APPLICATION NOTE

MICROWAVE HEATING APPLICATIONS
PART 1: FUNDAMENTALS

PROBLEM

Most people are familiar with heating as an application of microwave technology. Beyond the microwave oven in your kitchen, however, there are many industrial scale heating applications that can benefit from the use of microwave technology. As well, the design and implementation of effective industrial-scale microwave heating systems requires specific knowledge that only a limited number of equipment suppliers possess.

These perceptions not withstanding, it is often beneficial to use microwave heating in industrial applications since the ROI in heating systems employing microwaves is often superior to that in systems using IR heating lamps. The key is to understand when microwave heating is more cost effective than conventional heating. Non-specialists can assess whether or not microwave technology is advantageous in a particular heating application by applying some simple rules for analyzing the energy transfer characteristics in common industrial heating processes, and by considering the different ways that microwaves and conventional heating techniques supply energy to the substrate to be heated. This Application Note provides an introduction to microwave fundamentals and addresses the considerations necessary for choosing microwave or conventional heating.

Two companion Application Notes provide:

a) An overview of equipment and process factors to be considered when implementing industrial-scale microwave heating processes

b) A detailed discussion of the operational aspects of magnetrons, microwave power supplies and applicators.

BACKGROUND

Microwave heating is one of the most rapid and energy-efficient ways of heating materials; most people have some familiarity with its use owing to the presence of microwave ovens in most homes. Microwave heating differs from conventional thermal transfer at a fundamental level. Whereas conventional heating operates via thermal transfer from the surface of an object toward its center, microwaves deliver heat uniformly and simultaneously throughout the bulk of a material. This difference can provide unique advantages for microwave heating in many applications.

Large scale industrial applications of microwave heating leverage the advantages of uniform heat distribution that is not achievable with conventional heating methods. Industrial applications include wood and coal drying, plastics and rubber processing, ceramic curing and food processing among others. It should be noted that microwave technology is increasingly used in industrial chemical processing due to microwave's influence on reaction kinetics, providing shorter time to reaction completion.

Microwaves and Matter

Microwaves are electromagnetic waves in the frequency range between 300 MHz and 3000 MHz (wavelengths from 1 meter to 1 mm, respectively). When incident upon different materials, microwave radiation interacts in different ways, dependent on the electrical properties of the material. Microwaves incident on conductors such as metals are absorbed very efficiently by the free electrons in the metal and re-radiate at the same frequency and in phase. The net effect is essentially perfect reflection of the microwaves. Insulators such as glass and various ceramics, on the other hand, are transparent to microwaves, transmitting with little or no loss. In between these extremes lie dielectric materials which absorb microwave radiation to varying degrees. When microwave radiation is incident on a dielectric material, the molecules of the material (which typically have permanent or induced dipoles) try to align themselves with the rapidly alternating electric field component of the microwaves. At high frequencies, the inertia of the molecules retards this alignment and the dipole motion lags behind the electric field. At GHz (i.e. microwave) frequencies, the phase lag absorbs power from the applied field, an effect known as dielectric loss. This power loss manifests as heating in the dielectric. In this way, irradiation by microwaves becomes a means by which certain materials can be heated.

The frequencies most commonly used for microwave heating applications are 2450 MHz for domestic and some industrial applications, and 915 MHz for most large scale industrial applications. The frequency choice is dictated by FCC regulation and application-specific characteristics such as materials permittivity.

Microwave wavelengths are defined by the relationship:

$$\lambda_o = \frac{c}{f}$$

where λ_o is the wavelength, c the speed of light and f the microwave frequency. For microwaves with a frequency of 2.45 GHz, this translates to a wavelength of 12.25 cm.

Microwave Generation and Delivery

Microwave heating systems consist of three primary components: the microwave source, including power supply and magnetron; waveguides that transmit the microwaves from the source to the point of application; and the applicator, a chamber designed to promote effective coupling of the microwave energy into material heating.

