AN APPARATUS FOR PROVIDING CONSTANT AND HOMOGENEOUS TEMPERATURES IN LOW VISCOSITY LIQUIDS DURING MICROWAVE HEATING

By B.A. Welt, C.H. Tong, and J.L. Rossen

Abstract:

A computer controlled stepper motor was used to facilitate agitation of a liquid sample in a 40 ml glass vial during microwave heating in a domestic microwave oven. The apparatus incorporated a system for feed-back temperature control using a modified microwave oven. The stepper motor was controlled by an IBM-compatible computer in a manner that provided an oscillating "wrist-shaker" action. The extent of mixing was controllable via entry of deflection angle and rotation speed into the computer. Performance of the system was assessed in terms of the unit's ability to uniformly attain a desired set-point temperature, and its ability to maintain this temperature for a prescribed time. The effects of sample viscosity, salt content and agitation rate were studied. Experimental data indicate that the apparatus is well suited for kinetics research for lossy reaction media with viscosities less than or equal to 200 centipoise ("cp") or 0.375% carboxymethylcellulose solution.

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It is well recognized that microwaves offer an efficient mode of heat transfer which translates into significant reductions in heating time. This fact has made microwaves attractive to consumers, researchers and the food industry. In the food industry, processes that are considered suitable for microwave applications include dehydration, freeze-drying, blanching, baking, thawing, pasteurization, sterilization and curing. A review of work in these areas was provided by Decareau [1985]. Although heating characteristics of materials can be predicted by dielectric properties [Metaxas and Meredith, 1983], a question remains as to potential non-thermal effects of microwave on chemical interactions and reaction rates within complex materials. The knowledge of whether microwaves offer additional non-thermal effects is important to process engineers who strive to optimize process efficiency and/or product quality through predictions of changes of the product throughout the process.

Much work has been done in comparing the effects of microwave versus conventional heating on biological, chemical, and food systems [Fujikawa et al., 1991; Diaz-Cinco and Martinelli, 1991; Hall and Lin, 1981; Klein et al., 1981; Fung and Cunningham, 1980; Mabesa and Baldwin, 1979; Goldblith and Tannenbaum, 1968; Stevens and Fenton, 1950]. The conclusions reached in these works may be questionable due to several practical and common limitations associated with research in typical household microwave ovens. The problems involved with traditional microwave heating research include: (1) lack of on-line temperature measurement; (2) uneven heating due to uneven electric field distributions and microwave heating characteristics; (3) lack of temperature control; and (4) evaporative losses which results in a continuous change of solute concentration throughout the experiment.

Although an on-line temperature measurement method for using a standard thermocouple in a microwave cavity has been published [Van de Voort, et al., 1987], the most convenient and accurate solution to on-line temperature measurement in the microwave cavity is by fiber-optic temperature systems. Such systems became commercially available during the 1980s.

The problem of uneven heating is well known. The most common approach employed to minimize this problem involves geometric adjustments along with the size reduction of the sample. However, uneven heating is still possible when a sample is not continuously and thoroughly mixed during heating.

The problem of controlling the sample temperature at a specified set-point during microwave heating is reliant upon the acquisition of real time temperature data. Using fiber-optic temperature sensing technology, Tong et al. [1991] provide a solution to this problem with a computer controlled feedback control scheme, using a modified domestic microwave oven.

The prevalence of water as a major ingredient in products treated by microwaves introduces the significant problem of vaporization. Vaporization of solvent continually increases the concentration of solutes, altering kinetic results. Although attempts have been made to correct for this effect [Fujikawa et al., 1992], no published literature exists that demonstrates a satisfactory solution to this problem. For safety reasons, it is important to be able to control and limit the temperature of a hermetically sealed sample treated by microwaves.

The purpose of this work was to develop an apparatus that is able to maintain a uniform temperature throughout liquid samples over a useful range of viscosities, during all phases of heating in a microwave oven.

Using feedback temperature control, the sample should uniformly approach and maintain a desired set-point temperature at nominal and slightly elevated pressures, without significant loss of solvent due to vaporization.

Materials and Methods

The apparatus used in this study is shown in Figure 1. The main features include a Toshiba microwave oven (Model ERS-6831B) that was modified in accordance with the method of Tong et al. [1991]. As a review, the power supply circuit of the oven was modified so as to allow on/off control of the magnetron. A variable transformer or Variac (Model 3PN1510, Staco Energy Products Co., Dayton, OH) was incorporated into the circuit, which provides continuous variability of magnetron power.

The features also include an IBM/AT compatible computer that provided the control signal to the on/off relay, based on an input signal supplied by a temperature sensing unit through an RS-232 port (Luxtron Corp., Santa Clara, CA).

Finally, there is an Airpax stepper motor (Model K82701-P2; Airpax Inc., Cheshire, CT) that was controlled by an IBM compatible computer equipped with a digital I/O board, through an in house built drive circuit. The stepper motor was coupled to a plastic sample holder by an 8 inch long and 0.25 inch diameter plastic rod. The stepper motor was mounted outside of the back wall of the oven, by a standard laboratory stand and clamp.

A hole was drilled in the back wall of the oven to accommodate the coupling rod such that the sample vial would be closer to the center of gravity. The coupling rod attached to the sample holder in such a way that when a sample vial is placed in the holder, the center of rotation coincided with the center of the sample. The sample holder was designed for 40 ml EPA sampling vials with hole caps and Teflon septa (Supelco, Inc., Bellefonte, PA).

The stepper motor was controlled by in-house programmed, user-friendly software. To begin agitation, the vial was adjusted to a convenient starting and sampling position (typically vertical), by stepping the motor counterclockwise ("CCW") or clockwise ("CW") at the computer keyboard. A default agitation protocol was initiated, causing the motor to make a half-turn CCW and then continuous and repeating cycles CW and CCW. If the starting position was vertical, and 180° turns were used, the vial would first make a 90° turn CCW to the horizontal position, and then complete 180° turns CW and CCW through vertical, stopping and reversing rotations each time it arrived at opposing horizontal positions.

When agitation was stopped, the vial was automatically returned to the starting position. Adjustments to the maximum deflection angle and rotation speed were made by inputs at the computer keyboard once agitation was underway.

