Review

Microwave Processing of Materials: Part III

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Abstract: Part I and part II of the paper in the same series, Review Microwave Processing of Materials: Part I and Review Microwave Processing of Materials: Part II, described the fixed frequency microwave processing of materials and variable frequency processing of materials respectively. This paper, Review Microwave Processing of Materials: Part III, details the simulation of fixed and variable frequency heating and processing of materials. Numerical techniques applied by different researchers include finite-element time-domain (FE-TD), finite-difference time-domain (FD-TD) and finite-volume time-domain (FV-TD). Two successful examples of fixed frequency heating simulation packages developed at two Australia universities are described. One American, one British and one Germany simulation codes are cited. Their advantages and limitations are also discussed. The cost and benefits of using fixed and variable frequency facilities are also described in detail. The cost of a complete system of fixed frequency facility of 2.45 GHz (NRC, 1994; Sheppard, 1988) is approximately 1600-8000 Australian dollars per kW. While the cost of a complete system for a variable frequency microwave (VFM) oven of 750 W is as high as 330,000 Australian dollars.

1. Introduction

Computer modelling and simulation can provide valuable information involving various aspects of microwave processing. Numerical modelling has a significant impact on research into microwave processing of materials, because without a detailed understanding of the electromagnetic field structure together with the induced heat and mass transport phenomena, it is impossible to achieve an optimal design of the heating system. Numerical techniques like finite-element time-domain (FE-TD), finite-difference time-domain (FD-TD) and finite–volume time-domain (FV-TD) methods have been developed and used by many researchers to accurately model the electric field and thermal patterns generated during microwave irradiation. The first step to achieve the goal is to develop a computer software package that can predict the electromagnetic phenomena that arise in arbitrarily shaped microwave applicators loaded with arbitrarily shaped materials.

The electric and magnetic fields for a closed microwave system are governed by Maxwell's equations and are listed as follows:

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2}$$

$$\nabla . B = 0 \tag{3}$$

$$\nabla . D = \rho \tag{4}$$

with constitutive relationships:

$$D = \varepsilon E \tag{5}$$

$$B = \mu H \tag{6}$$

$$J = \sigma E \tag{7}$$

where H and E are the magnetic and electric field intensities respectively;

J and $\frac{\partial D}{\partial t}$ denote the current density and displacement current density respectively;

B denotes the magnetic induction;

ρ is the volumetric free charge density;

μ is the permeability;

ε is the permittivity and

σ is the conductivity.

Tailor-made simulation packages for microwave and conventional heating as well as commercially available ones are discussed.

In the cost and benefit analysis section, the cost of running a conventional heating or drying facility is compared with that of a fixed frequency one. In most applications, savings, other than energy, are factors to be considered. The cost of setting up a fixed frequency microwave facility, eg 2.45 GHz, as well as that of a variable frequency oven is also fully discussed.

2. Computer Simulation

In the past the finite element method (FEM) has been employed with success to solve Maxwell's equations in the frequency domain (Silverster, 1969). Many researchers extended this method to three-dimensional electromagnetic field problems. Jia et al. (1992) presented a three-dimensional finite element algorithm for studying microwave field and power distributions generated in a multimode cavity. Recently, the finite-element time-domain (FE-TD) method was developed by Dibben and Metaxas (1994) to analyse the heating of a sample of lossy material located in a multimode cavity. At the sample surface the normal component of the electric filed will be discontinuous. To accommodate this and the model of the electric field directly, edge elements were used, with the degrees of freedom associated with edges rather than nodes. In 1996, Metaxas's research group carried numerical simulation of the microwaves in a multimode cavity. The complicated field field interaction generated within this system provides an excellent benchmark for computational models. Their results indicated that the FE-TD method could capture most of the heating phenomena, however, some particular phenomena, such as the edge heating effects, can escape this numerical approach. The method allows the determination of the field patterns at several different frequencies simultaneously and permits the frequency dependence of the field patterns to be determined. This has been shown to be extremely vital in modelling low loss materials, where there can be large variations in the heating pattern for small changes in frequency.

The first person to show that Finite-Difference Time-Domain (FD-TD) method could be used to model a closed microwave heating system was de Pourcq (1984). He used the FD-TD method to compute the electromagnetic fields and power density distribution in a waveguide that was loaded with a lossy material. Liu et al. (1994) extended the technique to an oven cavity excited by a rectangular waveguide, and loaded with a homogeneous lossy dielectric slab which occupied the whole cavity cross section. The study showed that the FD-TD method could simulate microwave-heating phenomena accurately. The FD-TD method is considered by many researchers to be one of the most accurate and simple for implementing numerical methods when solving electromagnetic problems. Yee (1996) described the basis of the first FD-TD numerical method for solving Maxwell's curl equations. In recent years, there has been an increasing interest in the numerical simulation of microwave heating problems via a direct solution of Maxwell's equations using the FD-TD method.

