VARIABLE FREQUENCY MICROWAVE HEATING OF FOOD

J. R. Bows

Industrial microwave food processing is universally based on single frequency microwave sources. With the emergence of variable frequency microwave ovens, it is possible to exploit the frequency dependence of a food's permittivity and/or choice of heating frequency, for example as a new route to achieving targeted heating. Variable frequency heating procedures are developed to overcome the geometry of a roughly spherical foodstuff dominating the heating pattern when heated in fixed frequency applicators. Target mean temperatures of 55, 75 and 90°C within 2 minutes and without physical damage were set; means of 54.5 ± 4.1, 75.1 ± 4. 7 and 87.6 ± 3.5°C respectively were achieved within the time constraint and with no major physical damage, based on combining 8 discrete frequencies between 2.4 and 6.2 GHz.

Key Words: Targeted, discrete, swept, multiple, thermal imaging

ABOUT THE AUTHOR:
John R. Bows is affiliated with Unilever Research Colworth, Sharnbrook, Bedfordshire, MK44 ILQ, UK.

Radio frequencies that may be used for heating are those allocated by the Federal Communications Commission and are referred to as ISM (industrial, scientific and medical) frequencies. Almost all industrial microwave heating uses 896/915 ± 10/13 MHz, depending on the country, and 2450 ± 50 MHz. Other available bands (in MHz), depending of the country, include 433.92 ± 0.2%, 3390 ± 0.6%, 5800 ± 75, 6780 ± 0.6% and 24150 ± 125 [Metaxas & Meredith, 1983].

Several workers have demonstrated the dependence of the heating uniformity on small changes in frequency in multimode cavities. Mackay et al. [1979] discussed exploiting the dynamic and sequential selection of discrete frequencies within the available ISM bandwidth for more uniform and efficient heating. Kashyap & Wyslouzil [1977] showed that sweeping the frequency of a voltage tunable magnetron over 2450 ± 25 MHz (i.e. within the ISM bandwidth) produced better or comparable heating uniformity to that obtained by using the oven's field stirrer. Dibben & Metaxas [1994] showed that a simulation of microwave heating of a low loss planar material in a domestic microwave oven (nominally 2.45 GHz) matched the experimental heating pattern when simulated at 2.46 GHz, which was the measured operating frequency of the oven. However, when the frequency dependence of the dielectric permittivity of typical foods is considered, it becomes apparent that being able to select heating frequencies over a GHz range rather than over the ISM bandwidth may offer even greater advantages for higher loss materials.

It has been proposed by Bows & Mullin [1994] that batter used to coat frozen substrates such as fish could be set by the use of high frequency microwave heating above 3 GHz. Figure 1 shows the permittivity and penetration depth versus frequency for a common formulation of batter used to coat frozen a food substrate in the manufacture of various foodstuffs (batter composition 58% water, 20% wheat flour, 20% starch, 2% salt). Two temperatures are shown, 10°C and 70°C, which are the enrobing temperature and the minimum temperature required to set the batter respectively, over 1 to 7 GHz. Assuming an enrobing thickness of 2 mm, at the enrobing

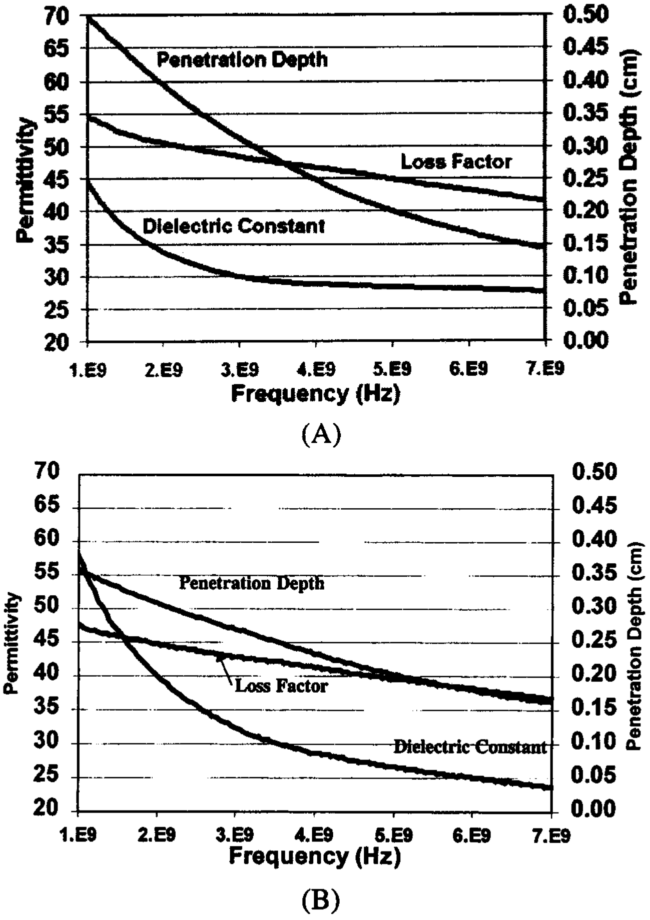


FIGURE 1: Permittivity of batter at 10°C (A) and 70°C (B).

temperature a microwave signal at 7 GHz would be concentrated largely in the coating, compared with heating at 2.45 GHz, as the penetration depths (at 10°C) are 1.5 and 3.5 mm respectively.