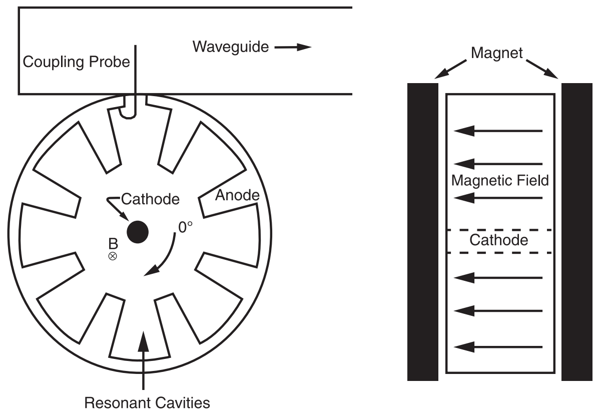

Figure 1. Resonant cavity magnetron a) top view; b) side view (from Ref. 5).

The most common microwave source in use today is the resonant cavity magnetron (Figure 1), which was developed for use in radar systems by the Allied forces during the Second World War. The magnetron consists of a cylindrical cathode surrounded by a hollow, circular anode containing a number of resonant cavities tuned to the operating microwave frequency. During operation, a magnetic field is applied parallel to the cylinder axis. A kV potential is applied across the electrodes producing orthogonal electric and magnetic fields during operation of the magnetron. Under these conditions, electrons ejected from the cathode follow cycloidal paths and a rotating space charge is produced within the cavity between the cathode and the anode. The resonant cavities in the anode interact with the electrons in this space charge to produce electron “bunches” moving around the cathode at microwave frequencies. The microwave power is extracted from the self-sustained oscillation within the cavity by a coupling loop. More elegant and complete descriptions of the physics of microwave generation are available in the literature [1-4].

Waveguides are metal tubes, usually rectangular in cross-section, which are designed so that the electrical and magnetic field distribution within them resemble standing waves. Detailed designs for waveguide cross-sections are therefore dependent on the wavelength of the microwaves being transmitted. Microwaves propagation within the waveguide typically occurs in what is known as transverse electric (TE) mode. In this mode the electric intensity in the direction of propagation is zero. The most common waveguide mode used is the TE_{10} mode. (In TE_{mn}, m is the number of half-wavelengths across the width of the waveguide, and n is the number of half-wavelengths across the height of the waveguide.) References 1-5 provide more detailed discussion of waveguide characteristics and physics.

The "guided" wavelength within a rectangular waveguide, denoted λg, depends on the dimension of the broad side of the waveguide, a, according to:

$$\frac{1}{\lambda_g^2} = \frac{1}{\lambda_o^2} - \frac{1}{4a^2}$$

Standard waveguides used at 2.45 GHz are:

Name	Internal Size a x b (mm)	λg (mm)
WR 284	72 x 36	231
WR 340	86 x 43	173
WR 430	109 x 54.5	147

The name refers to dimension a in inches (i.e. 2.84", 3.40" and 4.30").

The third critical component for microwave heating is the applicator. An applicator in industrial applications can be either a purpose designed reactor volume or an integral part of the microwave waveguide. Applicator designs determine the efficiency with which microwave energy will be absorbed by the material to be heated. This is due to the fact that the temperature fields within the material being heated are directly determined by the distribution of electric fields within the applicator which are, in turn, defined by the applicator geometry. Microwave applicator designs include waveguides, single and multi-mode cavities and traveling wave applicators. Single and multi-mode applicators dominate heating applications owing to their high field strengths.

Material Properties and Microwave Heating

The characteristic properties that most impact how a material will behave when subjected to microwave radiation are its electrical permittivity:

$$\varepsilon = \varepsilon_o\left(\varepsilon' - j\varepsilon''\right)$$

and its magnetic permeability:

$$\mu = \mu_o\left(\mu' - j\mu''\right)$$

ε and μ are positive real numbers with magnitudes ≥1 that define the electric and magnetic "storage" capabilities of a material. The energy dissipation mechanisms for EM fields in a material are defined in terms of these properties.

