Modelling and Designing of Industrial Microwave Aplicators
Theoretical and Practical Approaches

by
Serge Lefeuvre, professeur émérite, INP-Toulouse(France)
Manager of Creawave SARL
Ali Oktay, professeur, Uludag University-Bursa(Turkey)

Introduction

Microwave applicators are pieces of equipment, such as dryers, used in chemical engineering processes to increase the quality of a production line. It could be to shorten the time, to get a better quality of the material, to facilitate the process control, …

These equipments are usually more expensive than the usual ones. This is due to the investments in microwave equipments but also to the usual ones which need to be modified. For instance, microwave dryer are usually ten times faster than the normal ones, this implies that the air flow, necessary to evacuate the vapour, must be ten times more powerful.

These racing equipments have to be designed as carefully and accurately as possible, and for designing, it is important to keep in mind that the material under process is always modifying its physical and chemical parameters.

The first step is to understand the behaviour of the material all along the process by the necessary measurements performed on appropriate samples. In fact, the size and the shape of the sample have to be appropriate to the expected knowledge of its thermal and electrical properties.

Some Aspects of Microwave Applicators

The quality of microwave applicators can be quantified in terms of its ability to provide a uniform temperature distribution in the workload. Industrial microwave applicators (ovens) may be designed with several microwave sources (magnetrons), each supplying one ore more applicators. For simple types of applicator, such as single mode resonant cavities, it may be possible to predict analytically the field distribution and therefore the temperature distribution. For inhomogeneously loaded multimode cavities, however, it is necessary to resort to numerical techniques. There are many different techniques that have been used to solve Maxwell's Equations in three dimension.

Microwave heating analysis requires the unification of several analytic models, wave theory for electromagnetic power absorption, convection and diffusion for thermal motion, mass transport for particle motion, and thermal analysis of materials changing state. Generally, analytically determining the temperature and field distribution inside an inhomogeneous material is nearly impossible. Practically some geometries of applicators are constructed to increase energy absorbtion at specific locations. Figure 1 plots regions of maximal and minimal temperature growth in a lossy cylinder.

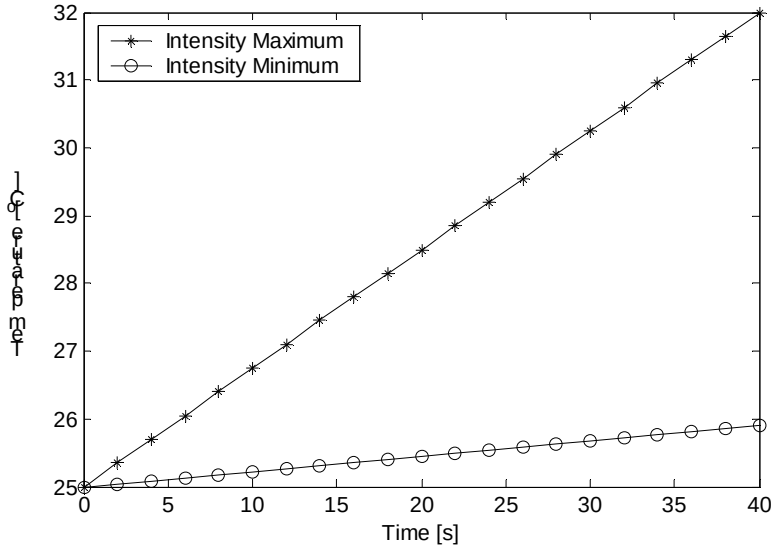

Fig. 1. microwave heating at field maxima and minima in a cylinder.

The loss power is determined from the equation,

$$P_L = \frac{\sigma}{2}\iiint_V \left|\vec{E}\right|^2 dV$$

where $\vec{E}$ is the complex electric field inside the material and $\sigma = \omega\varepsilon''$ is the effective conductivity of the material.

For an inhomogeneous material, the wave equation can be write as follow,

$$\nabla\times\nabla\times\vec{E} - \omega^2\varepsilon(\vec{r},t)\mu\vec{E} = j\omega\mu\vec{J}$$

The complex permittivity [$\varepsilon(\vec{r},t) = \varepsilon'(\vec{r},t) - j\varepsilon''(\vec{r},t)$] is a function of both position and time.

