Microwave foods: basic design considerations

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The development of food products and containers has been complicated by the lack of standard nomenclature and power levels in microwave ovens.

The spectacular sales of microwave ovens have led to the development of several support industries, with food, packaging, and cookware being prime examples. The cookware industry was the first to pursue the microwave owner with the view of providing special microwave cookware. Although sales of these products continue, surveys of U.S. consumers indicate that people rarely cook food in their microwave ovens. Rather, this appliance has become a "reheater" for warming up leftovers and convenience foods.

The market for microwaveable foods began to grow in earnest in 1984, when the saturation level of microwave ovens passed the 40% mark. Since then, the number and variety of microwaveable foods on the market has increased steadily. A recent study by the Campbell Microwave Institute predicts that U.S. sales of microwaveable-only foods will be $750 million by 1990.

While the technology for developing microwaveable foods is improving, it still has a long way to go. Many of the products reaching the marketplace are of low or intermediate quality. The number of products that work well in all microwave ovens is very small. The reasons for the difficulties evolve from the very unusual ways in which microwaves heat and the unusual ways in which foods and other materials respond to microwave energy. For this reason, it is essential that developers of microwaveable foods understand the fundamentals of microwave heating in order to be successful in product development.

Parameters affecting microwave heating

The ability to heat a material with microwaves is affected by the type of equipment being used and the nature of the material being heated. The impact of each of these must be considered in the design of a product.

Frequency

The frequency of microwave oven heating is fixed at 2450 MHz. Wavelength also plays an important role in microwave heating, but its effect in foods is often misunderstood. While the wavelength at this frequency is 12.2 cm in air, it decreases dramatically as the waves pass through materials, as seen in Eq. 1.

$$\lambda_m = \lambda_0 / (\epsilon')^{1/2} \qquad (1)$$

where

λ_m = wavelength in a material

λ_0 = wavelength in free space

ϵ' = relative dielectric constant of the material.

Thus the wavelength in water is almost 1/9 that in air, since the relative dielectric constant of water at room temperature is 78, while that of air is 1.0.

Wavelength affects the depth of penetration of the microwaves into a material, as seen in Eq. 2.

$$D = \lambda_0 (\epsilon')^{½}/2 \pi \epsilon'' \qquad (2)$$

where

D = the penetration depth, i.e., the depth at which 63% of the incident energy is absorbed

For example, the penetration depth for water at 2450 MHz is approximately 1.4 cm. At 915 MHz, this increases to 3.7 cm, largely because the wavelength at this frequency is 33.0 cm.

Frequency has another role, since the dielectric properties vary with frequency. For example, for pure water at room temperature, the loss factor at 2450 MHz is approximately three times greater than it is at 915 MHz, while for a 0.1-*m* sodium chloride solution, the loss factor is more than twice as large at 915 MHz.

Microwave power and speed of heating

The higher the microwave power input, the faster is the heating for a given mass. However, it is possible to heat too rapidly. Cooking, baking, and other food-preparation processes are complex physicochemical systems that require the input of heat to initiate and accelerate reactions. These reactions must occur in the proper sequence, and each reaction requires a certain period of time for completion. Microwave ovens can provide heat faster than the food can keep up with it. One can "cook" chicken parts in 30 s or less with microwaves if "cook"

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means only to raise the internal temperature to some desired level, say 170°F. However, this would not provide enough time for the cooking reactions that tenderize the meat, and the rubberlike texture of the resultant product would render it inedible.

Excessive heating speeds also can lead to nonuniform temperature distribution. This occurs when the heating speed is so fast that there is no opportunity for the transfer of heat to the cooler portions through thermal conductivity.

Mass

Generally, the greater the mass of a material, the longer it will take to heat in a microwave oven. However, the efficiency of heating usually increases as the mass gets larger. That is why if it takes 4 min to cook a single potato, it may only take 7 min to cook two and 10 min to cook three potatoes. This is a phenomenon known as load factor.

Moisture content

Water is usually the dominant influence in how well a material, particularly a food item, absorbs microwave energy. In most cases, the greater the moisture content, the higher is the dielectric loss factor and, hence, the better the heating. However, a product with lower moisture also may heat well because of its lower specific heat capacity. The effects of specific heat are addressed later in this article.

Density

The density of a product has an effect upon its dielectric constant. The dielectric constant of air is 1.0 F/m and air is, for all practical purposes, completely transparent at microwave heating frequencies. Thus, the presence of air within a food product will reduce the material's dielectric constant. (Conversely, the dielectric constant of a material increases almost linearly with density.) Very porous materials, such as bread dough, contain a lot of air and thus are good insulators. As these materials are baked, their density increases, which makes them even better insulators. Heat transfer into these well-insulated materials is very slow in conventional ovens. However, the deep penetration of microwaves allows bread to be baked in about one-third the time needed in a conventional oven.

