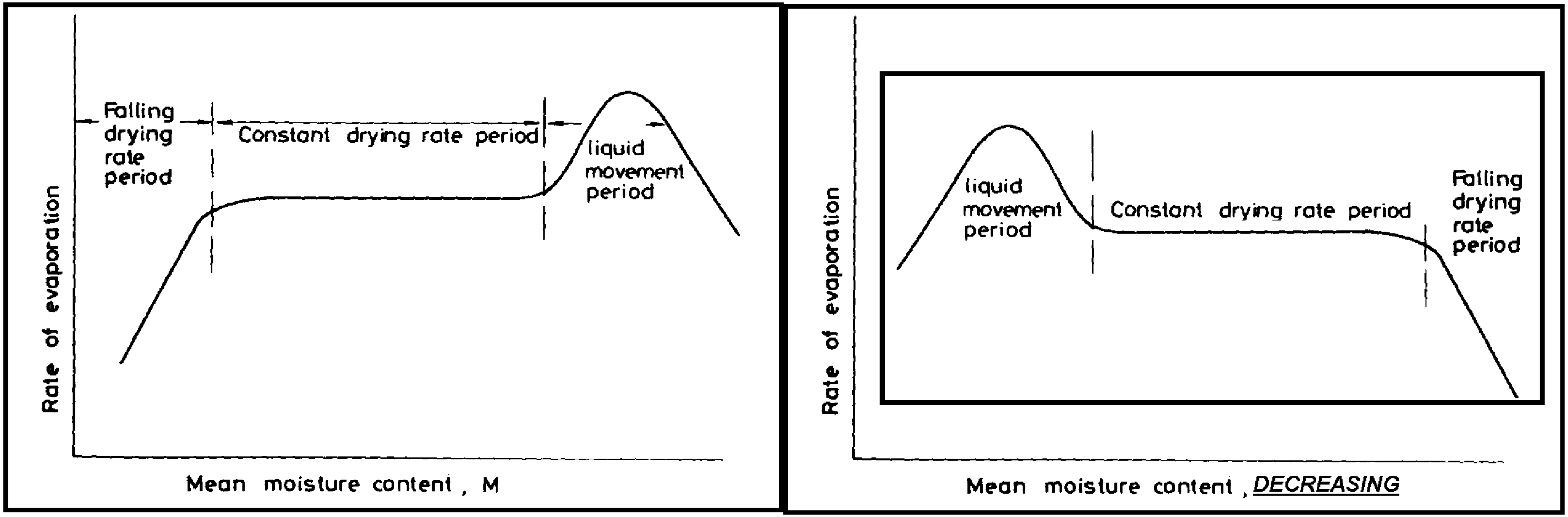


Figure 7. Main phases of microwave drying. Left: from [3]; right: the figure mirrored.

7. The burnt stripe effect – 1

The images in Figures 5 and 6 indicate that there will be a quite even drying-out if the water just evaporates perpendicularly outwards from the circular surfaces. The particular amplification of the heating in a typical small centre as in Figure 1 – and in particular the narrow diametrical zone as shown in Figure 2 – cannot be deduced by this approach.

The burnt stripe effect is indeed a runaway phenomenon, where an already dried-out region absorbs additional power so a burnt region is created.

It is concluded that liquid water transport is necessary for the effect to occur, since a maintained high peripheral moisture content is needed.

Actually, the phenomenon has several similarities to the three-dimensional potato fire effect: a single raw potato of about 80 to 130 g will start smoking in less than about 7 minutes in *any* household microwave oven. Again, the water driven away from the centre by the external resonance exploding egg effect [2] results in a combustible dry centre residue, which is further heated into pyrolysis by the surrounding still wet parts of the potato maintaining the field focusing to the centre.

This moisture depletion is then driven by the cold rim effect, as seen in Figure 3: there is a tendency to overheating in the centre region and liquid water will then move radially outwards before – or dominating over – moisture evaporation from the circular surface. The overall surface will initially remain cooled by the relative large amount of liquid water available for evaporation and also available for transport radially outwards, driven by the radial temperature gradient that is developed by the more intense centre heating.