2.1 Tailor-made Simulation Codes

In Australia, Liu et al. (1996) coupled Maxwell’s electromagnetic equations to the heat transfer equation and solved them numerically to simulate microwave heating of a polymeric material inside a ridge waveguide. The electromagnetic fields and power distribution in the polymeric material within the ridge waveguide were predicted by means of the finite-difference time-domain technique. By applying the contour path technique the FD-TD method was modified to predict the field component adjacent to the curved surface of the ridge waveguide. The contour path (CP) method is based on a direct discretization of the Ampere and Faraday laws, which can be written in integral form as follows (Liu et al., 1996):

$$\oint_C H.dl = \iint_S \left(\frac{\partial D}{\partial t} + J \right).dS \tag{8}$$

$$\oint_C E.dl = -\iint_S \frac{\partial B}{\partial t}.dS \tag{9}$$

where the contour C encloses the surface S.

Liu et al. (1996) conducted several tests in an effort to provide a quantitative validation of the simulation code developed, using FORTRAN 77. In these experiments, Nylon 6 was used because it is a commonly used engineering plastic and the dielectric properties (at 2.45 GHz) of the material at different temperatures are readily available. Their values are tabulated in Table 1 (Moore, 1993). The apparatus used for the experiments is schematically illustrated in Figure 1. It operates at 2.45 GHz with a maximum power of

2kW. The waveguide used was WR 340 having length of 700 mm, ridge width of 30 mm and central gap of 7 mm. The width of the Nylon 6 specimen used was 20 mm and its thickness is 4 mm. Three Nylon 6 test pieces were heated at varying input power levels of 300, 350 and 400 W respectively for 30 seconds. The test pieces were placed at the maximum of the standing wave in the ridge waveguide. To compare the power distributions predicted by the FD-TD model with experimental results, the heat affected zone (HAZ) of each test piece was measured and examined.

At 300W, most of the heating occurred at the centre of the test sample where the electric field is maximum for this standing wave configuration. The central region of the material showed signs of melting, while the outer edges displayed no obvious signs of melting, thus indicating that the temperature did not exceed the melting point of Nylon 6, $220^{o}C$ (Flinn and Trojan, 1990). At 350W, the temperature was sufficient to melt the specimen all the way through the exposed area, causing it to separate into two pieces after 25 seconds. There was a slight discolouration in the region exposed to microwave irradiation. At 400W, the test piece melted through the exposed area and separated into two pieces after 15 seconds. The more pronounced discolouration indicated that the final temperature was much higher than the polymer melting temperature. In the simulations, the temperature distribution of Nylon 6 was predicted until the temperature of the material just exceeded $150^{o}C$. A numerical simulation result is shown in Figure 2 (Liu et al., 1996). Although, the model computed the temperatures along the breadth of the test piece up to $150^{o}C$ only, the times for which it predicted the polymer to reach the temperatures indicated on the figure (Figure 2) were qualitatively consistent with observations made during the experiments. With the FD-TD model, the simulation results can help a lot in the design of ridge waveguide applicators. The simulation code was implemented in FORTRAN 77 and could be run on a workstation or mainframe.

The model developed by Liu et al. (1996) caters for the change of dielectric constant and loss with respect to temperatures in a ridge waveguide. It also successfully predicts the temperature distribution along the width of the sample and hence the waveguide with great accuracy. However, the main drawback of this work is that the numerical model does not take into account the temperature distribution along the length of the ridge waveguide. Moreover, the variation of the dielectric properties with respect to frequency was not considered and the model at its current configuration cannot simulate the variable frequency microwave (VFM) processing of materials.

In Australia, Lye et al. (2000) used a numerical technique to study the temperature distribution within a heated bonded paper web placed in a waveguide. The mathematical model for simulating the microwave drying of the bonded paper web within the waveguide was implemented in FORTRAN 77 code, and was run on a workstation. The parameters of the problem were selected so as to best locate the test sample so that it would absorb the desired power. The method of false transient (Mallinson and de Vahl Davis, 1973) was utilised to accelerate the numerical convergence and the equations were discretised with central difference in both time and space. The resulting system of equations was solved using an Alternating Direction Implicit (ADI) scheme (Hirsch, 1991). The method of false transient and the Alternating Direction Implicit (ADI) scheme are numerical solution techniques.employed to solve the propagation equation derived from Maxwell's equations. The non-dimensional form as given in Lye et al. (1999) represents the equations for the propagation of waves within the waveguide:

$$\frac{1}{\alpha}\frac{\partial E}{\partial \beta} = \frac{\partial \mu \varepsilon E}{\partial t^2} + \frac{\partial \mu \sigma E}{\partial t} + \nabla \text{ x } \nabla \text{ x E} \tag{10}$$

where σ is an effective conductivity of the dielectric material;

ε is the effective complex permittivity;

μ is the permeability;

E is the electric fields;

t is the real time;

α is a constant and

β is the fictitious time.