The temperature profile was measured by a Luxtron 755 temperature sensing unit equipped with three detachable-tip fiber-optic temperature probes (Luxtron Corp., Santa Clara, CA). The glass sample vial was modified in order to fix the positions

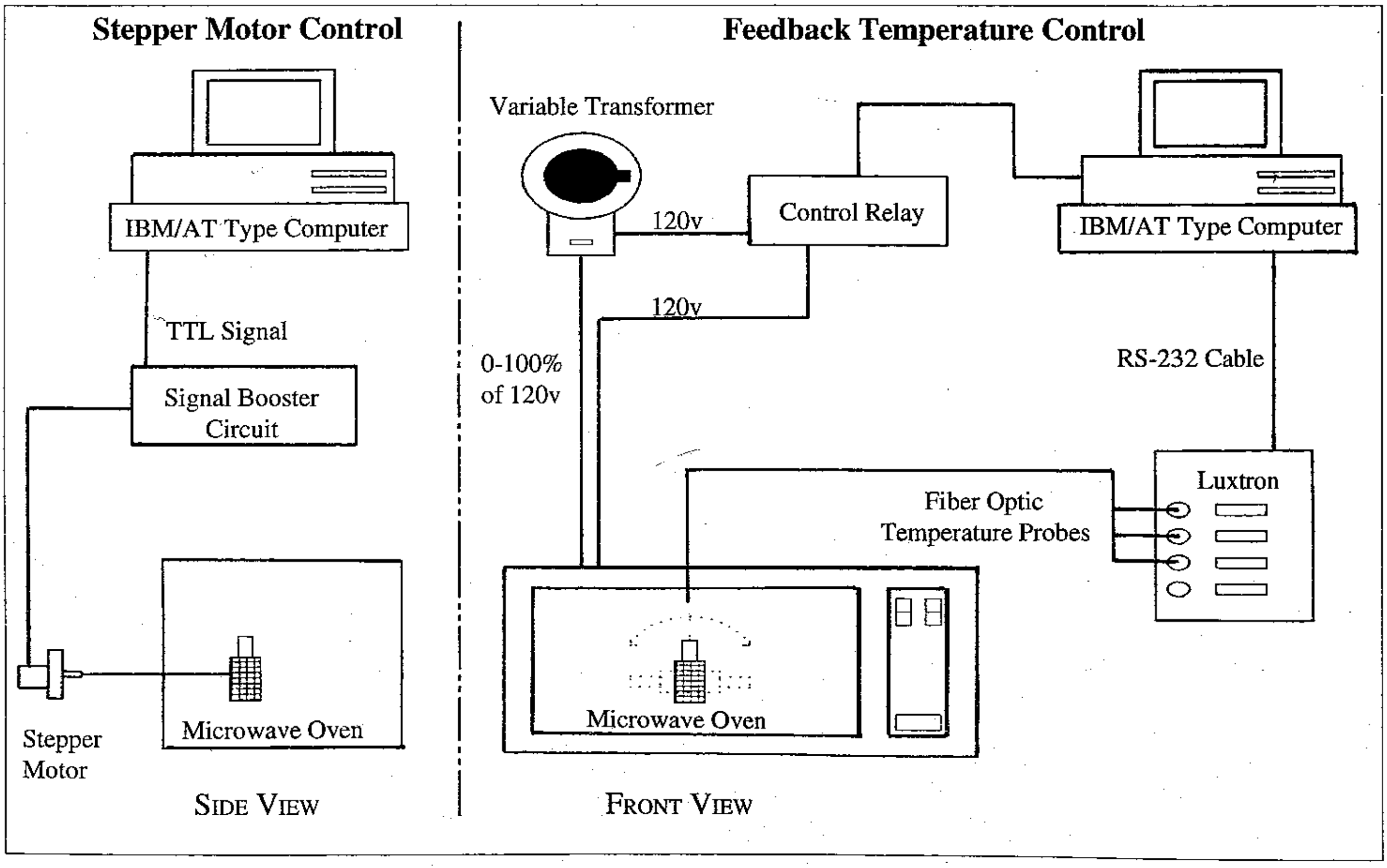

Figure 1: Diagram of Apparatus (Note the feedback temperature control loop and the agitator [stepper motor] control loop)

of the temperature probes within the vial (Figure 2). The "center" probe was located at the geometric center of the vial. The "side" probe was located at the same height as the "center" probe, but at the inner surface of the vial. The "bottom" probe was located along the central axis of the cylindrical vial, approximately 4mm from the bottom. Short pieces of Teflon PFA tubing (Cole-Parmer, Chicago, IL) were epoxied across the internal diameter of the vial to provide support for the probes. Small holes were drilled in the tubes in order to accommodate the probes and to allow circulation through the supports. The probe locations were selected in order to view both vertical and horizontal temperature profiles.

Experiments

Although there were many combinations of maximum deflection and rotation rates possible, in this study, the maximum deflection was fixed at 90° from starting position. Three rotation rates were used: slow (3 radians/second; 172°/sec); medium (4.5 rad/sec; 260°/sec); and fast (6 rad/sec; 344°/sec). The computer's internal timer calculated the elapsed time during each 180° rotation, and continuously provided the rotation rate, in radians per second, of the sample vial.

It should be noted that although it was believed that the volume of sample would have an impact on the degree of mixing, a minimum amount of 35 milliliters was required in order to keep all three temperature probes submerged throughout each rotation.

The set-point temperature was fixed in all experiments at 80°C. Due to the nature of the on/off feedback control system, an upper temperature limit (above which the magnetron is turned off) of 80.15°C and a lower temperature limit (below which the magnetron is turned on) of 79.85°C were established as the control parameters. The temperature was maintained at 80 ± 0.5°C.

Solutions of varying viscosities were prepared from variable concentrations of carboxymethylcellulose ("CMC") and distilled water. The solutions prepared included 0% (100% distilled water), 0.25%, 0.375%, 0.5%, and 1% CMC by weight. Viscosities were measured at room temperature by a Brookfield Model RVT viscometer (Brookfield Engineering Lab., Inc., Stoughton, MA) with a #21 spindle, and were found to be dependent on shear rate. The following data for 0.375% CMC are provided in order to gain a feeling for the magnitudes of the viscosities used: (1) 220 centipoise ("cp") at 5 RPM; (2) 185 cp at 10 RPM.