7. The burnt stripe effect – 2

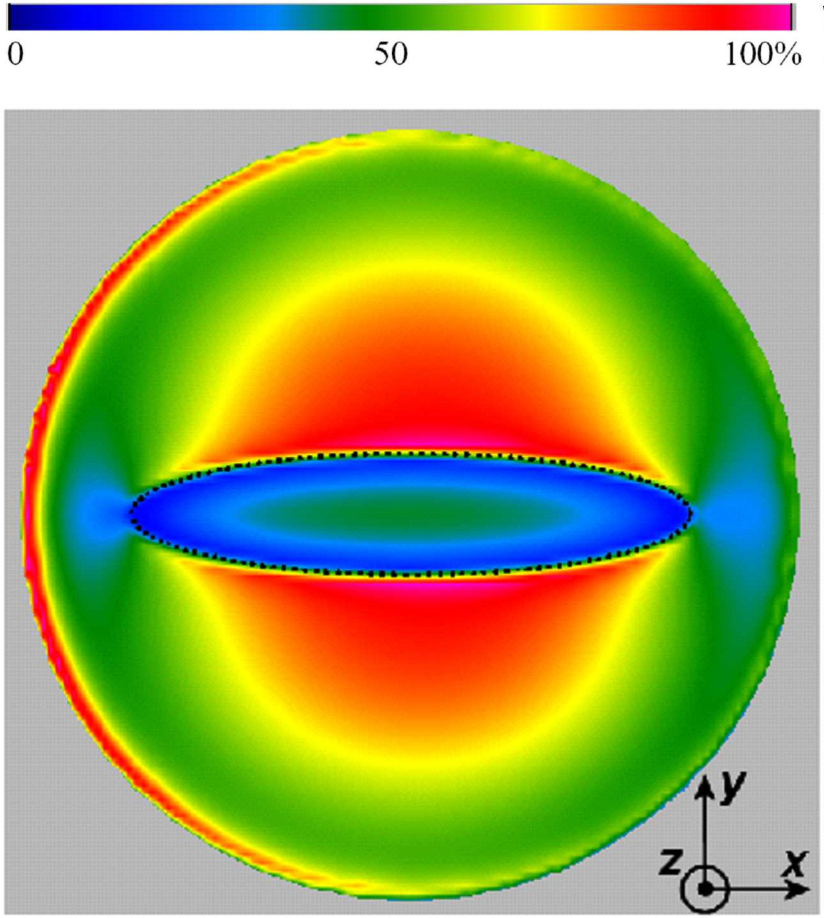


Figure 8. Modelled heating pattern in a diameter 24 mm thin high-ε load with a central inclusion of a low-ε load, under TM-polarised 82° incidence from the

What happens is illustrated in the numerical modelling scenario in Figure 8. This shows a circular 24 mm diameter thin flat potato chip at 100 °C. Its permittivity ε is 50–j16 throughout, except in a (marked) elliptical inclusion with axes 18 and 4 mm, representing a partially depleted region with permittivity ε =8–j1,6. As in Figure 3, the magnetic source field is thus *y*-directed and the main current *x*-directed; the dominating electric field is *z*-directed.

The resulting sharp heating gradients cause the boundary between the outer relatively moist and the inner drier region to become relatively constant, while the inner region continues to dry out. The resulting narrow regions are clearly seen in the figure. That an intense centre heating (green colour) occurs is of particular importance.

7. The burnt stripe effect – 3

The following phenomena can be distinguished:

- There is a heating (and thus current) concentration in the high-ε part close to the low-ε area. This is due to the current following the shortest path with high ε. The boundary is concave and not convex as is the case with the cold rim effect.
- There is a significant heating in the centre region of the low-ε area. This is due to direct action by the strong external *z*-directed electric field. The phenomenon is amplified by the fact that the load is thin. It is to be noted that the heating intensity in the centre is quite strong and will indeed cause overheating, in consideration of the limited amount of remaining water for evaporative cooling of this semidry region.
- There is a significant heating intensity minimum just inside the low-ε area boundary. This is a result of the *z*-directed electric field being almost short-circuited there, by the high-ε area nearby.

References

[1] Risman, P. O. *Puddles and droplets – an investigation of their influences on microwave system performance*, IMPI symposium, Vancouver Canada, 2007.

[2] Risman, P. O. “Advanced topics in microwave heating uniformity”, chapter 3 in *Development of pack-aging and products for microwave ovens* (M. Lorence and P. Pesheck, ed.), Woodhead Publishing (UK), 2009.

[3] Metaxas A.C. and Meredith R.J. *Industrial microwave heating.* Peter Peregrinus Ltd, UK, 1983.