A schematic diagram of the apparatus used for carrying out the experiments is shown in Figure 3. It consists of a magnetron, a tuner, an impedance analyser and a sample (cardboard). The sample consisted of 7 layers of 3.3 mm thick cardboard and was placed at L1 where the distance, d, is 110 mm measured from the centre of the sample to the short circuit. With the aid of a six-port impedance analyser, the incident power together with the real and imaginary parts of the impedance was recorded. The temperatures at three locations of the test piece along the width of the waveguide were measured at different locations with an infrared thermometer. One location was at midway along the width of the waveguide, namely the centre, another point was at 8.6 mm right from the centre and the final point was at 7.6 mm left from the centre. The experiment was repeated by moving the test piece to L2 where d was 98 mm. At L1, the sample was exposed to microwave irradiation at three different time spans. Temperatures were recorded after launching 2.45 GHz microwave power of 1 kW for 12 seconds. While the test pieces were located at both L1 and L2, and readings were taken at locations approximately 25 mm, 43 mm and 52 mm along the width of the waveguide. It was observed that both the experimental, denoted by E, and numerical, denoted by T, temperatures were in agreement. At L2, the temperature distribution curve nearer the input plane differed by a range of approximately 1% to 30%. This, however, was sufficient to conclude that the pattern of both temperature curves were analogous. The result of this comparison is illustrated in Figure 4.

The microwaves were operated at different times while the test samples were located at L1. When the temperatures were recorded at locations approximately 25 mm, 43 mm and 52 mm along the width of the waveguide, both the numerical and experimental temperatures were in agreement after 12 seconds. But after both 10 seconds and 8 seconds, the predicted temperatures were lower than the experimental temperatures by 1% to 3% for the 10 seconds' test, and 38% to 43% for the 8 seconds' test. However, all three temperature distribution curves along the width of the waveguide exhibited a similar pattern. Since the numerical solutions were similar to experimental results, it was possible to predict the outcomes of material processing along the width of the waveguide using the fixed frequency microwave irradiation of 2.45 GHz.

It was observed experimentally that when the microwave was operated for 12 seconds while the test sample placed at L1, the temperature at the centre of the last cardboard piece along the length of the waveguide nearer the short circuit was similar to the initial temperature. This was in line with the simulation result shown in Figure 5. It was also observed experimentally that when the microwave was operated for 12 seconds, while the test piece was located at L2, the temperature at the centres of the last cardboard piece along the length of the waveguide nearer the short circuit was similar to the initial temperature. This was again in agreement with simulated result. Since the simulated solutions were similar to experimental results, it was possible to predict the outcomes of material processing along the length of the waveguide using the fixed frequency microwave radiation of 2.45 GHz.

Since it has been found that the temperature distribution along the width and the length of the waveguide obtained from experiments and those found through simulations are in good agreement, it was now possible to predict the temperature distribution across the bonded paper web with this numerical model. Therefore the numerical model was successfully used to predict the outcomes of the temperature distribution when applying microwaves within a WR 340 rectangular waveguide for a maximum period of 12 seconds. Figures 6 and 7 show the results.

Figure 6 shows the numerical prediction of temperature distribution on the sample nearest the input plane along the width of the waveguide with respect to time at L1. Similarly, Figure 7 illustrates the numerical simulation of temperature distribution along the centres of the sample with respect to time at L1. At L2, similar results were obtained. The results were sufficient to conclude that this numerical method can aid the paper and cardboard industries to visualise how to apply microwave irradiation to dry or cure their products, using fixed frequency microwaves. The model is not only beneficial for the paper and cardboard industries employing microwave irradiation for drying, but also for other industries, eg leather, as processing of leather using microwaves is becoming popular.

In this numerical modelling, the heat transfer equation was coupled to the electromagnetic propagation equations and solved numerically. Good agreement was proved between numerical and experimental results. The model is, however, quite similar to that of Liu et.al. (1996) except that it is capable of predicting the temperature distribution along the length of the waveguide. This can be considered as a considerable improvement to the work of Liu et al. (1996). While predicting the temperature distribution along the width and length of the WR 340 waveguide during microwave processing of the cardboard pieces with respect to time, the relative temperature for each duration of microwave irradiation was recorded instead of the absolute temperature. The model could be more powerful if it can be further developed to predict the relative as well as the absolute temperature. Lye et al. (2000) did not mention whether the variation of the dielectric properties of the cardboard with temperature had been taken into account or not when the simulation package was developed. This has to be taken into account in the modelling process as the dielectric property of many materials that are suitable for microwave processing do vary with temperature.

For problems involving general non-rectangular domains, ‘stair-stepped’ orthogonal approximations to irregular boundaries have been used. Unfortunately, although relatively simple to implement, this approach often gives rather poor approximations. Madsen and Ziolkowski (1990) presented a three-dimensional modified finite volume technique for solving Maxwell’s equations, where the concept of overlapping hexagonal dual grids was used. For each cell the barycentre is located at the average of the coordinates of the notes that define the primary cells. The dual grid is constructed by connecting the barycentres of the adjacent primary cells. The electric field is computed by using volume integration around the dual cells that contains the primary cell edges where the electric field components are located. The magnetic field was computed in a similar manner using the primary cell. The scheme was marched in time by the explicit leap-frog algorithm. Liu et al (1996) also developed a finite-volume time-domain (FV-TD) technique for solving microwave-heating problems, in which both the cavity and the load can be of arbitrary shape. The mesh may consist of structured and unstructured primary cells that can be of any shape and form. The FV-TD method was applied directly to the integral forms of the Faraday and Ampere Laws in the Time-Domain. The FV-TD technique provided a very good tool for optimisation, since it can easily be utilised to investigate the effects of varying important parameters that include the dimension, shape and position of the material within the cavity.