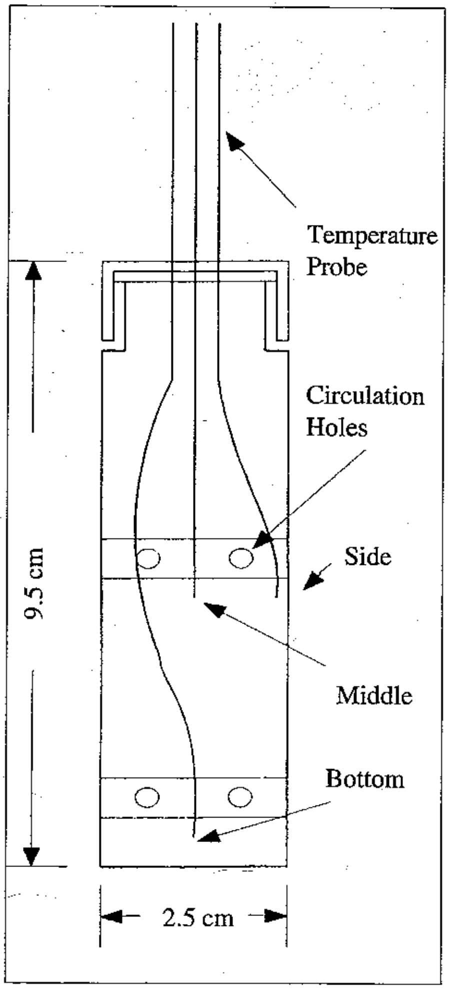

Figure 2. Fiber-optic temperature probe locations in sample vial

Variable salt concentrations were prepared by adding sodium chloride to the CMC solutions. With the exception of the 0% CMC solution, all other salt solutions were prepared as either 0% NaCl or 1% NaCl. Salt contents of 0%, 1%, 2% and 5% salt by weight were prepared with the 0% CMC solution.

Each experimental run consisted of the following sequence of events: (1) calibrating the Luxtron temperature probes; (2) pouring the test solution into the sample vial; (3) securing the temperature probes; (4) placing the test vial into the sample holder; (5) establishing a steady state agitation setting; (6) providing a file name to store the time-temperature data and temperature control parameters; (7) adjusting the magnetron power to 100% at the variable transformer; (8) powering up the microwave oven; (9) acquiring approximately 60 seconds of initial sample temperature; (10) activating the temperature control system; (11) reducing magnetron power to 80% upon reaching the setpoint temperature.

Results and Discussion

The problem of uneven heating by microwaves is well known. In order to use a "uniform temperature" assumption, researchers have traditionally attempted to use relatively small sample sizes. Figure 3 clearly shows that even for a 35 ml sample of distilled water, a 20°C to 30°C temperature gradient exists even after ten minutes of controlled heating at a maximum setpoint temperature of 80°C. Most work done used sample sizes larger than 35 ml; it is clear that the existence of uneven heating, in the absence of continuous agitation, was possible.

The capability of the apparatus to avoid a temperature gradient in the sample during heating was the basis of the overall performance assessment of the apparatus. The performance was viewed to be mainly affected by the sample's viscosity, salt content and volume together with the rotation angle and rate of the agitator. Performance was gauged by the degree to which the agitator was able to minimize the temperature gradient within liquid samples of variable viscosity and salt content.

The addition of salt tended to decrease the initial vertical temperature gradient. However, this effect is not significant in unagitated aqueous solutions, as relatively high concentrations of salt were required to achieve small improvements in temperature uniformity. For a 2% brine solution, the initial temperature gradient was almost ten degrees smaller than that for distilled water, however, the rate at which the temperature gradient diminished in the brine was slower than that for water. After ten minutes the water showed a smaller temperature gradient under similar heating conditions. These results may be specific to the sample size and geometry used in these experiments.

Relatively mild agitation was required to achieve a uniform temperature profile in

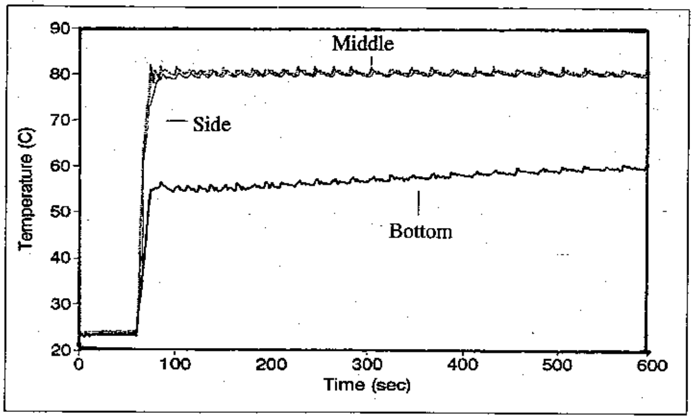

Figure 3: *Temperature at three locations in a 40 ml glass vial during on/off controlled microwave heating (set-point temperature = 80°C; 0% CMC; 9% NaCl; Agitation = NONE)*

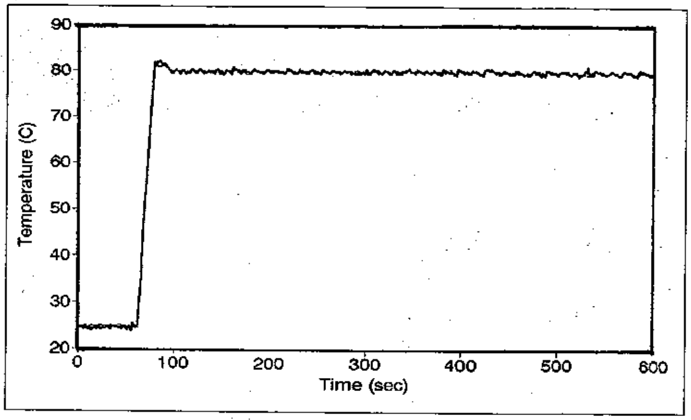

Figure 4: *Temperature at three locations in a 40 ml glass vial during on/off controlled microwave heating (set-point temperature = 80°C; 0% CMC; 2% NaCl; Agitation = 3 rad/sec)*