The temperature change representing stored energy due to microwave heating can be modelled with the following equation,

$$\frac{\partial T}{\partial t} = \frac{\omega\varepsilon_o\varepsilon'' E^2}{2C\rho_o}$$

where C is the specific heat and ρ_o is the density.

Additionally, the dielectric constant is dependent on the temperature and frequency. For example, the complex permittivity of a composite ceramic can be formulate practically by the following expression at (T = 25 ^oC) :

$$\varepsilon_o = 3.9 + j0.46 \ (F/m)$$
$$\varepsilon = \varepsilon_o + 0.0001(T-25) + j0.001(T-25)$$

Permittivity measurements in low field of an heterogeneous sample.

Let us start with the permittivity measurement of the wet sample of plaster shown on fig.2.

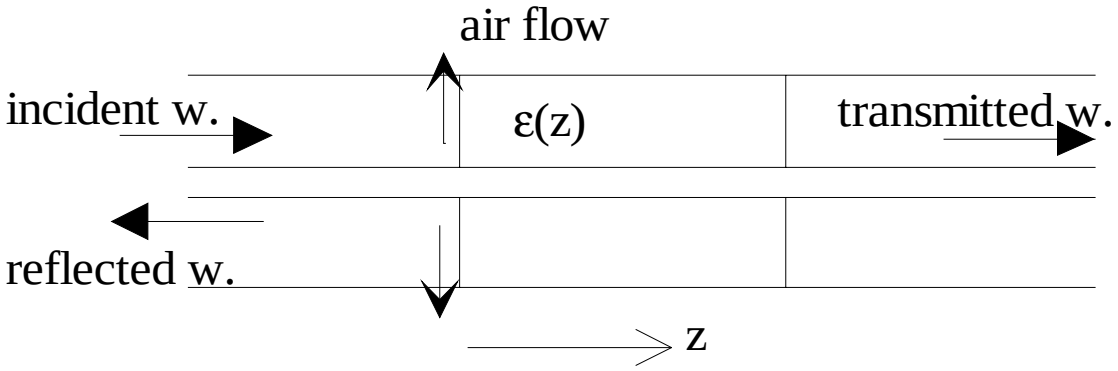

Fig. 2. Permittivity measurement of a sample(plaster)

The heterogeneity is produced by the drying of the sample, which is included into a coaxial line with an axis symmetry. The hot air, issued from the hollow inside conductor, leaps the input face of the sample and is extracted through the outside conductor. Because there is no extraction of water from the lateral surface (but just by the input face) it is not unreasonable to assume that the permittivity ε is a function of the depth z only. Moreover all the equipment is isolated to prevent from thermal exchanges. The microwave are just used as sensors to scan the sample.

With this assumption the profile of permittivity is extracted from the measurement of the reflection coefficient Γ(ω) or of the transmission coefficient T(ω), or both. The frequency bandwidth has to be chosen carefully, depending of the size of the coaxial line, of the width and the moisture of the sample. Outside the sample, as well as inside, just TEM modes are excited and propagates, i.e. the scalar product $\vec{E}\,\vec{g}\vec{e}$ is zero and the wave equation looks like the homogeneous case.

To extract $\sum_i (T_{measured}(w_i) - T_{computed}(w_i))^2$, the sample is divided into numerous slabs in which a_0, a_1, a_2, a_3 ε is supposed constant to use a matrix decomposition and the function $e(z)$ is supposed to be under the form $e(z) = \sum_N a_n z^n$ which is rather smooth and can be easily fitted to a drying profile. The coefficients a_n are a complex numbers and N=4 (that is a 3rd degree polynome) is large enough to give a useful representation.

The set of the a_n (i.e. a_0, a_1, a_2, a_3) is computed by minimizing a least square coefficient, for instance : $\sum_i (T_{measured}(w_i) - T_{computed}(w_i))^2$.

It is important, to try to avoid errors, to choose the bandwidth of ω so that the permittivity of the wet and homogeneous sample is not a function of ω. In this case the bandwidth was 13GHz to 17 GHz.