In the United States of America, Zathi et al. (1997) compared the results of a series of material processed via variable frequency microwave (VFM) energy with computed results from numerical modelling techniques. The finite-difference time-domain (FD-

TD) technique developed provided 2-D models of the electric and thermal field distributions inside the microwave cavity as well as inside the processed materials. The physical and chemical characteristics of the materials from the empirical trials were evaluated for both variable and fixed frequency irradiation. A Finite Difference Time Domain (FDTD) technique was used to model the heating profiles generated during fixed frequency irradiation as well as VFM irradiation. The simulation was performed by investigating 41 frequencies within a 1 GHz bandwidth. Results illustrated the need to have various frequencies in order to achieve uniform heating. The variable frequency simulation resulted in the establishment of a thermal gradient across the sample of about 11 ^{o}C, while the thermal gradient across the test piece in the fixed frequency had been evaluated to be on the order of 90 ^{o}C. These numerically calculated thermal gradients are very close to those observed experimentally.

In the United Kingdom, Dibben and Metaxas (1994) employed a finite element time domain (FETD) method for the solution of Maxwell's Equations in a multimode applicator. The package was tailor-made for Unilever Research Colworth, a foodstuff company, and was implemented in C++. Edge elements were used for the discretization. The FETD methods allowed information at a range of frequencies to be obtained from a single calculation. Results obtained from both low loss materials and high loss food-like materials were compared with experimental data. They were found to be in good agreement. The method allows the determination of the field patterns at several different frequencies simultaneously which permits the frequency dependence of the field patterns to be determined. This has been shown to be extremely important when modelling low loss materials, where there can be large variations in the heating pattern for small changes in frequency. This software code is more advanced than those mentioned earlier as it caters for the variation of the dielectric properties of materials with temperature and frequency. On top of it, it can also simulate the heat distribution pattern in hybrid ovens.

In Germany, Haala and Wiesbeck (2000) developed an efficient simulation tool for predicting heating and drying results for conventional, microwave and combined heating. A new thermal modelling technique was used for simulation of conductive and radiant heat transfer. The conductive heat transfer was modelled by a finite difference algorithm. A finite difference scheme is not applicable for the radiant heat transfer, as radiation from a material surface is not bounded to the immediate vicinity, as is the conductive transfer. Therefore, ray optical methods were used. Rays connecting mutually visible surfaces were obtained by a new fast method. Some simplifications which are necessary to achieve fast computing were also carried out. The algorithms were combined with an electromagnetic FDTD program. Simulations were presented for an oven heated conventionally, with microwaves, or by a combination of both.

The resultant simulation tool is very powerful and helpful in determining heating rates and patterns in conventional and microwave heated facilities and allows an optimisation of such ovens or even a hybrid oven. Temperature distributions can be determined inside material samples to optimise the heating pattern. The capability of the code to deal with hybrid ovens is its great success because it has been anticipated that most microwave processing system in the future will be the integration of conventional heating and microwave irradiation (Metaxas and Meredith, 1983; NRC, 1994). Again the main drawback for this code is not to integrate variable frequency microwave (VFM) irradiation into it. It only caters for fixed frequency heating of 2.45 GHz. VFM heating is a new invention and it has been proved to have special characteristics that cannot be performed by its fixed frequency counterpart. To include VFM processing entities in the development of simulation code will make the numerical model even more powerful.

An important element of microwave process development and system design is the capability to model electronic interactions. An understanding of the variation of dielectric properties with temperature and processing state is crucial for simulations and process modelling. Computer modelling can be used to optimise generator or applicator system design, establish achievable processing windows, and conduct realistic process simulations for given dielectric properties, sample size, and desired processing conditions (NRC, 1994). All of the above tailor-made simulation codes can, to a certain extend, perform the required functions in predicting the heat distribution in a sample processed by fixed and or variable frequency microwaves.

2.2 Commercial Packages

Some research has been done through trade journals and web sites to find out the commercially available simulation packages for microwave heating. The information of some simulation packages that have been researched in more details include:

- QuickField simulation package by Tera Analysis Company, USA.

- Vector Fields by Opera Software, USA
- Ansoft Maxwell 3D Field Simulator by Ansoft, USA.
- CFX-Radiation by Computational Fluid Dynamics Software Services, USA.

The CFX-Radiation may be the most suitable package from the above mentioned list. It is 5,600 Australian dollars. But after talking to a technical support representative based in Sydney, it becomes clear that the word radiant refers to thermal radiant and not electromagnetic radiation, eg microwaves. Therefore, all of the above packages are unable to perform numerical simulation for microwave heating or drying. Bows (1999) claimed that commercially available market is limited because the market is very small and most models are developed by academics for specific use. His company, Unilever Research Colworth, uses the simulation code developed by Dibben and Metaxas (1994) which is tailor-made.