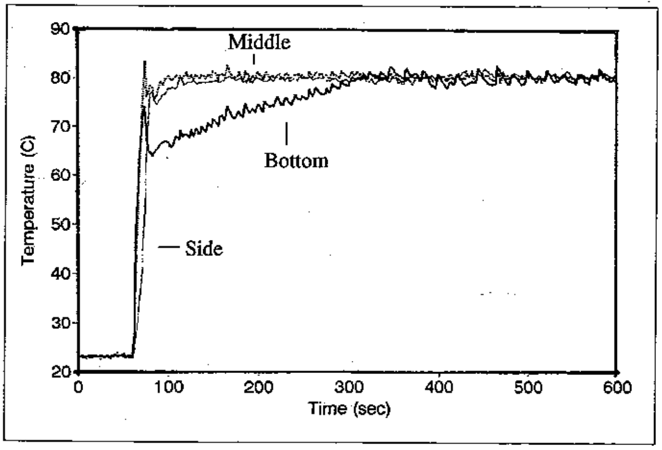

Figure 5: *Temperature at three locations in a 40 ml glass vial during on/off controlled microwave heating (set-point temperature = 80°C; 0.5% CMC; 0% NaCl; Agitation = 6 rad/sec)*

all of the aqueous solutions without CMC. Figure 4 shows that the slowest agitation setting (three radians per second, 172°/sec) provided sufficient agitation in the 2% brine. Similar results were obtained for pure water and a 5% brine solution. Salt content showed no observable effect in terms of temperature gradients on the agitated aqueous samples. It was learned that the initial temperature overshoot observed in Figures 3 through 8 may be eliminated by reducing magnetron power just before reaching the set-point temperature.

The 1% carboxymethylcellulose ("CMC") solution was found to be too viscous to achieve temperature uniformity with any agitation rate available. Figures 5 and 6 show the temperature profiles for 0.5% CMC without and with 1% salt at the maximum agitation rate, respectively. It is evident that salt helped to minimize the temperature gradient. It can be inferred from these figures that the viscosity corresponding to 0.5% CMC represents the upper viscosity limit of the apparatus, as the maximum rate of agitation was marginally able to achieve a uniform temperature during come-up.

An important phenomenon of the microwave heating of cylindrical and spherical objects is evident in Figure 7. The figure shows the temperature profile for a cylinder geometry of the viscous 0.5% CMC solution, without salt and without agitation. Looking at the radial cross section (i.e. the temperature difference between the center temperature and the side temperature at the same level in the vial), it is evident that the center temperature is greater than that for the side. This is due to a "focusing" or an increase in microwave power density as the microwave energy impinges on the center of the cylinder in the radial direction. The focusing effect has been shown by Ohlsson [1973].

Data obtained from the 0.375% CMC solutions (approximately 200 cp) confirmed the upper viscosity limit of approxmately 200 cp. Figure 8 shows the temperature profile of 0.375% CMC with 1% salt and the maximum rate of agitation. Data for the same solution, but for the minimum agitation rate showed a 5°C vertical temperature gradient at the end of the come-up time, which was totally eliminated in about two minutes. Data for the 0.375% CMC solution without salt were similar to those with 1% salt at the maximum agitation rate, but were inferior to those at the minimum agitation rate.

There are many conceivable applications for this apparatus in the comparative study of microwave to conventional heating techniques. Work underway in our laboratory involves the study of migration kinetics of plasticizers from packaging films, the kinetics of degradation of food quality factors in aqueous systems, and microbial inactivation kinetics.

The device is unique in that it (1) provides real time temperature data, (2) is able to eliminate the problem of temperature gradients during microwave heating, (3) provides a very quick come-up time, and (4) minimizes evaporative losses through the use of an hermetically sealed cap.

The maximum temperature limit of the apparatus depends on the integrity of the septum and the vapor pressure versus temperature relationship of the solvent used. Experience shows that the hermetic sealing capacity of the septum about the temperature probe fails at temperatures above 100°C for aqueous solutions. The septum offers the ability to withdraw samples with a syringe during heating, and also provides a penetration route for the temperature probe.

Improvements being made involve a custom-made "vial"

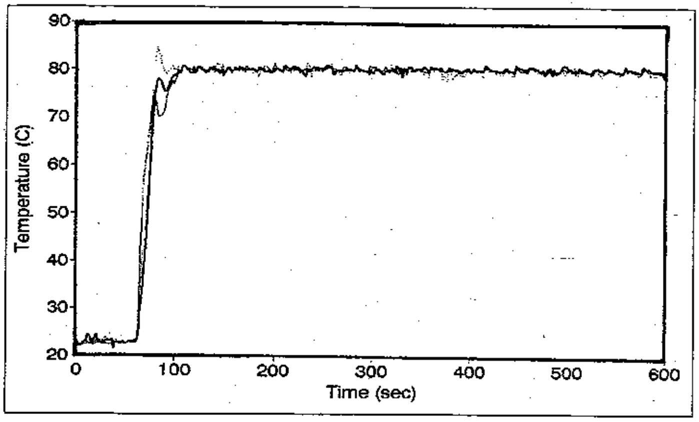

Figure 6: *Temperature at three locations in a 40 ml glass vial during on/off controlled microwave heating (set-point temperature = 80°C; 0.5% CMC; 1% NaCl; Agitation = 6 rad/sec)*

constructed from a high temperature and high mechanical strength plastic, which utilizes Teflon compression fittings for securing the temperature probe. Without the septum, it's believed that temperatures in excess of 130°C will be possible.

Conclusions

In summary, the design and performance of an apparatus capable of agitating a sealed vial in a microwave oven under controlled temperature conditions was described. The performance of the apparatus was determined on the basis of sample temperature uniformity during come-up to, and extended operation at a set-point temperature. The effects of agitation rate, solution viscosity and salt content were studied. The data indicate that the apparatus is suitable for solutions with viscosities less than or equal to 200 cp (0.375% CMC solution).