The optimum choice of frequency may involve establishing a resonant condition by setting up a maximum reflection at the batter/frozen food substrate interface. In the past, establishing a resonant heating condition required careful control of formulation and dimensions as the heating frequency was fixed. Clark & Holt [1989] describe how to heat the interior of an ice cream dessert, melting a chocolate core whilst the outer ice cream remains frozen. To achieve this within a domestic oven, with fixed operating frequency, would require manufacture of the product to within millimeter precision, which is not realistic with commercial manufacturing practices.

With the recent commercial availability of variable frequency heating ovens, it is now possible to experimentally investigate control of microwave heating directly by choice of frequency(s). To date, only fixed frequency sources have been used commercially because of the limitations of both the microwave tubes being used and the associated microwave components required. The conventionally used microwave tubes employ resonant structures (e.g. magnetrons and klystrons) which inherently limit them to narrow operational bandwidths.

Everleigh, et. al. [1994] discussed the use of variable frequency heating using high-power traveling wave tubes (TWTs). TWTs work in the following way [Lauf, et al., 1993]: Microwave signals are generated by a voltage controlled oscillator at a power level around +15 to 20dBm (30 to 100mW). Control voltages are used to vary the oscillator frequency. The microwave signal is then passed through a pre-amplifier (to equalize power vs. frequency), and then through a high power TWT amplifier to generate powers up to a few kW. The signal is finally launched into a cavity.

Johnson, et al. [1994] have demonstrated the use of variable frequency microwave heating. The heating uniformity at different planes within a cavity was determined using thermally sensitive paper. Swept frequency heating was performed over bandwidths of 5 to 40% for center frequencies of 5 and 15 GHz. The results showed that less bandwidth was required to achieve the same level of heating uniformity as the center frequency increased, due to excitation of a larger number of higher order modes at the higher frequency.

Variable frequency has been investigated for a number of processing applications. Fathi, et al. [1995] investigated heating thermoset polymer matrix composite materials and showed that thermal runaway and hot spot problems associated with fixed frequency heating were overcome. Qiu, et al. [1995] showed how frequency switching enabled modes with high heating rates and desirable heating patterns to be selected to allow uniform heating of a graphite/epoxy load. Surrett, et al. [1994] showed that swept frequency heating produced more uniform curing in thermosetting composite systems (carbon fiber/epoxy resin laminates). Wei, et al. [1998] have looked at variable frequency heating for bonding applications in polymer composites and electronic packaging applications.

Metaxas [1996] discussed the use of swept frequency applicators, such as tuneable magnetrons and traveling wave tubes, for obtaining good uniformity of heating, for example through time-average heating at different frequencies.

This paper presents work on the use of frequencies between 2.4 and 7.0 GHz to achieve controlled heating in a foodstuff whose geometry dominates the heating pattern when heated in fixed frequency applicators.

Basic Equations of Microwave Heating

The equation governing microwave power absorption is given by:

$$P_V = 2\pi f \varepsilon_0 \varepsilon'' E_{RMS}^2 \qquad (1)$$

Where P_V is power absorbed per unit volume (W/m^3), f is frequency (Hz), ε'' is the dielectric loss factor, ε_0 is 8.854×10^{-12} F/m, and E is the electric field strength within the material (V/m).

The measure of how opaque a material is to a microwave field is given by the penetration depth, that is the depth at which the microwave power has fallen to l/e of its initial value, and is approximately given by:

$$Dp = (4.8/f)\sqrt{\varepsilon'}/\varepsilon'' \qquad (2)$$

where Dp is in cm when f is in GHz, ε' is the dielectric constant.

Note that ε' and ε'' can be dependent on both frequency (f) and temperature, the extent of which depends on the foodstuff.

Thus in a simple analysis of variable frequency heating of foodstuffs in a resonant cavity, it is difficult to isolate the effect on changing the frequency term f in equation 1 because ε'' usually changes, too. Additionally, E will change in practice because changing f results in different field patterns being excited in a resonant cavity. There may be other applicator-specific effects of changing frequency, such as changing the impedance matching to the cavity (i.e. how much microwave energy gets into the cavity).

In addition, the penetration depth Dp may also change in a complex manner with f due to the frequency dependence of ε' and ε''. Penetration depth not only governs the depth of effective heating, but the relation of Dp to the physical dimensions and geometry of the foodstuff can give rise to well known effects such as resonant heating conditions which are responsible for strong center heating or localized heating in some spherical and cylindrical materials.

Variable Frequency Microwave Oven

The variable frequency microwave oven (VFMO) used in the study was a Vari-Wave LT502A (Lambda Technologies Inc., Morrisville, US), specified with a power output of 500W at any frequency between 2.5 and 7.0 GHz. The cavity dimensions are 381 mm wide, 305 mm high and 300 mm deep. A TWT launches a microwave signal from a coaxial cable to a double ridged waveguide (WRD 250D30) and a tapered double ridged launcher (WRD 250) into the cavity (located on an upper corner of the back wall). The double ridge waveguide ensures the fundamental TE_{10} mode is propagated over the operating frequency of the TWT into the cavity.

The heating chamber is based on a resonant cavity similar in principle to a domestic microwave oven. However, in the case of domestic ovens, which operate at 2.45 GHz, the cavity dimensions are selected to both support a large number of microwave field patterns (to maximize heating uniformity), and provide a good impedance match (to maximize power delivery) over a large range of (food) load types (frozen, thawed, large, small, etc.). Additionally, turntables and/or mode stirrers are always provided in domestic oven designs (and industrial systems) to further encourage uniform heating.