3. Cost and Benefit Analysis

In addition to considering the advantages brought about by microwave processing of materials, the cost in implementing the process is also vital to industry. The cost of capital equipment for microwave processing differs widely and depends on power rating, frequency, size, applicator design, manufacturer and market volume of the equipment. Fixed frequency microwave processing equipment is usually higher in cost than its conventional counterpart, eg oven heating or drying and fusion bonding (NRC, 1994). The cost of a complete system is approximately 1600-8000 Australian dollars per kW. This refers to the fixed frequency system, eg 2.45 GHz. The generator and the applicator are about 50% of the total. The power transmission, instrumentation and external materials handling costs are 1600-4800 Australian dollars each. The installation cost is 5-15% of system cost. The operating costs include cost of energy, maintenance, repair and replacement. The cost to replace a magnetron is 2-20 Australian cents per kW-hour. The cost of electricity is around 10-20 Australian cents per kW-hour. Routine maintenance cost will be 5-10% of system cost. The overall energy efficiency in industrial microwave processing is 50 –70% (NRC, 1994; Sutton, 1989). A Canadian source estimated that the energy savings in drying and firing of ceramics using microwave energy is as much as 80% of its conventional rival (Sheppard, 1988). In alumina sintering, the energy savings can be as high as 90%. There have been a number of reports regarding savings in terms of time and improvements in productivity obtained by microwave processing (NRC, 1994; Sheppard, 1988). These are summarised in Table 2.

By and large, the cost of setting up a fixed frequency microwave processing system is more expensive than that of conventional heating or drying facility as the energy efficiency of the former is only 50 to 70%. Factors, other than energy, generally account for savings realised from microwave processing. Such factors include process timesaving, increased process yield and environmental compatibility.

The cost of variable frequency microwave (VFM) facility is very high when compared with its fixed frequency counterpart. The cost of capital equipment for VFM depends on power rating, operating frequency range, size and applicator design. A VFM oven uses high-power helix travelling wave tubes (TWTs) as the source of microwave energy and this is one of the reason for its high cost (Everleigh; 1994). Another reason for its high cost is that it is still being manufactured under the patent of an American company (Lambda Technology, undated). The price of the Microcure 2100 model 250 shown in Figure 1 was 180,000 Australian dollars and that of Microcure VW 1500 illustrated in Figure 2 was 140,000 Australian dollars in the middle of 1998. Both facilities share the disadvantage of a low maximum power output, which was found to be inadequate in some applications, eg joining thermoplastic matrix composite materials. A similar batch oven, Microcure 2100 model 750, which has a maximum output of 750 W, is now available but the price is much higher than the model 250, it is 330,000 Australian dollars. Moreover, the manufacturer now supplies an in-line system VFM furnace, Microcure 5100, and the price is 510,000 Australian dollars.

As far as the relationship between simulation packages and design and development cost of microwave heating system is concerned, there is no literature found mentioning the amount of money and or time saved in carrying out the simulation capable of predicting the temeprature distribution of a material when it is processed by microwave irradiation. However, as expected simulation is less expensive than building hardware and performing the tests. Therefore, it is anticipated that the saving in time and money is tremendous provided the prediction made by the simulator is not too far away from reality. However, this has to be justified by the one-off development cost of the simulation code, which is usually quite high.

4. Conclusion

Of the tailor-made simulation codes, the one implemented by Dibben and Metaxas (1994) in C++ seems to be the most powerful option. It is suitable for predicting the heat distribution in a material undergoing fixed and variable frequency microwave (VFM) heating as well as conventional heating and hybrid heating. The one developed by Faithi et al. (1997) is also a very good and powerful simulation code and applicable in most situations as it has been developed for simulating the heating pattern of a material subjected to fixed and variable frequency microwave (VFM) heating. However, it fails to cope with conventional heating and hybrid heating. The one developed in Germany (Haala and Wiesbeck, 2000) caters for mixed frequency microwave heating of 2.45 GHz and conventional heating or both. It can be used in most industrial situations. The two Australian codes, particularly that developed by Liu et al. (1996) appear to be useful but more developmental work has to be done to perfect the code. The work done by Lye et al. (2000) will only be considered good if the code can simulate the heat distribution in a material generated by fixed and variable frequency microwave heating as well as conventional heating, and hybrid heating.

Due to the high costs of microwave generators, eg klystrons, magnetrons (other than 2.45 GHz), and helix travelling wave tubes (for the variable frequency microwaves), and the relatively poor efficiency of electric power for heating applications, factors other than energy generally account for savings realised from microwave processing. Such factors include process time savings, increased process yield and environmental compatibility.

By and large, the VFM facility is more flexible and has more potential applications than its fixed frequency counterpart, but it is too costly. In simple applications, eg wool bale warming, fixed frequency facility is adequate (Clayton, 1999), but in more sophisticated applications like curing of the encapsulant of flip chip in a printed circuit board assembly, only VFM furnace can be used because of the presence of metallic parts within the microwave field (Fathi et al 1998; Wei et al, 1998; Zou et al 1999).