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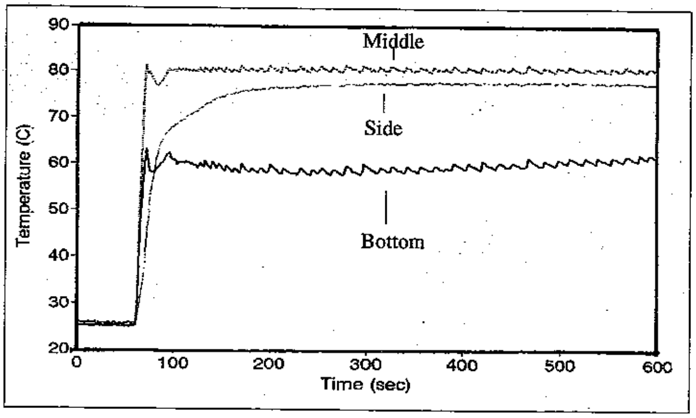

Figure 7: *Temperature at three locations in a 40 ml glass vial during on/off controlled microwave heating (set-point temperature = 80°C; 0.5% CMC; 9% NaCl; Agitation - NONE) [Note the "focusing" effect, which causes the center to heat preferentially over the surface.]*

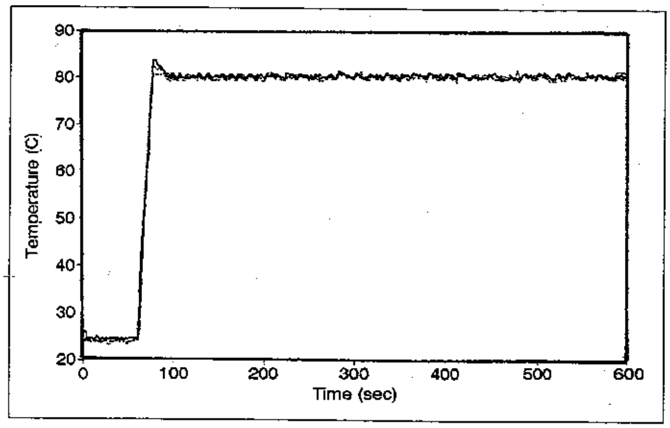

Figure 8: *Temperature at three locations in a 40 ml glass vial during on/off controlled microwave heating (set-point temperature = 80°C; 0.375% CMC; 1% NaCl; Agitation = 6 rad/sec)*

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IMPROVING THE FINAL QUALITY OF MICROWAVABLE FOODS

By Richard M. Keefer and Mel D. Ball

With tightly competitive prepared food markets, the final quality of microwavable foods has become an important topic to food scientists and packaging engineers. Pricing, nutritional design, and ingredient quality all assume secondary importance if the product that comes out of the microwave oven is unappealing. Poor heating performance limits the potential of many products, and can be disastrous for repeat sales of new ones. However, good performance in the microwave oven has yet to be commoditized, and these problems therefore offer exciting opportunities for developing new edges in product performance and sales.

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In exploring how food and packaging design can improve the final quality of microwavable products, we will start by summarizing the central problems of microwave heating. These problems include widely variable total energy absorption, non-uniform heating distributions in individual food components, uneven distribution between the components of meals and in layered foods, and surface heating intensities that are insufficient for browning and crisping.

Total Energy Absorption

Total energy absorption is vital both to final product quality and the proper development of heating directions. While microwave oven power output is the most conspicuous factor affecting total energy absorption, oven cavity, feed design, and location of the food within the cavity must be considered, in addition to the size of the food load, its geometry, and composition. Oven power ratings are determined from temperature-rise measurements in water loads. By contrast, the measurement of food energy absorption is complicated by uneven heating distributions, poor convection, heat conduction, variable heat capacities, and changes of state. For a frozen product, energy has to be supplied to raise the food to the freezing point, thaw the product, and then heat it to the desired final serving temperature. Weight losses due to evaporation and boiling also expend much of the energy provided. Figure 1 shows the relative amounts of energy corresponding to each of these stages.

For many frozen products, the energy needed to raise the food from freezer temperatures and thaw it is comparable to the energy requirement of raising the thawed product by 90°C (194°F). Figure 1 also shows that an average weight loss of 10% represents nearly the same energy expenditure as bringing the product through 70°C (158°F). In addition to its adverse effect on product quality, this energy is essentially wasted.

However, only a small portion of the energy budget of a product that is well designed should go to evaporative losses. This brings dividends in final quality, reduced heating times, and energy conservation. Development priorities should include methods of controlling total energy absorption and heating rates, together with doneness indication where appropriate.

Non-Uniform Heating Distributions

Non-uniform heating impacts heavily on the final quality of microwavable foods and may account for stagnant categories and short product life-cycles. It is first seen as uneven thawing in frozen foods, then as hot and cold spots in thawed products, and finally, in localized excessive weight losses as product temperatures approach the boiling point. These problems are exacerbated by runaway effects in designs allowing high heating rates or with inherently uneven heating. In frozen foods, uneven heating distributions need to be considered in the context of the total requirements of thawing and heating to a target temperature.