With the VFMO used here, the technical consequences of delivering variable frequency heating capability have raised several hurdles for targeted heating of foodstuffs. Heating takes place in a fixed wall cavity, which by definition, means that below a certain frequency, *not all microwave frequencies* can be physically supported as some will have such poor impedance matching that virtually no microwave energy enters the cavity. This is made worse at food-like permittivities. A further consequence is that mode stirrers and turntables cannot be included, as they would constantly change the impedance matching of a particular frequency, unfavorably at certain frequencies. This VFMO reacts to a large impedance mismatch (when the reflected microwave power exceeds around 50W) by shutting down to protect

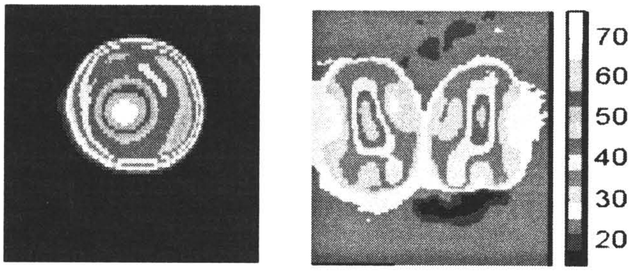


FIGURE 2: *Center plane thermal images of a roughly sperical foodstuff after heating in two different domestic microwave ovens showing center heating tends to dominate the heating patterns. Left image shows one half of the foodstuff, right image both halves.*

the microwave source (a design limitation of the oven that could be overcome through the use of a wide band circulator for example).

The complications of using the VFMO in the study here were due to the oven design and not the physics of variable frequency microwave heating. A further limitation of the VFMO was that, at any given frequency, non-symmetric heating is likely because the field pattern is fixed. Thus variable frequency heating may have to be used to achieve symmetric heating, especially for generating heating uniformity in the outer region of a foodstuff. The advantage of variable frequency heating, even with the oven used here, is that more controlled or targeted heating should be possible in certain categories of foodstuffs. These include foodstuffs whose geometries impose a dominant heating pattern, such as spheres and cylinders.

Thus the experimental approach adopted in the study was as follows:

1. Characterization of the VFMO to find "processing windows", that is, frequencies and powers at which the foodstuff could be heated at high powers
2. Determination of the heating pattern produced by these frequencies
3. Construction of heating procedures that will achieve targeted heating (e.g. even heating)

A solid PTFE cylinder (50 mm thick, 130 mm diameter) was supplied by Lambda Technologies which they use as a base for a standard load for diagnostic testing purposes. This cylinder was used for all experiments to avoid consequences of heating a product directly in contact with a metal surface, such as a minimum electric field condition at the contact of the foodstuff with the metal base of the cavity.

Experimental and Results

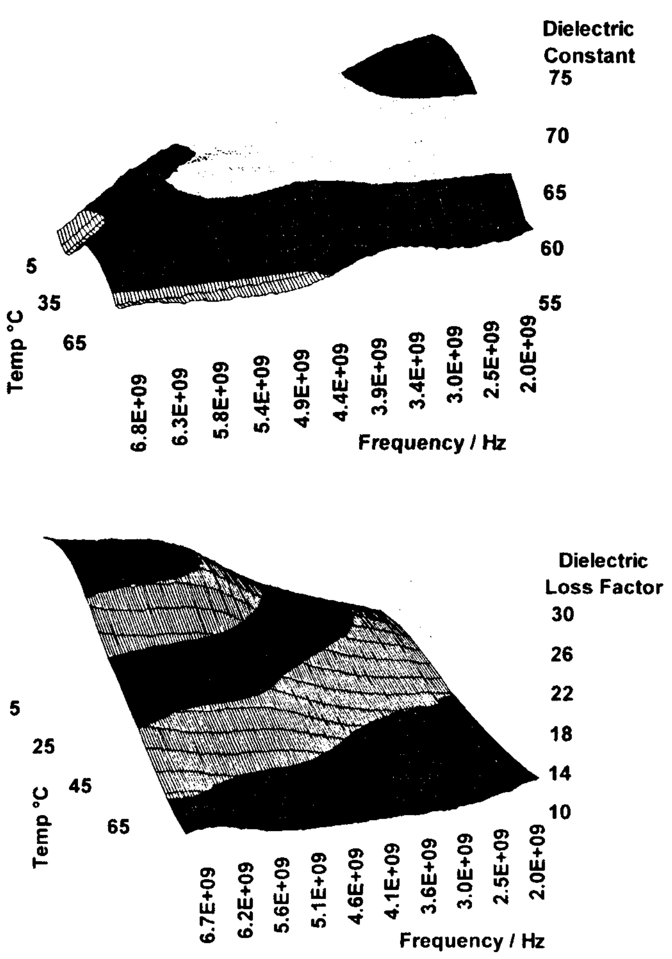
Material Characterization

A roughly spherical natural foodstuff was used throughout the study. The foodstuff is composed of around 90% water and has some internal cellular structure. The diameter was between 5 and 7cm. The geometry and material properties of this foodstuff tend to dominate the heating pattern. For example, in domestic microwave ovens, center heating occurs irrespective of the model of oven used (Figure 2).