ε_o and μ_o are the electrical permittivity and magnetic permeability of vacuum space, respectively:

$$\varepsilon_o = 8.854 \cdot 10^{-12}\ \text{F/m}$$
$$\mu_o = 1.256 \cdot 10^{-6}\ \text{A/m}$$

In vacuum/air there is no energy dissipation, and:

$$\varepsilon' = 1,\ \varepsilon'' = 0,\ \mu' = 1 \text{ and } \mu'' = 0$$

"Normal" materials interact most strongly with the electrical component, E, of a microwave EM field; that is, $\varepsilon' > 1$ and dielectric losses occur in the material, $\varepsilon'' > 0$. Conversely, "normal" materials do NOT interact strongly with the magnetic component, H, of the microwave EM field, so for most materials $\mu' = 1$ and $\mu'' = 0$. ε', ε'' μ' and μ'' are not constants, but rather depend on temperature, physical state and the frequency of the microwave EM field. Note that the frequency of microwaves is shortened in materials other than air, according to the relationship:

$$\lambda = \frac{\lambda_o}{\sqrt{\mu'\varepsilon'}}$$

For example, in Teflon®, with $\varepsilon' \cong 2.3$ and $\varepsilon'' \cong 0.0023$, 2.45 GHz microwaves have a wavelength of 8 cm as compared with 12.25 cm in air.

As noted above, a material with $\mu'' = 0$ and $\varepsilon'' = 0$ is lossless in a microwave field. In heating processes, dissipative losses occur within a material which manifest as heat. These losses are defined as the absorbed power, P, in a volume, V, of a material with dielectric losses ε" subjected to a constant electrical field, E. The relationship between these parameters is defined as:

$$P = (2\pi f)\varepsilon_o\varepsilon^{"}\frac{E_{max}^2}{2}V$$

At 2450 MHz this relationship reduces to:

$$P = 0.1363\varepsilon^{"}\frac{E_{max}^2}{2}V$$

or

$$\frac{E_{max}^2}{2} = \frac{P}{0.1363\varepsilon^{"}V}$$

Thus, to dissipate power, P in a material with dielectric losses ε", requires an electric field with intensity E. Materials with very low dielectric loss require a very high field, E, for effective heating of the material. This can preclude the use of microwave heating with very low dielectric loss materials.

SOLUTION

Common Industrial Heating Processes

The planning necessary for implementation of a microwave heating system involves a number of specific considerations. The first consideration is to fully understand the heating characteristics of the application. Depending on whether the material under consideration is to be simply heated or whether drying or defrosting are involved, these characteristics will vary. Once the heating characteristics of the application are understood, a comparison should be made against more conventional approaches to determine which represents the more effective and economical solution.

Most industrial heating processes fall into one of the following three categories:

(a) The product is simply heated.

(b) The product is to be dried.

(c) The product is to be defrosted (or, more rarely, melted).

Depending on the category, the quantity of heat necessary to raise the material temperature by a set amount will vary.

(a) The Product is Simply Heated

This is probably the most frequent case. For simple heating, the heat required to raise the temperature of a kilogram of material is defined as:

$$Q = c \bullet (T_2 - T_1)$$

where the total heat, Q, is expressed in Kcalories, c is the specific heat of the material in Kcal/Kg and T_2 and T_1 are the final and starting temperatures of the heating process, respectively. For most materials, c has a value of between 0.3 and 1. Microwave heating is very effective in simple heating applications.