Figure 2 correlates frozen food energy

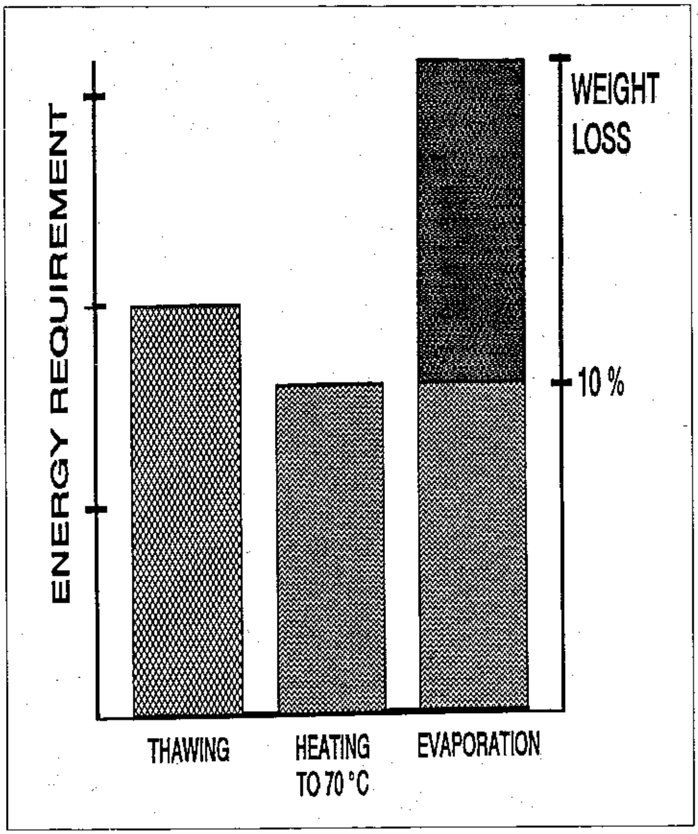

Figure 1. Energy budgeted for a frozen food

absorption with product temperatures. Against the overall energy absorption corresponding to a target temperature of 70°C (158°F), it can be seen that a 10% reduction of absorption would lower final temperatures by more than 20°C (36°F). On the other hand, relatively subtle changes of food and packaging design bringing small changes in energy absorption may increase final temperatures sufficiently to compensate for much heating non-uniformity.

Overall weight losses, and their distributions resulting from non-uniform heating are important indicators of final product quality. For refrigerated items, total weight losses will seldom exceed 5% in reaching a final temperature of 70°C (158°F). However, as distinct from conventional heating, these losses are usually concentrated at the edges of a product, and are negligible at its center. In frozen foods, overall weight losses are considerably higher, often resulting in toughness and heat damage. While high weight losses detract from appearance and other attributes, toughness may render the products unsuitable for children, or the elderly with dental problems. At overall weight losses of 10%, losses at the edges of a frozen food product may be 30% or more. Consequently, an overall weight loss of 10% provides a useful design threshold in avoiding final quality problems.

Figure 3 compares weight losses and temperature distributions over an idealized container cross-section. Product weight losses are represented stepwise, owing to practical sampling requirements. The flattening of temperature distributions near the boiling point is often confused as an improvement of heating uniformity with lengthened heating cycles. However, on examining weight losses, energy which would otherwise be applied to heating is instead found to be absorbed as latent heat of evaporation. At the boiling point, food power absorption of 700W will cause desiccation at a rate of approximately 18.6 grams per minute, corresponding to a weight loss of 6.2% for a 300 gram product. As may be seen from DSC and TGA measurements, this rate decreases slightly on extended heating, because of the larger energy requirements in removing bound water.

Beyond temperature and weight loss issues, uneven heating has led to controversy over the microbiological safety of microwavable foods. While scattered publications had appeared previously, a study commissioned by MAFF in the U.K. raised concerns over the presence of cold spots, and the ability of the microwave oven to provide pasteurization in contaminated foods. This controversy grew out of the larger presence of chilled foods in the U.K. and Europe, and the public perception that heating should render products safe. There is no basis for microbiological concerns in North American frozen food supplies, but this is offset by the same consumer expectations of heating, combined with the greater heating problems of frozen foods. Because the perception of quality is linked with thorough heating, good practice calls for product design and directions yielding a minimum temperature of 70°C (158°F) at the end of the heating cycle. The presence of lower product temperatures is a flag for problems of product design or directions.

Mechanisms Accounting for Non-Uniform Heating

There has been much study of microwave heating mechanisms, led by food companies such as Unilever, Grand Metropolitan, Kraft General Foods, and Nestlé, and such packagers as James River and Alcan. In addition to experimental studies of microwave interactions with food, important theoretical work has been carried out using both numerical and analytical modelling techniques. Nu-