The permittivity of the foodstuff was measured using a Hewlett Packard HP85070B open ended coaxial probe from 2 to 7 GHz, and the dielectric constant, loss factor and penetration depth as functions of temperature were obtained. The accuracy of this probe is quoted by the manufacturer to be 10%. The three distinct anatomical regions of the foodstuff were measured (a 10 mm diameter core, an outer 5 mm layer and the annular region). Samples were cut from the foodstuff and measured directly or after pulping with a hand-held blender. Permittivity measurements were carried out over a range of temperatures, from 5°C to 85°C, every 5°C, taking care to minimize moisture loss, ensure an intimate probe/material contact without applying excessive pressure or trapping air bubbles.

Figure 3 shows the dielectric constant and loss factor for the unpulped annular region, between 2.0 and 6.8 GHz, to demonstrate temperature and frequency dependency. It was found that the permittivity of the other regions of the foodstuff were not significantly different. The effect of water loss due to evaporation or the effect of comminution were estimated from the difference between measurements carried-out on pulped and unpulped foodstuff. The effect was small, up to 10% in a few cases, in both the dielectric constant and loss.

The foodstuff is seasonal and a further study was conducted to determine if the maturity of the foodstuff affected permittivity. Additionally, three varieties of the foodstuff were available. Measurements were made directly on cut surfaces of the foodstuff at a depth of 3 mm or at the mid-radius depth in the annular region. The trial was conducted over a period of eight weeks. Figure



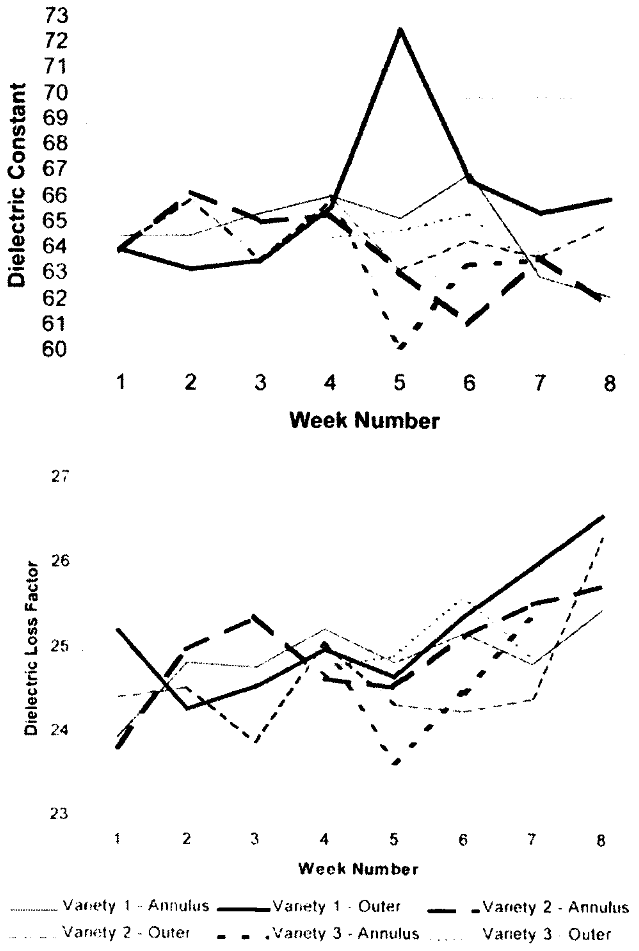


FIGURE 3: *Dielectric loss factor (upper) and loss factor (lower) of unpulped annular region of foodstuff.*

FIGURE 4: *Dielectric loss factor (upper) and dielectric constant (lower) of foodstuff at 5.8 GHz.*

4 shows the dielectric constant and loss factor at 5.8 GHz (variety 3 matured over a narrower period), showing no significant differences with maturity or variety within the accuracy of the probe. This finding was also shown at other frequencies between 2 and 7 GHz.

Characterization of the Cavity

Cavity characterization, with a representative product within the cavity, was required to determine which frequencies could and could not be used for full power heating.

Automatic Characterization

Automatic cavity characterization software was provided by Lambda Technologies. The microwave source was automatically operated across a quartile of its frequency range, and forward and reflected power were measured, *with a representative load in place.* Reflectance was calculated as:

$$\textit{Reflectance} = 100\% \times (\textit{Reflected Power}/\textit{Forward Power}) \quad (3)$$

A point of minimum reflectance indicated that the discrete frequency could be used to heat the representative load. Similarly, an area of minimum reflectance indicated that a frequency band could be used to heat the load. The next stage would then be to examine the heating pattern and its robustness at that frequency or across the frequency range, which is discussed later.

The automatic software characterization was repeated six times for each quartile with a fresh portion of foodstuff in place each time. The PTFE block was always present, located centrally, and the foodstuff was placed centrally on top. One purpose of this characterization was to examine if the foodstuff's inherent biomaterial variability (e.g. shape, weight, moisture content) had an effect on the impedance characteristics of the oven and therefore suitable heating frequencies. Forward power, reflected power and calculated reflectance for a given quartile were plotted on the same axes for 6 different experiments. The fourth quartile (upper frequency range) showed no reflected power at all.

Figure 5 shows a set of 6 reflected power data for the second frequency quartile (3.55 to 4.70 GHz), illustrating several important features also found for the first and third quartiles:

- The reflected data for the 6 data sets overlaps showing that the small, inevitable biomaterial variations between the 6 portions of foodstuff had no significant impact on the profile of the reflected data with frequency
- Small frequency spans of the order of 10 MHz exist where there appears to be no reflected power
- There are several narrow-frequency ranges (several MHz) or frequency points of very large reflected power

It should be noted that a reflected power reading was not triggered until a value of above 10W was measured (the forward power meter displays a similar triggering effect, occurring at 2W).