Temperature

The temperature of the material can affect microwave heating in several ways:

1. The dielectric loss may increase or decrease with temperature, depending upon the material. Since the temperatures and moisture levels change during heating, they may have a profound effect upon the dielectric constant, dielectric loss factor, and loss tangent, and it is important to know what functional relationships exist among these parameters in any material.
2. Freezing has a major effect upon a material's heating ability because of the vastly different dielectric properties of ice and water, listed in **Table I**. Whereas water is highly absorptive and heats well, ice is highly transparent and does not heat well at all. The usual experience with microwave thawing is runaway heating, with one area of the product heating excessively while the remainder is still frozen.
3. The starting temperature of food products being heated by microwaves should either be controlled or known, so the microwave power or time can be adjusted to obtain uniform final temperatures.

I. Dielectric properties of water and ice at 2450 MHz

Substance	*Relative dielectric constant (ϵ'), F/m*	*Loss tangent (tan δ)*	*Loss factor*
Water (25°C)	78	0.16	12.48
Ice	3.2	0.0009	0.0029

II. Differences among microwave ovens on the consumer market

Power output	300-750 W or more
Cavity size	0.3-1.8 ft^3
Microwave feed system	Mode stirrer Rotating antenna Rotating waveguide
Location of microwave input	At top of oven cavity At both top and bottom of the oven At the sides of the oven
Cavity wall construction	Stainless steel Painted cold-rolled steel
Presence or absence of turntable	
Use of glass shelf or metal rack	
Applied energy	Microwave only Microwave-convection Microwave with a browning element

Physical geometry

The physical geometry of the product also affects microwave heating.

Size. If the size of each individual piece is very large in comparison with the wavelength and, more importantly, with the depth of penetration, the heating will not be uniform. In other cases, where the size is closer to the wavelength, the temperature may be highest in the center.

Shape. The more regular the shape, the more uniform is the heating. Sharp edges and corners should be avoided, since these areas tend to overheat. Round is better than square, and a torus is an ideal shape. If the shape is unusual, i.e., highly nonuniform, as in a chicken leg, there is a real risk of overheating the thinner portions near the ankle, while the large muscle portion is still being cooked.

Conductivity

Conductivity describes a material's ability to conduct electric currents by the displacement of electrons and ions. While dipolar rotation is the dominant means of generating heat in microwave systems, ionic conduction plays a major role in many cases, especially in food systems. The addition of salt can affect the microwave heating of a product, in some cases increasing its heating rate. However, such modification must be done judiciously, since it also will affect the depth of penetration, possibly causing more intensive heating near the surface and leaving the interior much cooler.

Thermal conductivity

Thermal conductivity can be a significant factor affecting microwave heating in cases where the material is subjected to an extended heating time or when the depth of microwave penetration is not great enough to uniformly heat the center of a large material. In cases where the time is short, thermal conductivity plays a secondary role, and it may be necessary to extend the heating time to achieve its benefits.

Specific heat

Specific heat capacity is an important but often neglected factor in microwave heating. It is this property that can allow a material with a relatively low dielectric loss to heat well in a microwave field. An example is the heating of fats and oils. The specific heat of cooking oil is 2.0 kJ/kg·°C, whereas that of water is 4.2 kJ/kg·°C. At first glance, one would predict that oil will not heat well in a microwave field. In fact, oil may heat considerably faster than water because of its far lower specific heat.

Problems of microwave product development

We can classify the problems in the development of microwaveable foods into three categories:

1. Problems related to the microwave oven
2. Problems related to the interaction with food materials
3. Problems related to the packaging or utensils.

In some cases, the line of demarcation between these categories is fuzzy, and a problem may fall into more than one category.

Problems related to the microwave oven

Lack of uniformity of the microwave field within an oven. Each individual microwave oven has its own distinct electromagnetic field pattern that creates hot and cold spots when heating a food product. Field stirrers, turntables, and similar devices have been fairly effective in minimizing or overcoming this problem. Food packagers take a similar approach, recommending that the product be turned 90° or 180° once or twice during the cooking cycle, as well as the use of lower power settings or standing times to allow for thermal equilibration via conductive heat transfer.

Lack of uniformity between ovens. Ovens made by different manufacturers, as well as different models made by the same manufacturer, have various power levels and ranges of power. A top-of-the-line model by a manufacturer may have 10 different power settings, with intermediate models having two or three settings (high, medium, and defrost) and the least-expensive model having a single power level. The problem is further complicated by the fact that in domestic and commercial microwave ovens, the differences in power levels are achieved by changing the amount of time the microwave oven is on during its duty cycle, and these duty cycles vary from one manufacturer to another. Pulse times may be as long as 60 s or as short as 1 s or less. Table II shows that the lack of uniformity in microwave ovens goes well beyond the issue of power output.

Lack of standard nomenclature and power levels. There are no agreed upon cooking terms for microwave ovens. Thus, one oven's "high" setting may be another's "roast" setting. In addition, that high power may be anything from 350 W to 750 W. To make it all worse, there are no standard procedures for the measurement of output power.