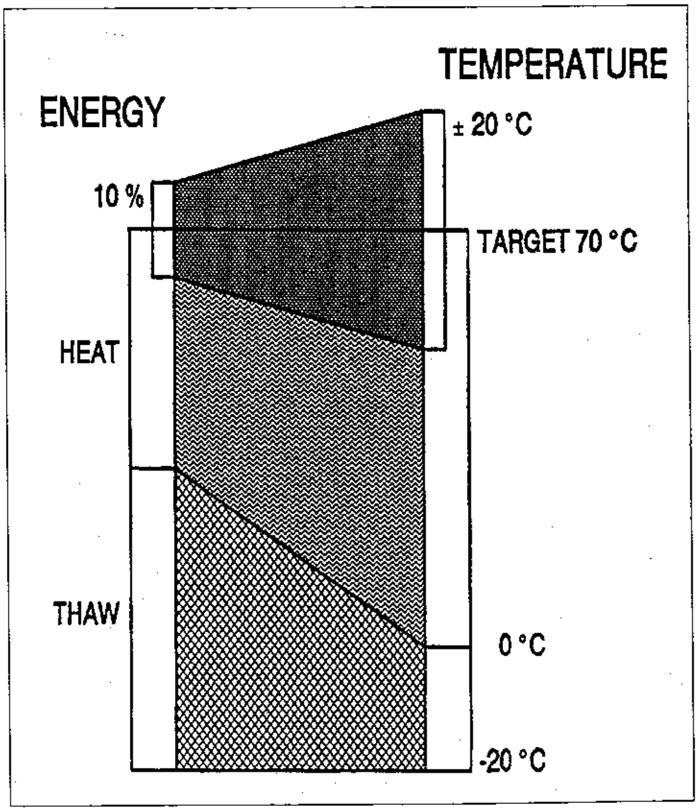

Figure 2. Final temperature versus energy absorption

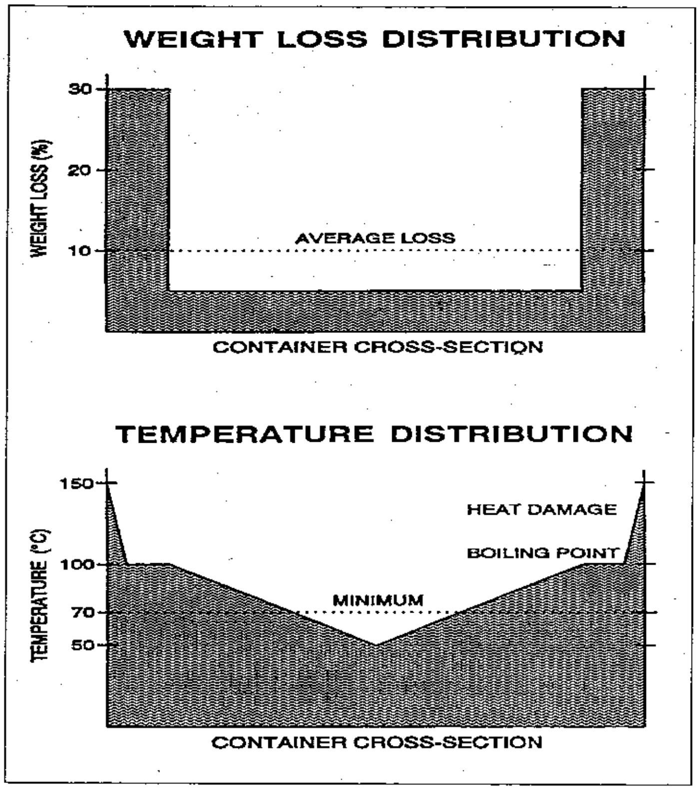

Figure 3. Weight loss and temperature profiles

merical methods allow complex systems to be described on a workstation or mainframe scale, but beyond describing an existing set of assumptions, they offer few tools that can be applied to new design iterations. Analytical methods can only be applied to a limited range of food geometries and structures, but they provide useful predictive insights. Because of their simplicity, analytical solutions can be evaluated on basic PCs and laptops.

Taking a composite view of the work in this field, uneven heating can be explained as a blend of resonant and absorption mechanisms. The surfaces of high moisture foods are highly reflective to microwave energy, and food dimensions are of roughly the same order as the 12.2 cm (4.8 in) wavelength of this energy. Microwave energy entering a food will be partially absorbed on traversing it, but it will also be reflected between opposing surfaces. The resulting multiple reflections give rise to interference or resonance effects, and resonant storage of energy within the food. Because the energy storage of a dielectric resonator increases in direct proportion to its dielectric constant, it is worth considering that in the absence of losses, a refrigerated entrée is capable of storing roughly the same amount of energy as the oven cavity itself.

Resonant effects provide a simple explanation for the symmetrical heating patterns that can be observed in many foods, and through their additivity, explain the shifts of heating patterns which result from changes of oven position or the use of active packaging components. The thermal image of Figure 4 provides an example of these symetrical patterns, with the lightly shaded regions hottest and dark regions showing relatively little heating. Lobed heating patterns can be observed in other geometries and will often persist over a range of ovens and positions within the oven cavities.

Uneven Heating Distributions in Multi-Component Foods

Design of multi-component meals or layered foods must contend with a compounding of the total energy absorption and heating distribution problems of the individual food items. As depicted in Figure 5, the heating rates and energy requirements of meal components can vary dramatically for differing component compositions and densities.

Commercial frozen meal designs have approached these problems empirically, using plating, tolerant ingredient combinations, and covers or wraps to retain moisture. In some instances, heating of central regions of the products is as much a result of steaming as the direct absorption of microwave energy, as may be seen from temperature and weight loss measurements of the uncovered meals.

Steaming narrows the range of possible meal combinations, and gives a "crock pot" taste, or averaging of flavors. Empirical design requires a large number of iterations, which lengthens development cycles and limits flexibility. Better final meal quality should expand sales against other alternatives, as well as enlarge institutional and meal plan opportunities.

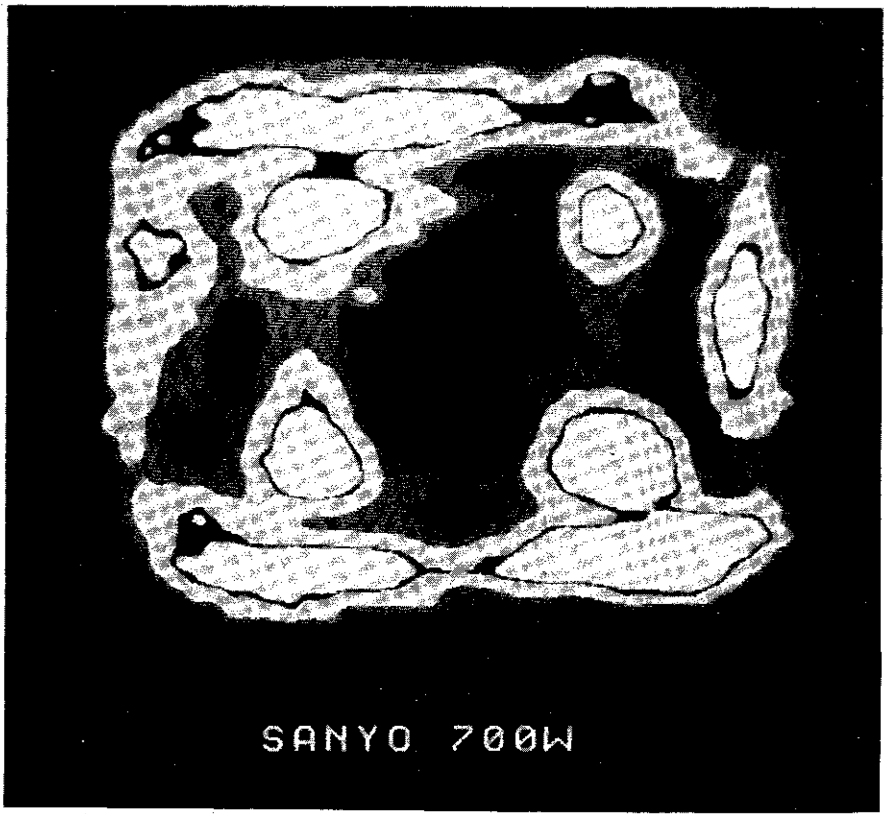

Figure 4. Heating distribution in square plastic container

Browning and Crisping

The inability of the microwave oven to provide browning and crisping has given rise to many innovative susceptor developments. Temperature profiles of most susceptors are influenced by the same factors that give rise to uneven heating in an adjacent food bulk, suggesting that quality improvements should address all aspects of heating.