Automatic characterization was also performed with 67ml (mean weight of a representative batch of the foodstuff was 67g) of deionized water in a 100ml Pyrex beaker for comparison with the foodstuff reflectance data, to further test impedance matching stability (the permittivity of water changes far more with temperature compared with the foodstuff). One water sample was run for each quartile, replacing the water for each successive quartile. This data was compared against the averaged foodstuff data for that quartile.

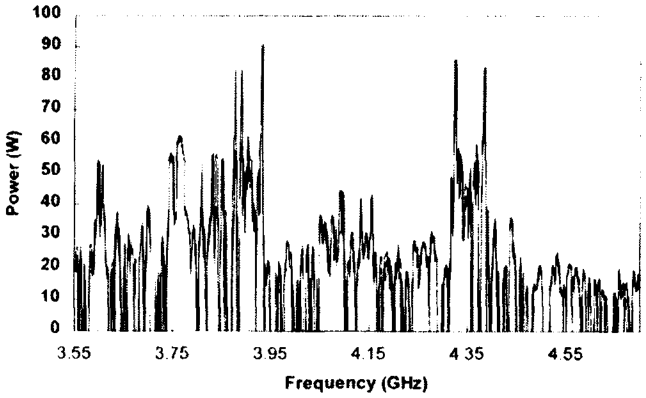


FIGURE 5: Reflected power over second frequency quartile. Six foodstuff data sets are superimposed.

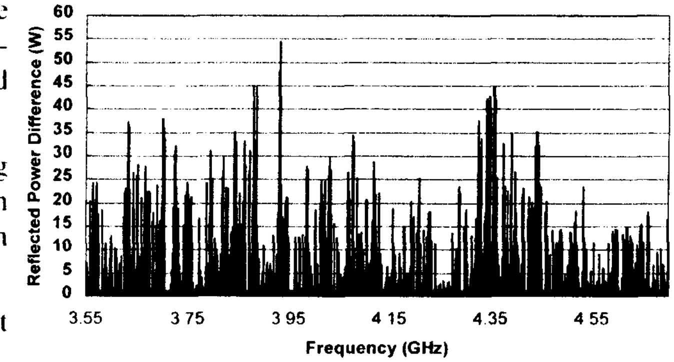


FIGURE 6: Absolute reflected power difference between mean foodstuff and 67 ml water for second frequency quartile.

Figure 6 shows the absolute difference between the reflected data for the water load and averaged foodstuff data for the second quartile (from Figure 5): 67ml water in a Pyrex beaker has similar impedance matching characteristics to the foodstuff. From Figure 6, the difference in reflected power for 64% of the frequency points (1024) in the second quartile was less than 10W, and 85% were less than 20W. This suggests that inherent variations in the foodstuff shape, weight, moisture content, etc. should not adversely effect the optimum choice of frequencies, and that some degree of temperature-dependent permittivity can be tolerated.

Manual Characterization

The automatic characterization procedure had one major limitation. Forward power is controlled manually by an analog power knob. Additionally, an operating characteristic of the microwave source in this oven was that forward power decreased with increasing frequency. Therefore, it was very difficult to set the power level which satisfied these criteria:

- Sufficiently high forward power at the upper frequencies of a quartile to effectively pinpoint high reflec-

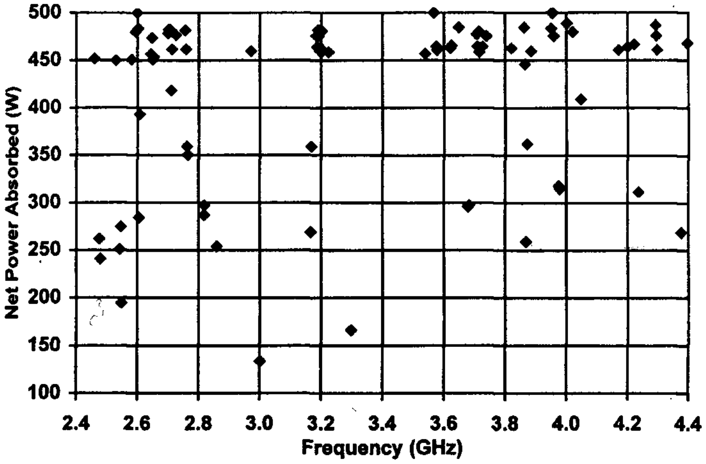


FIGURE 7: Net power absorbed for foodstuff portions from manual cavity characterization.

tance areas, because the reflected power levels below 10 W do not trigger a value

- Sufficiently low forward power at the lower frequencies of a quartile to prevent high reflected power areas shutting down the oven when reflected power exceed 50W, even though the reflectance may be low

The forward power setting had to be set to some intermediate value (e.g. 100W) for automatic characterization trials to meet these criteria, so it was not possible to simultaneously test those frequencies where full power (500W) could be applied with minimum reflectance. This was tested manually.

The manual characterization consisted of experiments investigating all possible processing windows. The oven was operated at each individual frequency within the processing windows highlighted by successful automatic characterizations. Where the windows were a number of MHz wide, frequencies were taken at intervals of about 3 MHz to keep the number of experiments reasonable. The experimental procedure was as follows:

1. Place a fresh portion of the foodstuff within the microwave cavity, insert four Luxtron 790 fiber optic thermometer probes (Luxtron, Santa Clara, US) to measure temperatures at near-surface, half-radius distance and center positions.