Fig. 3 gives an example of the permittivity computed inside the sample and during the drying.

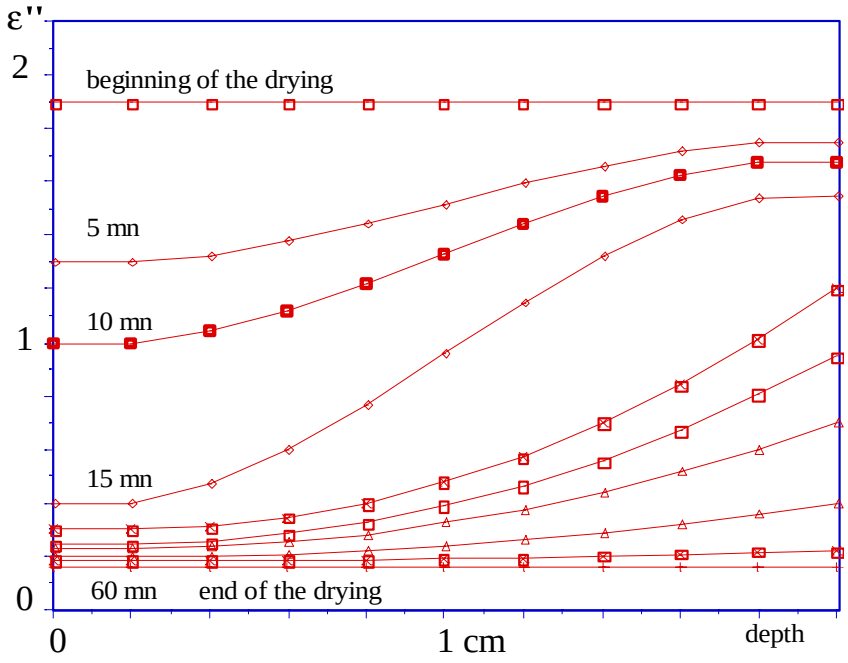

Fig.3. Evolution of the permittivity inside the sample(plaster)

The computation is highly simplified because the starting value of the homogeneous sample is accurately known. But it is clear that these measurements do not give any behaviour of the moisture inside de plaster. We can just imagine that the distributions are not too far from each other.

Permittivity measurements in high field of an heterogeneous sample.

High fields introduce drastic modifications to the measurement methods. Since the wave must heat, it is impossible to let it escape somewhere. In fact, it is necessary to work in a close cavity exactly as in an applicator. As a consequence it is no more possible to sweep the frequency to get more information. One way is to scan the diffracted field inside the cavity and to try to rebuild the permittivity distribution.

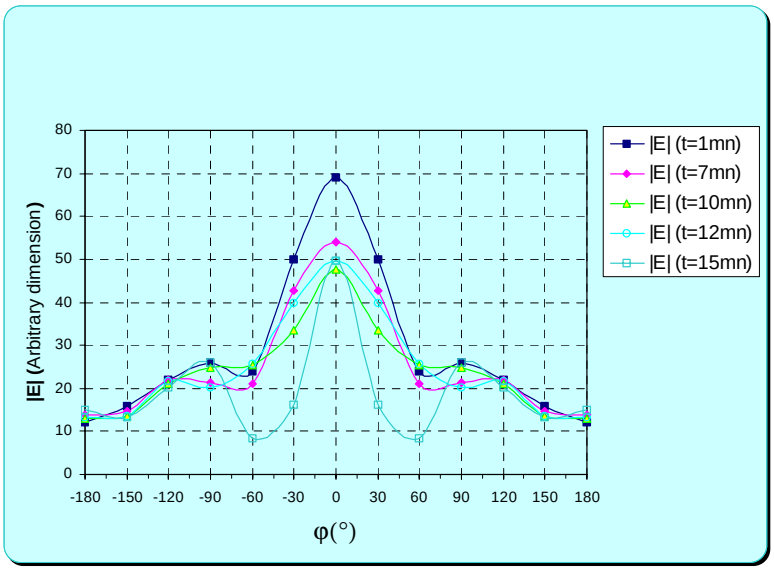

Fig.4. Diffracted electric field around a cylindrical sample

Fig.4 gives an example of the diffracted electric field measured all around a cylindrical sample located in a cylindrical cavity as shown on fig. 5.