There have also been a number of attempts at obtaining browning effects by acceleration of Maillard reactions, by inducing "controlled runaway," and through the concept of the "self-suscepting food." The shortcoming of schemes based only on compositional modifications is their dependence on absorption limited by the dielectric relaxation term $(\varepsilon_S - \varepsilon_\infty)$.

New Approaches in Food and Packaging Design

Having outlined some of the important issues affecting the final quality of microwave-heated foods, we are now in a position to discuss representative solutions. In recent years, a large number of innovative packaging and product designs have emerged, and several of these will be described in the following sections.

Total Energy Absorption

Starting with the need to control heating rates and total energy absorption, a variety of matching and shielding devices have been developed to increase or decrease the intensity of microwave energy incident on the food. Doneness indicators allow the consumer to identify an end-point in total energy absorption.

Shielding: Shielding broadly refers to the lowering of heating rates through the use of microwave-opaque metal components or highly reflective, artificial dielectric structures. When approached separately from the need to improve heating distributions or protect heat-sensitive regions of a product, the food is enclosed in a perforated metal container or composite, sometimes described as a moderator. The size and number of perforations determine the

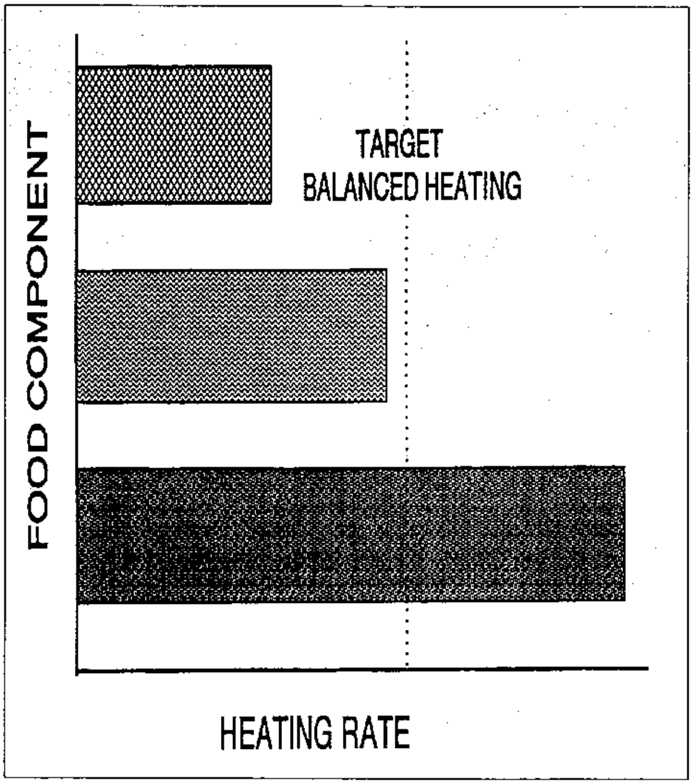

Figure 5. Multi-component meals: balancing of heating

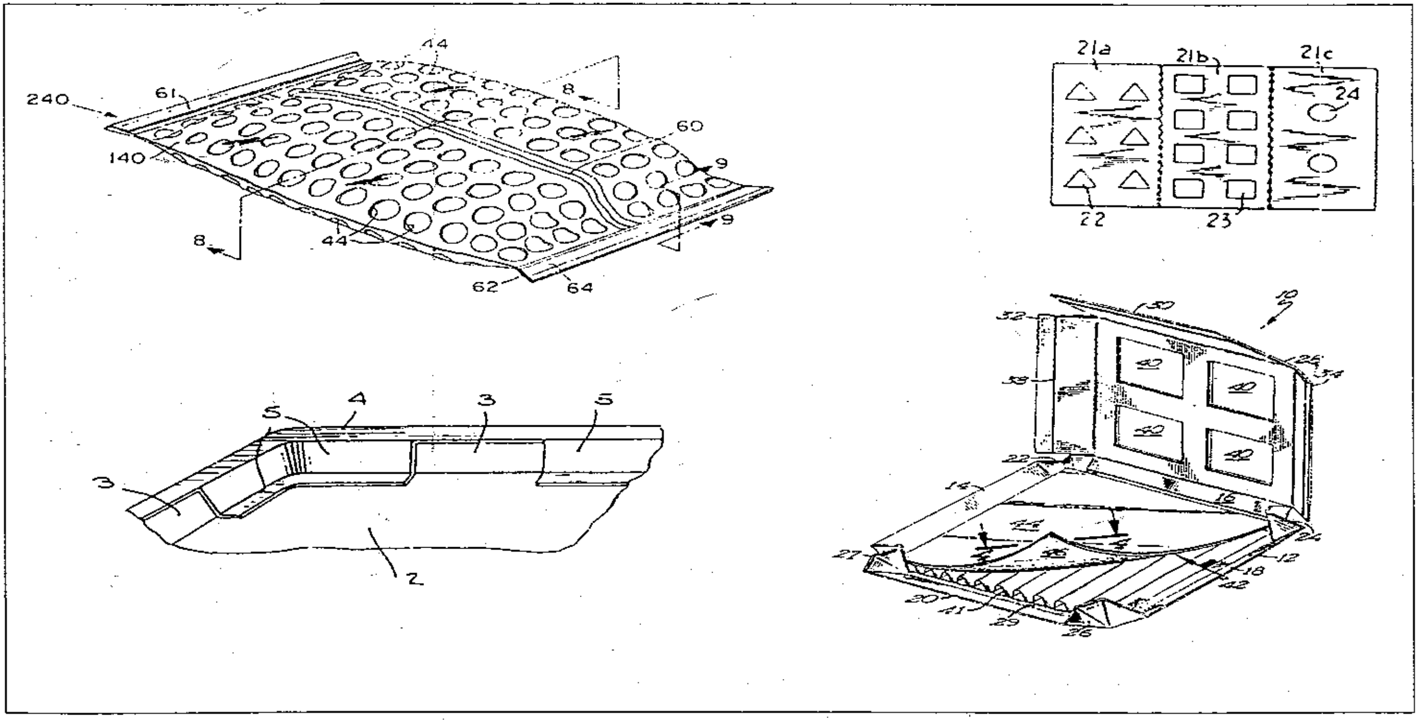

Figure 6. Examples of shielding devices