2. Set forward power to zero, set the single frequency for that run and turn the RF power on.

3. Increase power steadily until either 500W forward power is reached or the oven fails safe due to excess reflected power.

4. Note the forward and reflected powers at 500W or faulting value.

5. Start the oven at the highest power possible with a fresh portion of the foodstuff and heat until 50°C is reached, and monitor the net power flow (a check on repeatability).

Manual characterization trials isolated those frequencies at which 500W forward power could be achieved with minimum reflectance, so that the maximum net power is delivered to the foodstuff. Additionally, the trials allowed an assessment of any undesirable heating effects such as:

- splitting the foodstuff from internal localized heating as a result of a strongly resonant heating condition
- non-linear correspondence in how forward and reflected power changed with time due to temperature dependent permittivity, resulting in much less net power absorption than anticipated over the whole heating time

Frequencies were characterized up to 4.5 GHz, beyond which reflectance was a minimum for all frequencies (due to the decreasing wavelength resulting in no frequencies where microwave energy could not be delivered into some well coupled electric field pattern).

The results from the manual characterization are shown in Figure 7. Each point represents one manual characterization. It can be seen that there are many discrete frequencies where 90% or more of the forward power is absorbed, which represent possible starting frequencies for heating pattern analyses.

Determination of Heating Patterns

An evaluation of heating under different frequency conditions (sweeps and discrete points) allowed an evaluation of the best approach to uniformly heating of the foodstuff, as measured from fiber optic measurements and thermal imaging of the center plane of the foodstuff. Combinations of single sweeps or discrete frequencies were also evaluated. Heating strategies were optimized on the basis of mean and standard deviation measurements across center plane slices. All heating was done with a forward power of 500W to produce the

TABLE 1: Frequencies (GHz) selected for heating pattern analyses.

Frequencies Characterised	Frequencies above 4.5 GHz
2.599	4.700
3.568	4.950
3.956	5.800
4.001	6.200
4.222	

most rapid heating possible.

The following targets were set:

- Achieve a mean temperature of 55, 75 or 90°C throughout the foodstuff from a 20°C starting temperature. The temperature dependence of the permittivity may affect the selection of frequencies required to achieve each target.
- Reach target mean temperature within 2 minutes, to minimize the effects of heat conduction on the measured temperature distributions.
- Without significant physical damage (e.g. major cellular disruption, splitting of the skin). Heating on each frequency used must not cause excessively localized heating.

Heating Pattern Analysis

Several frequencies were highlighted from the previous section as particularly stable regions where slight deviations in the positioning of the foodstuff on the PTFE support or size/shape of the foodstuff had no significant effect on the reflectance data shown in Figure 7. Table 1 shows the frequencies selected for the heating pattern analysis.

It was decided not to include frequency spans at this point to simplify the heating procedure, as it was difficult to ensure that the VFMO did not occasionally shut down due to a badly coupled discrete frequency point within a span. The frequencies in the right hand column of Table 1 were arbitrarily chosen (5.8 GHz was included as this is a reserved industrial heating frequency). Nine frequencies were chosen as a reasonable working balance to maximize the number of heating patterns for uniformity and keep the total heating time within 2 minutes (500W at each frequency is achieved through time consuming turning of the power setting knob - it has not been automated in the VFMO model used). These frequencies also did not appear to cause unwanted heating effects such as setting up strongly resonant heating conditions.

Figure 8 shows thermal images of the halves of the foodstuff after slicing, for each heating frequency in Table 1. A comparative image from heating in a domestic microwave oven is also shown. It can be seen that there is an increasing tendency for periphery heating with increasing frequency, which is expected from equation 2, as the penetration depth diminishes with frequency. It can also be seen that there is no one frequency where anything approaching uniform heating is achieved.