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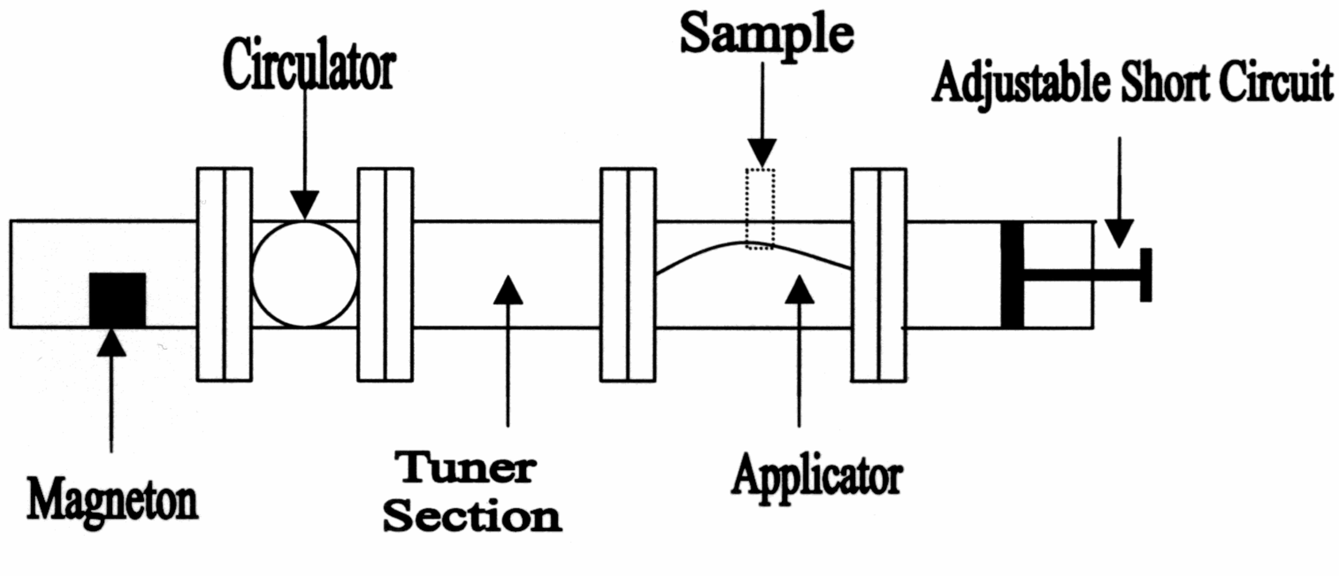

Figure 1: The Schematic Diagram of Microwave Configuration for Liu et al. (1996)

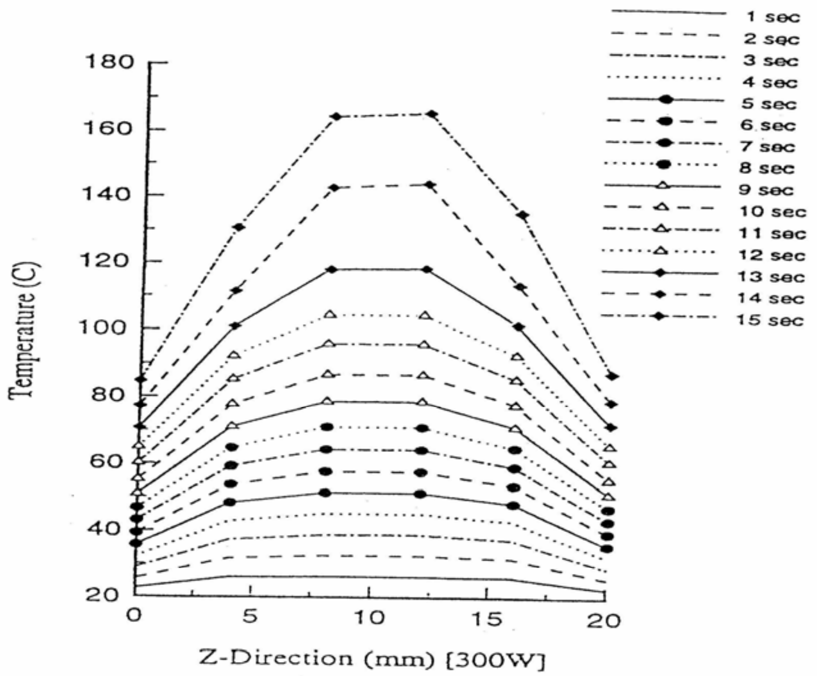

Figure 2: Numerical Simulation Result for Microwave Heating of Nylon 6 Using the Power Input of 300 W

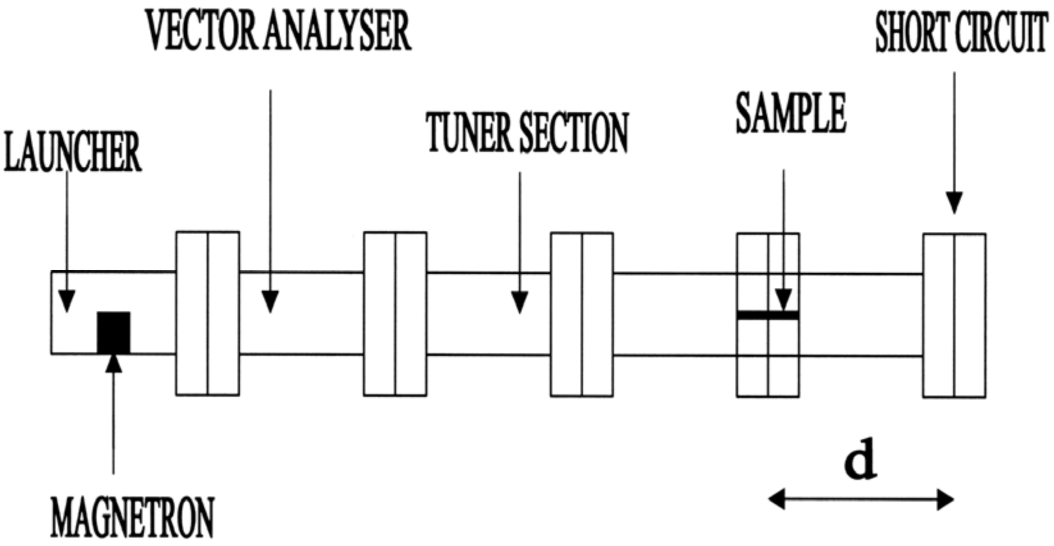

Figure 3: The Schematic Diagram of the Experimental Set-up for Lye et al. (2000)