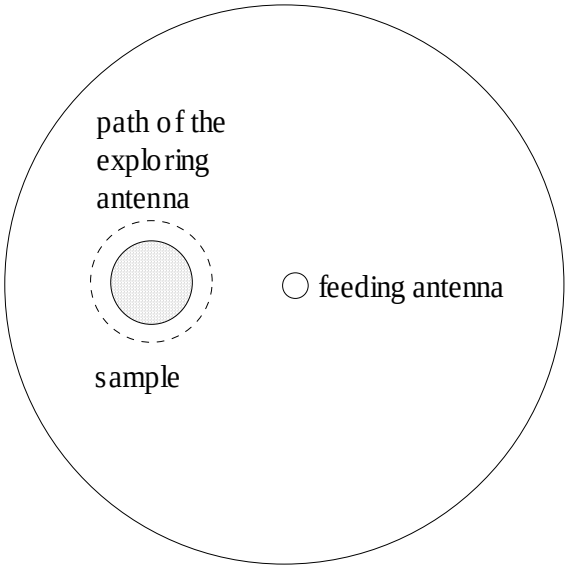

Fig.5.-transverse section of a cylindrical applicator

The experimental results show the great importance of the surroundings on the diffraction (for instance there is a weak and almost constant field in the shadow part). To overtake these difficulties, one possibility is to rotate the sample and assume an exponential penetration of the power, in this case of the form : $P_s I_0(ar)$, where P_s is the power density (computed with the initial value of the permittivity), I_0 the Bessel function of 2nd kind and a a parameter which has to be determined by measuring the absorbed power by :

$$P_{absorbed} = 2\pi P_s \int_0^a r\, I_0(\alpha r)\, dr$$

For instance, in the case of a sample of PVC (diameter=1cm), a (in cm^{-1} and after 1mn) is given by fig.6.

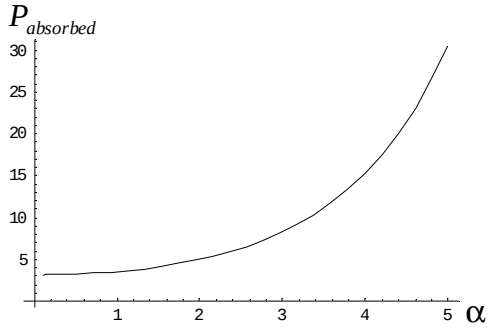

Fig.6. Absorbed power by the PVC rod

This result introduces an other way of modelling : the value of the permittivity is not always useful to design an applicator, the penetration depth of the power (that is of the chemical transformation) is sufficient.
Nevertheless it is possible to use a cavity with a better matching to the polymerisation measurements.

Let us start again with a cylindrical cavity fed in its axis and with a sample close to a flat metallic base.

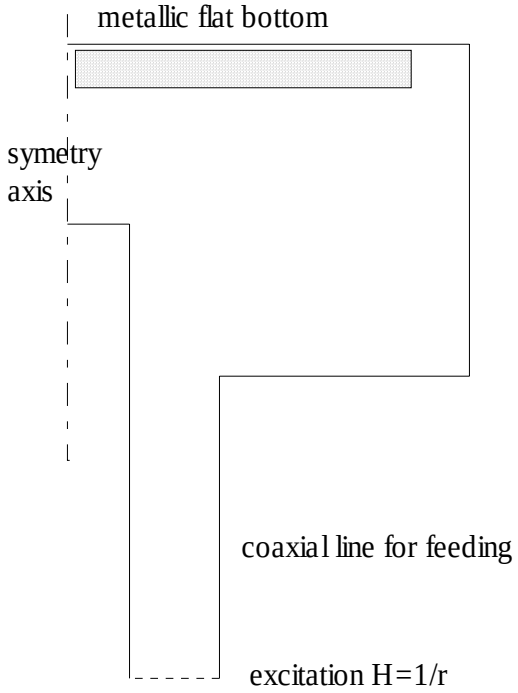

Fig.7. Semi-section view of a cylindrical applicator

In the symmetric case, the driving function is H which has just one component which is in the theta direction. The wave equation is the following :

$$\vec{\nabla} \times (r \vec{\nabla} H) + (k_0^2 r \varepsilon - \frac{1}{r}) H = \frac{\vec{\nabla} \varepsilon \times \vec{\nabla} r H}{\varepsilon}$$

The variation of permittivity during the curing is introduced has the second member in view of iterative solutions. Fig.8 gives a FEM-Matlab technical solution.