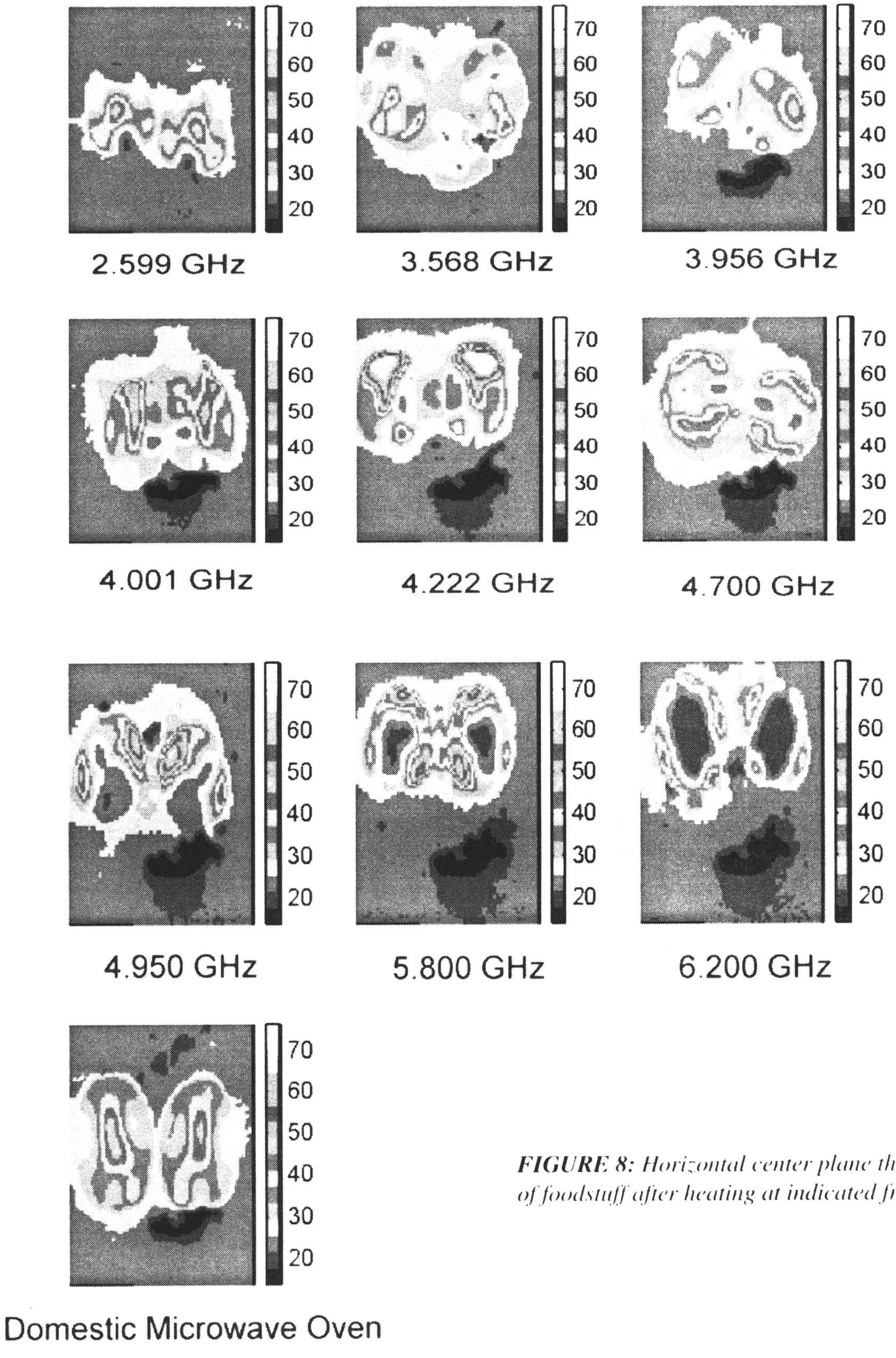
Heating Procedures For Uniform Heating

After numerous experiments minimizing the number of heating frequencies necessary to achieve the target means, those in Table 2 were selected, with 2.599 GHz being replaced with 2.450 GHz in a domestic microwave oven. A domestic oven provided more power thus reducing the heating time on this frequency, as well as reducing the amount of manual knob turning to set up each frequency for 500W power (both helped to achieve the 2 min heating goal).

These frequencies were combined in different orders and durations, to test whether the impedance matching changed with frequency due to the temperature dependence of the dielectric permittivity. Incident power was set to 500W, varying exposure time at a particular frequency (the same energy input P_V may require different exposure times at different frequencies, as seen from equation 1).

No significant dependence on the frequency order was observed, so heating was performed in ascending frequency (to minimize heat losses at periphery regions).

Table 2 lists the actual heating procedures required to achieve a mean center plane temperature of 55, 75 or 90°C, as measured by the temperature data from the 4 fiber optic probes and thermal image analysis. A domestic microwave oven (Sanyo EM-2614, with turntable, rated power output 650W) was used at full power for the 2.450 GHz condition, and the VFMO was manually set to 500W forward power at the other frequencies.



2.599 GHz

3.568 GHz

3.956 GHz

4.001 GHz

4.222 GHz

4.700 GHz

4.950 GHz

5.800 GHz

6.200 GHz

Domestic Microwave Oven

FIGURE 8: *Horizontal center plane thermal images of foodstuff after heating at indicated frequencies.*