(b) The Product is to be Dried

In this case, the heat needed to raise the temperature of the product must include the latent heat of evaporation in any volatile liquid in the material. The heat required to raise the temperature of a kilogram of material in this application is defined as:

$$Q = c \bullet (T_2 - T_1) + r \bullet (U_1 - U_2)/100$$

where r represents the latent heat of evaporation in Kcal/Kg, and U_1 and U_2 the starting and finishing moisture percentage. In the case of water, r is equal to about 550 Kcal/Kg. The power requirements of industrial drying systems are typically very large. For this reason, it is rare that microwaves can be economically employed as the only source of energy in drying applications (e.g. vacuum systems). More typically, mixed systems are employed where the microwaves are positioned as a preliminary drying step to quickly evaporate the initial moisture of the material to be dried, then the final steps are completed with hot air.

(c) The Product is to be Defrosted

For defrosting applications it is necessary to include the latent heat of defrosting in the heat versus temperature relationship:

$$Q = c_1 \bullet (T_f - T_1) + r + c_2 \bullet (T_2 - T_f)$$

Here, c_1 represents the specific heat of the frozen product; r the latent heat of defrosting; T_1 the initial temperature of the material; T_f the defrosting temperature (e.g. ice at ambient pressure = 0 °C); and c_2 the specific heat of the thawed product. Similar to drying processes, r is typically large enough (for ice r = 80 Kcal/Kg) that microwaves are only rarely used for full defrosting. It is usually more economical to take the product to the temperature T_f and to supply only a part (50 - 60%) of r using microwave radiation.

Microwave or Traditional

Depending on the system characteristics and the product to be treated, a well-designed traditional system might be more cost effective than a microwave system, if it reacts in favor of convection heating or transformation. As noted at the beginning of this Application Note, microwave heating differs from conventional approaches in that microwave heating deposits thermal energy equally throughout the bulk of a product, whereas conventional heating heats the product surface and this heat must diffuse inward to the bulk of the material in the product. The factors that favor the use of traditional heating systems over microwave systems include:

- Product to be heated has large surface area and small volume
- Product to be heated has a low specific heat
- Product to be heated has high thermal conductivity
- Long heating times are acceptable
- Increased coefficients of thermal exchange can be used
- Surface temperatures much higher than that required to achieve the end average temperature are possible

In contrast, microwave systems are frequently preferable and even irreplaceable in situations where the above factors are not dominant. For example, it is impossible to pasteurize the sacks of filter fiber used for oenological purposes with traditional heating, because the substrate has a large volume and a small surface area, and has very low thermal conductivity. An extended heating time is unacceptable in this application since it would cause the growth of bacteria that would damage the product. Finally, using conditions that increase the coefficient of thermal exchange is not possible in this case since the thermal conductivity is very low and increased surface temperature would damage the product.

Beyond the clear technical advantages for microwave heating that are demonstrated by applications such as filter pasteurization, there are additional secondary benefits that can be achieved through the use of microwave approaches. These secondary advantages include:

- Ability to process reduced quantities of a product
- Increased process speed
- Ability to interrupt and instantly restart the process
- Ability to improve shelf life
- Ability to improve the product's taste, color, and/or appearance
- Possibility of increased automation
- Reduction in equipment footprint

As well, a somewhat less direct advantage for microwave heating lies in the fact that it is possible to validate a process using small product samples and a good quality domestic microwave oven. This capability offers clear advantages in cost savings when evaluating a new heating process.

CONCLUSION

Microwave heating has many applications beyond the household food preparation familiar to most people. Many industrial heating applications can benefit from microwave heating, either as the sole source of energy or in conjunction with conventional approaches. The most common examples of industrial applications where microwaves can be cost effective are simple material heating, material drying and defrosting. Microwave heating is especially useful in applications where the conduction of energy through the material to be heated is limited. These applications include materials/products with a large volume and small surface area; materials with low thermal conductivity and materials that are sensitive to large temperature differentials between the surface and bulk. As well, microwave heating can be beneficial in applications in which prolonged heating at lower temperatures can lead to bacterial growth that can damage a product.

Non-specialists can determine the most effective approach for an industrial heating application by considering the different energy transfer characteristics of microwaves versus conventional heating and how the physical and thermal characteristics of the material/product to be heated react to this difference.

References

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