Lack of ambient heat. One of the strangest phenomena faced by the food technologist is the lack of ambient heat in most microwave ovens. The air temperature in the microwave oven remains at or near that of the room. This, plus the cooling effect of evaporation, leads to the unusual situation in which the surface of the product can be cooler than the interior. It is this effect that inhibits browning and leaves foods moist and limp rather than brown and crisp.

Problems related to the interaction of microwaves with food materials

There are a variety of problems related to the interaction of microwaves with food. The first three of the following items have already been addressed earlier in this article.

Change in loss characteristics with temperature and moisture content. The dielectric loss may increase or decrease with temperature, depending upon the material.

Frozen vs. thawed material. Freezing has a major effect upon a material's heating ability because of the vastly different dielectric properties of ice and water. Water is highly absorptive and heats well, while ice is highly transparent and does not heat well.

Shape, mass, and density of the product. Regular shapes tend to heat more uniformly. The mass of a material affects the depth of microwave penetration. The dielectric constant of a material increases almost linearly with density.

Lack of tolerance to rapid heating rates. The high power of microwave ovens may heat foods too quickly. The nature of this problem is apparent if one recalls that food systems are dynamic chemical and physical systems in which more than just heating must occur. Such things as enzymatic reactions, development of leavening gas, and structure setting must occur in carefully timed sequences. If the rapid application of heat disrupts this process, the result can be an inedible, unappetizing, or unacceptable food product.

Deep-heating effects. Microwaves promote bulk heating, in contrast to conventional ovens, where heat is transferred from the outer surfaces to the interior. This can lead to some unusual problems. Typical of these is excessive drying or even charring of the interior while the surface remains cool and moist. A more subtle effect is sometimes encountered in baked goods, which can rapidly become tough or stale, possibly the result of interior temperatures that are higher than normally encountered in baking, coupled with greater movement of moisture toward the surface. It appears that such phenomena can be eliminated through better control of the application rate of microwave energy along with judicious selection and formulation of food items.

Unusual temperature, moisture, and pressure gradients. The unusual temperature gradients in microwaved food—low surface temperatures, high interior temperatures, and edge-heating effects—have already been described. However, microwaved foods are subjected also to unusual moisture and pressure gradients. In a conventional oven, heat is applied externally and the transfer of heat from the outer surface to the interior is governed by the temperature gradient between these two areas. Similarly, the transfer of mass from the wet interior to the drier surface is governed by the mass-concentration gradient. In the case of the microwave oven, however, food is heated internally, and internal heat generation is the primary mechanism of energy transfer. Thus, mass transfer occurs primarily in response to a total pressure gradient resulting from the rapid generation of vapor inside the product. While often not severe, the effects can be important and even damaging at higher power levels. For example, this may cause eruption of the contents from food containers.

Multicomponent food systems. Multicomponent food systems—hamburgers and buns or frosted jelly donuts—present a significant challenge to the food developer. Each component is likely to have different loss characteristics, specific heats, and thermal conductivities. Thus, sufficient heating of one component often proves to be too little or too much for the other. In the case of the hamburger, the bun would tend to become very tough, while the meat would be fine. A simple expedient would be to heat each separately or partially shield the bun. In other cases, food formulation may be required to balance the specific heats or dielectric properties. If the rate of heating rate can be slowed down, thermal conductivity from one component to another may provide a solution to this problem.

Problems related to the utensils or packaging systems

The food technologist is faced with a bewildering array of products, materials, and problems in this area.

Changing loss characteristics. With the exception of susceptor films and browning dishes, most containers are designed to be transparent to microwaves. Unfortunately, the transfer of heat from the food to the container can cause plastic materials to melt or become distorted.

Possible conventional oven compatibility. Paperboard and plastic packaging for frozen products has made significant inroads into an area once dominated by aluminum foil. If these products are to be universally employed, however, they also must be capable of withstanding conventional oven temperatures.

Ability to withstand extremely high temperatures. Besides the problem of changing loss characteristics, there is the possibility of contact with food products that have been heated to very high temperatures. The result is distorted, scorched, or melted utensils. For example, the fat rendered from bacon can be heated to excessively high char temperatures of 260°C (500°F). Overheating also can be caused by misuse of susceptor films. These films can reach temperatures well in excess of 200°C (400°F), which can cause charring or melting of the containers and overheating of the contents.

Techniques for product development

Those engaged in product development are advised to:

- Understand the fundamental mechanisms of microwave heating as well as the interaction of microwaves with different types of food.
- Analyze the thermal requirements of the system.
- Analyze the microwave loss characteristics of the product.
- Develop products that can tolerate high heating rates.
- Develop products that can utilize lower power settings and the defrost cycle, reserving higher power to heating bulk liquids or foodstuffs such as roasts.
- Modulate loss factor, specific heat, and thermal conductivity to achieve the best results.
- Choose a container shape, size, and material to give the best uniformity and performance.
- Test the product in a variety of ovens under conditions of normal and abusive use.
- Cooperate with utensil or packaging materials manufacturers early in the product-development cycle.□

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