***TABLE 2:** Heating procedures to reach target temperatures from a 20°C starting temperature.*

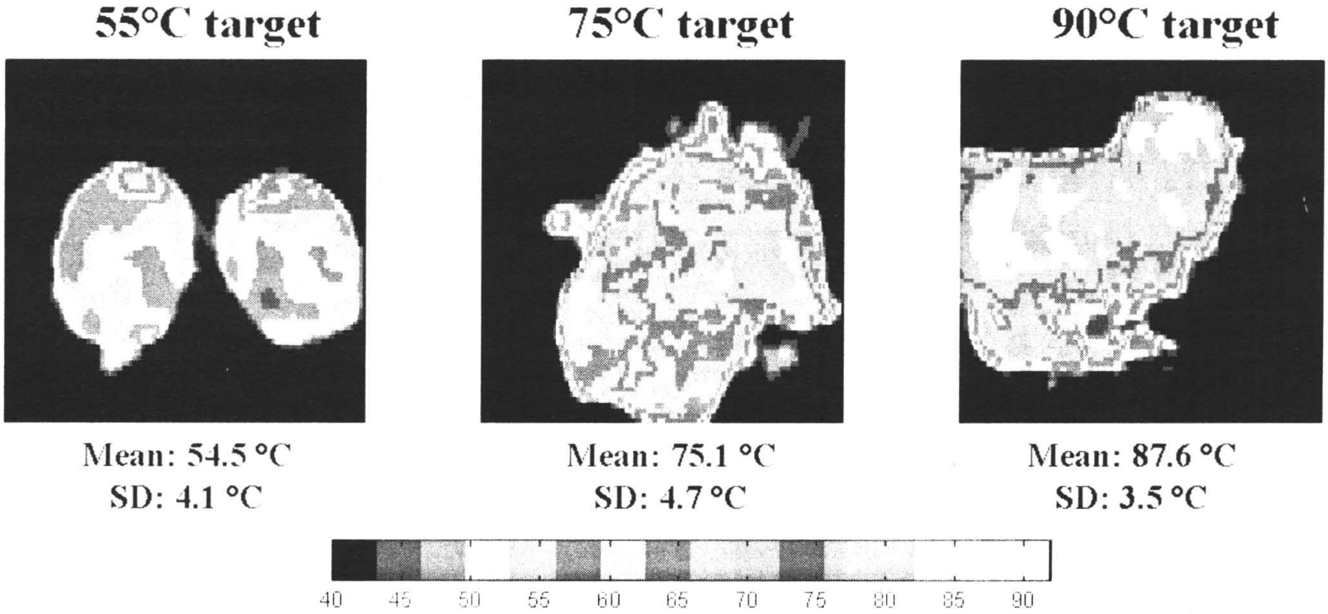
Frequency /GHz	Time/secs to 55°C	Time/secs to 75°C	Time /secs to 90°C
2.45 (domestic oven)	7	10	13
3.568	6	10	14
3.956	6	10	14
4.001	5	8	11
4.222	7	12	17
4.950	7	12	17
5.800	7	12	17
6.200	7	12	17

Figure 9 shows the resultant heating patterns after following each procedure in Table 2. The mean ± standard deviation values were 54.5 ± 4.1, 75.1 ± 4.7 and 87.6 ± 3.5°C for the 55, 75 and 90°C target procedures respectively. The temperature distributions for the three procedures produced more uniform heating than heating at any single frequency.

For the 90°C procedure, rapid cooling was observed during capture of the thermal image, so it is likely some cooling will have occurred during and after slicing the foodstuff open before the image could be captured. Additionally, on slicing the foodstuff open for the 90°C procedure, and to a lesser extent for the 75°C procedure, there was liquid escape as the internal tissue had been slightly disrupted. From Figure 9, the boundaries of the individual foodstuff halves are less clear by comparison with the 55°C images where there was almost no liquid loss. This liquid loss may have also contributed to the lower apparent mean temperature measured for the 90°C procedure. Heating for longer periods (around 10%) than those listed in Table 2 for the 90°C procedure caused major structural disruption (splitting of the skin), probably as a result of excess vapor pressure as temperatures approached 100°C.

Discussion

From inspection of the heating procedures in Table 2, it can be seen that each procedure applied the same fre-



55°C target

Mean: 54.5 °C
SD: 4.1 °C

75°C target

Mean: 75.1 °C
SD: 4.7 °C

90°C target

Mean: 87.6 °C
SD: 3.5 °C

***FIGURE 9:** Horizontal center plane thermal images of foodstuff (both halves) after following heating procedures in Table 2.*

quencies in the same order, following the same trend in duration. The main objective of this study, to achieve a target mean temperature within 2 minutes, was met but further work is required to reduce the temperature distribution. Computer simulations of variable frequency heating are recommended to reduce the time consuming experimental empiricism that was required to develop relatively simple heating procedures. Additionally, frequency spans were not fully investigated, which may be a route to increase the heating uniformity.

The VFMO used here is a research tool which readily allows many approaches to combining frequencies to be evaluated for a given product format. Certain design modifications are recommended to allow a more thorough analysis of variable frequency heating, such as the addition of a broad band circulator, automatic stabilization of power output with frequency and a mode stirring feature. For an industrial scale application, it is likely that multiple single-frequency sources (e.g. magnetrons) or narrow-band sources (tens of MHz) would be preferred as they are currently far cheaper and more powerful than amplified TWT devices.

Operating any microwave source outside the ISM bands for continuous processing would require careful choking and shielding to comply with strict telecommunications interference regulations for "out-of-ISM-band" limits on microwave leakage [LaGasse, 1998; Risman, 1998].

Conclusions

It has been shown how variable microwave frequency heating procedures can be used to control the heating pattern in a natural roughly spherical food product whose geometry dominates the heating pattern in fixed frequency applicators. A heating procedure was developed, based on combining 8 discrete frequencies between 2.4 and 6.2 GHz for different durations, to achieve more uniform heating than was possible at any single frequency. The objective of heating the foodstuff to target means of 55, 75 or 90°C within 2 minutes and without major physical damage (such as splitting) was largely achieved: mean temperatures of 54.5, 75.1 and 87.6°C (standard deviations 4.1 to 4.7°C) were measured from center plane thermal images after following the 55, 75 and 90°C procedures respectively. A combination of rapid cooling and liquid loss during preparation for the temperature measurement was thought to be have been responsible for the difference in the 90°C procedure target mean and measured mean. The temperature dependence of the foodstuff's permittivity did not appear to have a major influence in achieving each target mean, as the heating procedure used the same frequencies in the same order, following the same trend in duration. In order to reduce the spread of temperatures about each mean, optimization of each heating procedure to fully account for the temperature and frequency dependence of the foodstuff's permittivity is required. This would include investigation of the number, order and values of the frequencies used, consider discrete vs. spanned frequencies, and heating duration on each frequency.

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