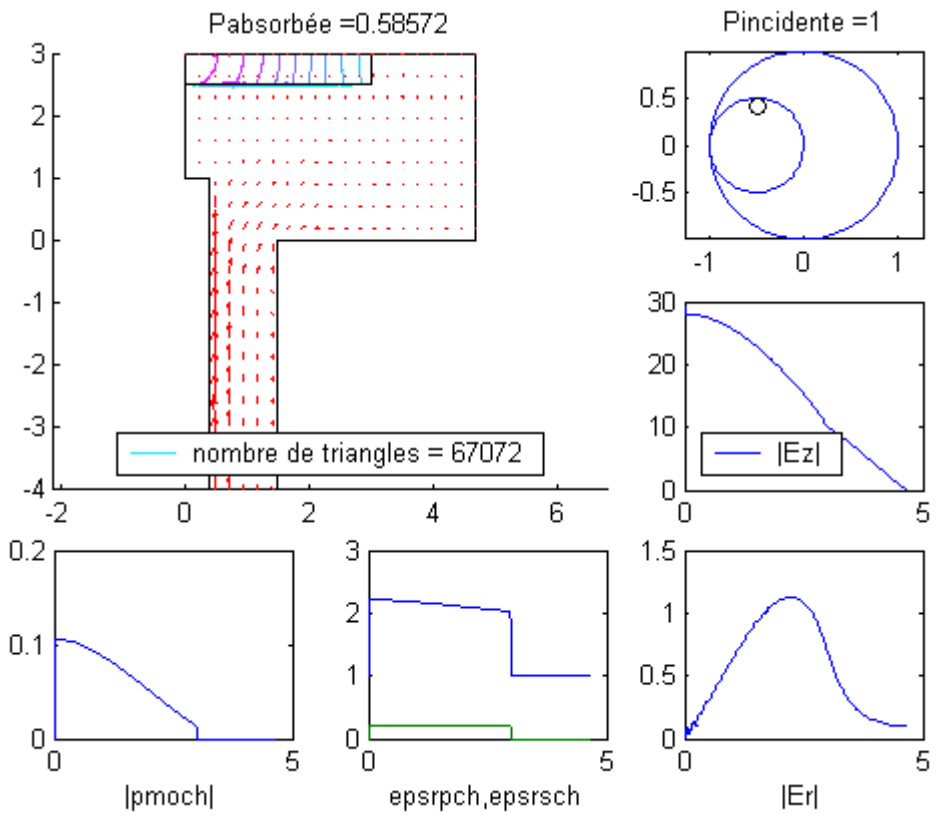

Fig.8. Variation of some physical values inside the applicator

During the different iteration, ε is looked for following the assumption :

$$e_{t+1} = e_t + a \ localpower_t / totalpower_t$$

t is the time. α is computed to get a regular curve between two consecutive experimental steps as shown on fig.9.