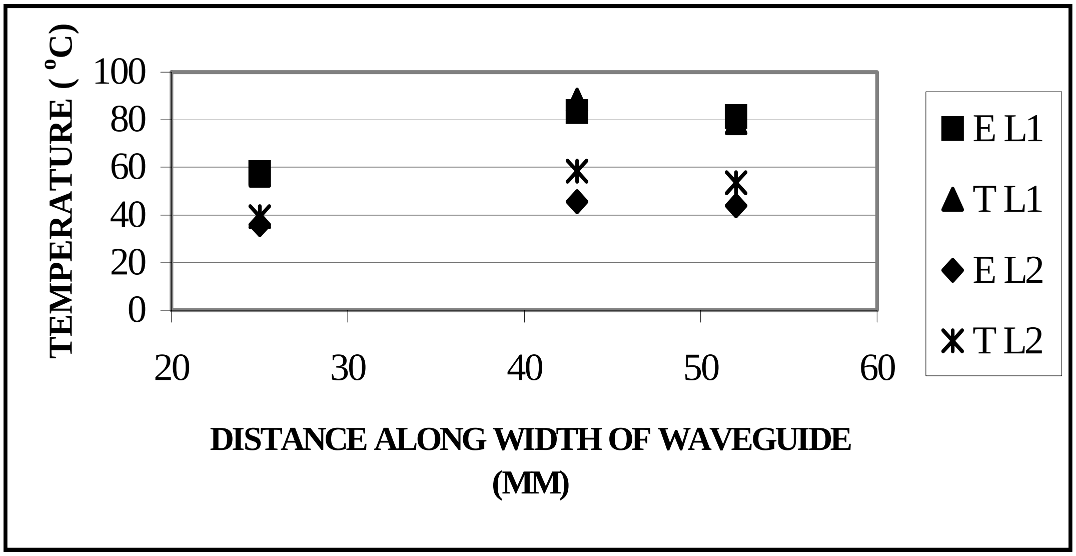

Figure 4: Comparison between Numerical and Experimental Results for t=12 seconds at L1 and L2

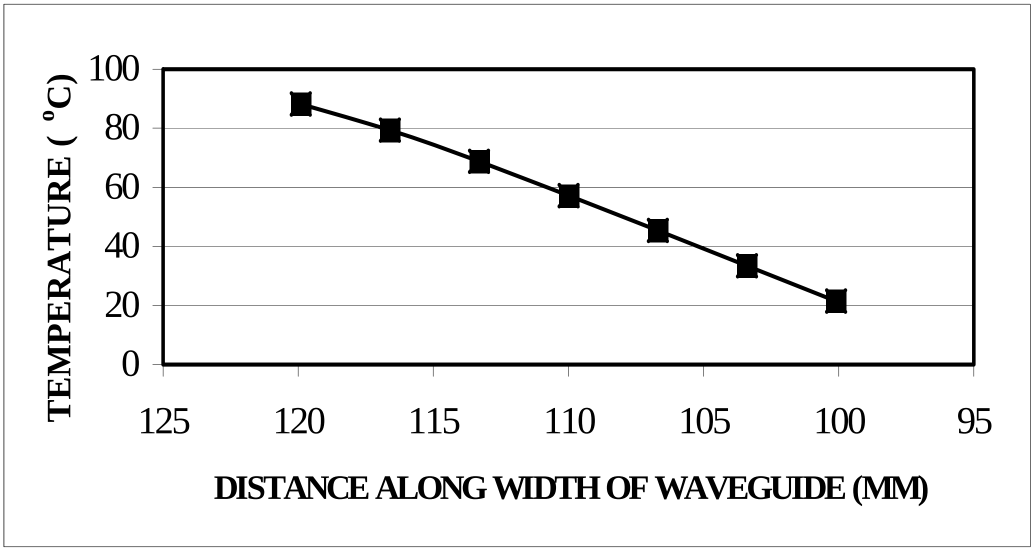

Figure 5: Numerical Prediction of Temperature Distribution along Centre of Sample (Length of Waveguide at L1 for time = 12 seconds