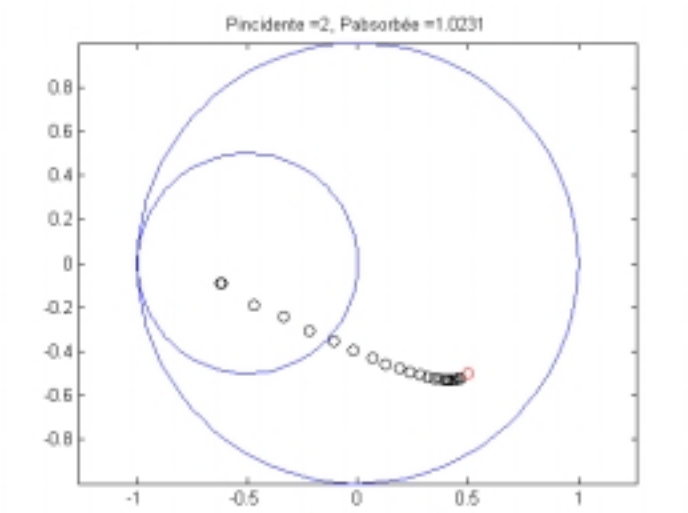

Fig.9. Variation of the constant “a” on Smith chart

Remarks and conclusion

- The accuracy of permittivity measurements in low fields of homogeneous sample is highly increased by using modelling methods. By that way, the field distribution inside the sample is perfectly known and there is no more reason to use old methods, for instance the perturbation method. The same remark remains valid in the case of an heterogeneity in only one direction, as shown in the case of a coaxial line.

- The knowledge of the permittivity gives just a small indication on the chemical reaction itself. It is necessary to correlate this information with chemical and physical measurements. Unfortunately it is often impossible to perform simultaneous measurements because the size of the samples must be matched to each measuring apparatus. As a consequence the knowledge of the influence of the microwave power on such or such reaction needs a long cooperative action.

- Many materials heated in microwave have a low thermal conductivity which can be neglected In that case, the heat equation takes the form :

$$\frac{\partial}{\partial t}(\rho C T) = P_{mW}$$

$$d(\rho C T) = P_{mW}\, dt$$

or

$$d(\rho C T) = P_{mW}\, dt$$

which equals the microwave energy dissipated during the time *dt* and used to transform the material. In the past years, a lot of questions raised in the international community on the meaning of the temperature T in microwave. In fact there is no difficulties to measure the total power but the temperature measurements are not obvious because any thermometer needs a rather large contact surface and time to get an equilibrium. More, the meaning of the temperature itself was unclear because the relaxation due to the shocks can be unable to get a rapid local thermal equilibrium. Now it is admitted that the word temperature keeps the same meaning it has in thermodynamics but the gradients inside the sample can be very high mainly in the case of heterogeneous reactions.

- The microwave energy initiate the chemical reaction which can be exothermic or endothermic but in both cases which continues its behaviour by itself with or without microwaves. During the experiments, it is important to carefully follow the time in order to be able to compare different results, that is the case for instance in the experiments reported on fig. 4 and 7.

- Finally, is it so important to know the permittivity. It is clear that without permittivity there is no modelling. But it remains that in many cases the answer is no because it is impossible to shape physically the computed fields. For instance in poly-condensation of PVC the use of a metallic mould prevents to use microwave but in that case, the mould itself is heated through a ferrite susceptor.

Modelling of large applicators

Let us assume the design of an industrial dryer of hide. To fix the ideas this dryer could have a rough scheme as shown of fig.10.

The air area is separated from the microwave one by a sheet of prolypropylene or any material transparent to the wave. The aim is to prevent wet air from disturbing the microwave devices and to keep the air close to the hide in order to increase the efficiency. The hot air flows inside and outside through metallic grids to prevent waves from escaping. The hide itself is under mechanical tension to avoid shrinkage.

The design of the main figures on energy is an important point in the strategy of the drier.

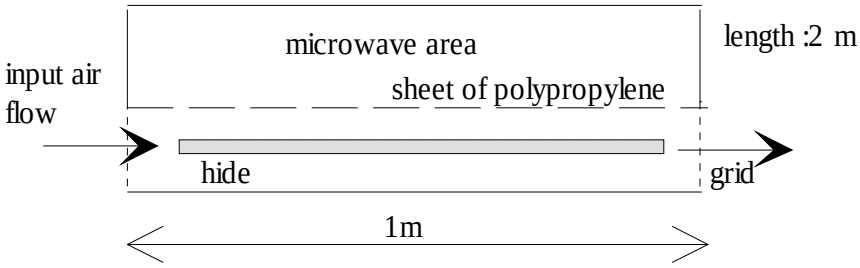

Fig.10. Schematical description of an industrial dryer

These figures are strongly correlated to the drying velocity and to the mass of water to be extracted. It is obvious that in a classical dryer, there is no microwave at all. The duration of the drying is in the order of half an hour may-be more. Microwaves are supposed to shorten in the order of some minutes. The shortest time is limited by the quality of the product and by the introduction of the dryer into the production line.