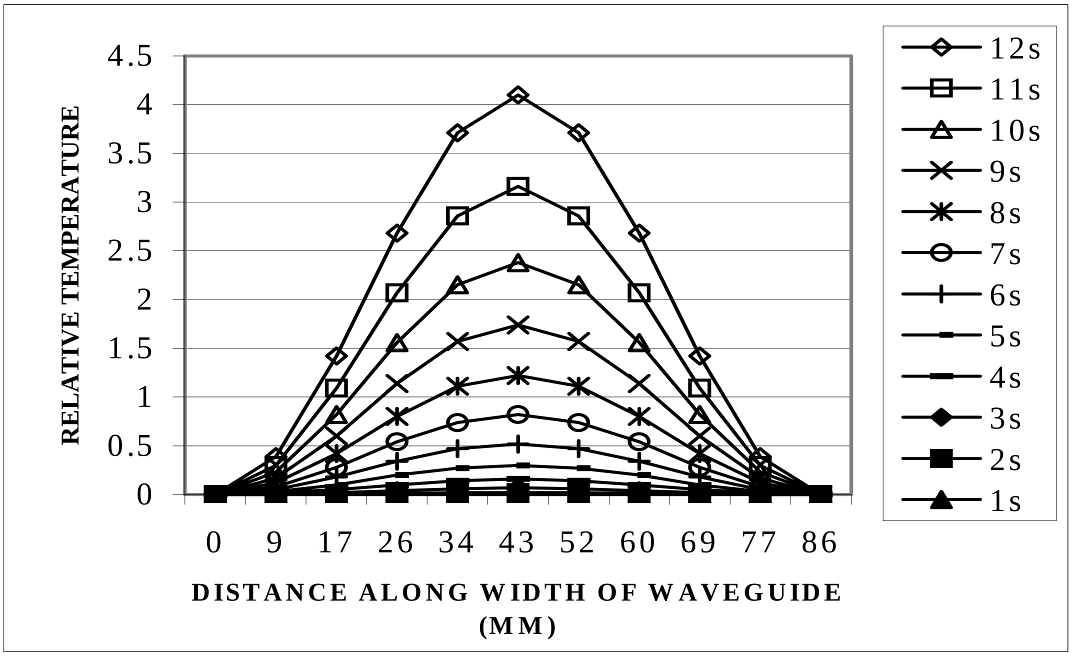

Figure 6: Numerical Simulation Result of Temperature Distribution on the Sample Nearest the Input Plane along the Width of the Waveguide with respect to Time at L1

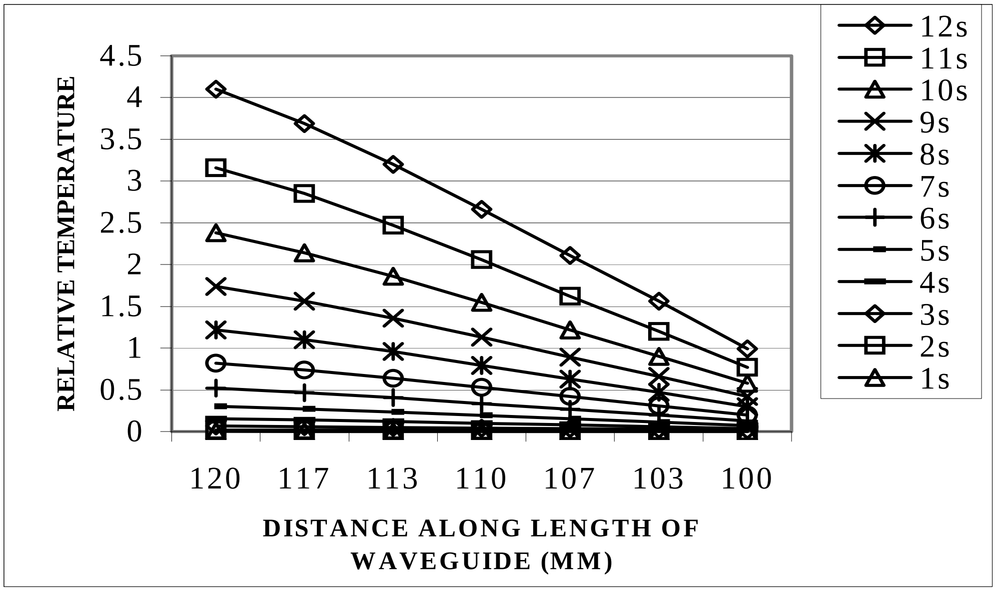

Figure 7: Numerical Prediction of Temperature Distribution along Centres of Sample with respect to Time at L1.

Price: AUD $ 180,000 (1998)
Frequency Range: 2 to 8 GHz
Maximum Power = 200 W

Figure 8: VFM Facility, Microcure 2100 model 250

Price: AUD $ 140,000 (1998)
Frequency Range: 6.5 to 1 8 GHz
Maximum Power = 125 W

Figure 9: VFM Facility, Microcure VW 1500

Table 1: Dielectric Properties of Nylon 6

Temperature (°C)	20	50	75	100	125	150
Dielectric Constant	3.0	3.1	3.2	3.3	3.7	3.6
Dielectric Loss	0.02	0.03	0.05	0.07	0.22	0.15

Table 2: Time-Savings/Productivity Improvements

Materials	Process	Time savings	Productivity Improvement
Whiteware	Slip Casting	66%	immediate mould recycling
Whiteware	Drying	24 h to 8 min	
Whiteware	Overall Process	70%	6.25 pieces to 27 pieces per worker per day
Boron Carbide	Sintering	>90%	
Structural Adhesive	Curing	66%	66% cost reduction
Varnish	Curing	<70%	