If the objective is to shorten the time, that means that the diffusion process does not help the homogeneity of the process. The best way is to use air just to carry the vapour and to use the microwaves just to produce this vapour. And roughly speaking, the following scheme gives the possibility of a 1kW magnetron :

$$2kW_{50Hz} \xrightarrow{efficiency\ 50\%} \begin{cases} 1kW_{2.45GHz} \rightarrow 20g/mn \\ 1kW_{hot\ air} \rightarrow 1m^3/mn\ 40°C \end{cases}$$

As a result, the unit of microwave power is 1kW which is well match to cure $.5 \times .5m^2$ which becomes the unit of hide surface.

Now, the modelling will deal just with this unit of hide. What can be expected from the microwave modelling ? Mainly the shape of moving antennas able to deposit a uniform mean value of energy with an appropriate speed of displacement. Fig.11 gives an academic example of the results produced by the modelling.

The left part gives the absorbed power together with the Poynting vector flux. The right part shows the Smith chart and graphs of the energy, which is more or less the temperature graphs. When the antenna oscillate from left to right, the repartition of energy changes. The time in each position can be adjusted in order to get an acceptable mean value repartition as shown of fig.12.

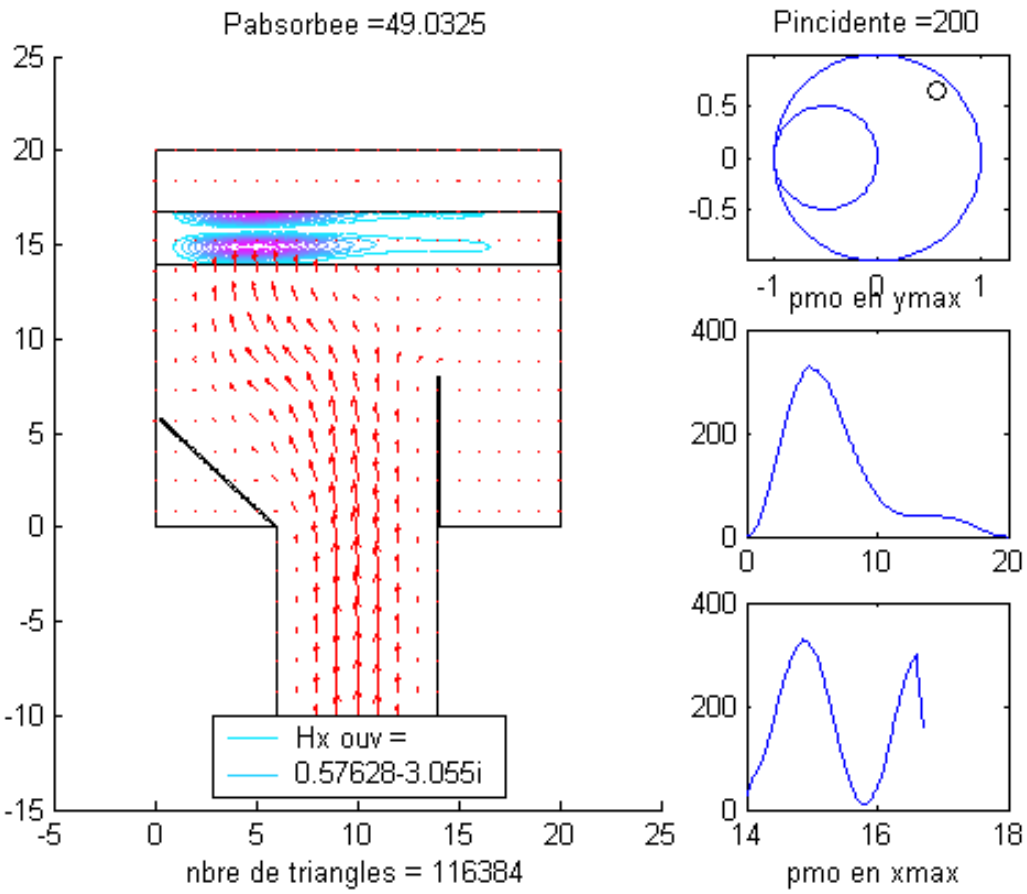

Fig.11. Typical case of the applicator

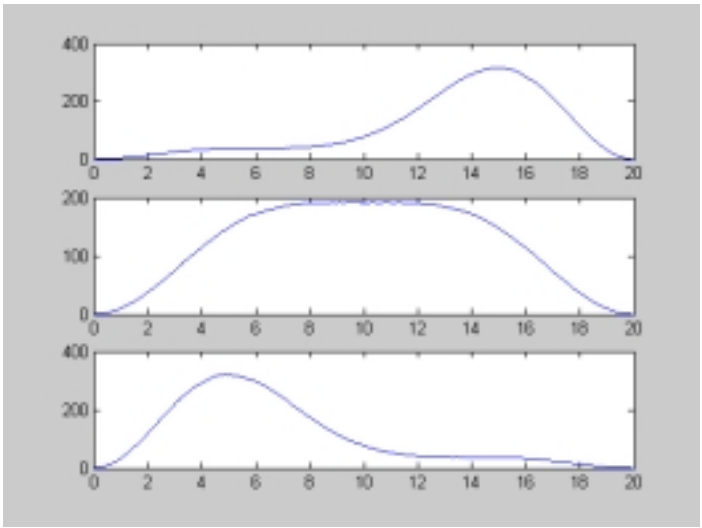

Fig.12. Evolution of temperature along the applicator

Conclusion

The modelling of the antennas, shape and timing, is precious help to optimise the dryers and increase their efficiency. It has to be added that the behaviour of the hide as a function f the air flow and of the microwave deposition is the fruit of a long cooperation between microwave and hide people

References

1. AUDHUY-PEAUDECERF M. and S. LEFEUVRE, Mathematical Modeling of EM Fields in a Loaded Microwave Oven. 28th Microwave Power Symposium, 201-205, July11-14, Montreal, CA.
2. BRAUNSTEIN J. and K.CONNOR, 1999. Investigation of Microwave Heating with Time Varying Material Properties. IEEE Trans. on Magnetics, vol.35, no.3, p.1813-1816
3. DIBBEN, D.C. and A.C. METAXAS, 1994. Finite Element Time Domain Analysis of Multimode Applicators Using Edge Elements, Journal of Microwave Power and Electromagnetic Energy, Vol.(29), pp.242-251.
4. FRANDOS, S., 1999. Simple Method for Estimating The Dielectric Properties of a Material and Their Dependence on Temperature at 2.45GHz, 7th Int. Conf. On Microwave and High Frequency Heating, Valencia, Sept. 13-17, 1999.
5. HATHOUTI A. 1994. Calcul des Champs dans les Fours Microondes. Thése, Institut National Polytechnique de Toulouse.
6. HARMS P.H. 1996. Numerical Modeling of Microwave Heating Systems. Journal of Microwave Power and Electromagnetic Energy, vol.31, no.2, p.114-121
7. JIA X. 1993. Experimental and Numerical Study of Microwave Power Distributions in a Microwave Heating Applicator. Journal of Microwave Power and Electromagnetic Energy, vol.28, no.1, p.25-31
8. MAJDABADINO M. 1992. Contribution au Calcul des Champs dans les Fours Microondes Charges. These, Institut National Polytechnique de Toulouse.
9. METAXAS A.C. and R.J. MEREDITH, 1983. Industrial Microwave Heating. IEE Power Eng. Series, London, UK.
10. READER H.C. and T.V. CHOW TING CHAN, 1998. Experimental and Numerical Field Studies in Loaded Multimode and Single Mode Cavities. Journal of Microwave Power and Electromagnetic Energy, vol.33, no.2, p.103-112
11. SETTI L., M. AUDHUY-PEAUDECERF and S. LEFEUVRE, 1995. Model of Microwave Oven Containing a Metal Grid. Conf. on Microwave and High Frequency Heating, B1.1-B1.4, Sept. 18-21, Cambridge, UK.