Chapter 1

Microwaves

Microwaves, like other radio waves, are a form of electromagnetic waves. Electromagnetic waves are wavelike oscillations of electric and magnetic fields. Electric fields are what makes electric charges attract or repel. Positive or negative electric charges produce electric fields which in turn act on other charges. In a similar way, magnetic fields cause magnetic forces [13]. These fields are perpendicular to each other and continually oscillate between maximum positive and maximum negative (pointing in the opposite direction). The microwaves used to heat food in microwave ovens have a wavelength of 12.2 cm and oscillate at a frequency of 2.45 gigahertz. Giga means billion, so the electric and magnetic fields oscillate fast enough to make 2.45 billion complete cycles each second [13-15].

Microwaves are electromagnetic irradiation in the frequency range 0.3–300GHz (wavelengths of 1mm to 1m), between infrared radiation and radio frequencies. Microwave radiation was discovered as a heating method in 1946, with the first commercial domestic microwaves being introduced in the 1950s. The first commercial microwave for laboratory utilization was recognized in 1978. Over the last decade, microwave dielectric heating as an environmentally benign process has developed into a highly valuable technique, offering an efficient alternative energy source for numerous chemical reactions and processes [16]. It has many advantages compared to conventional oil-bath heating, such as (1) non-contact heating, (2) energy transfer instead of heat transfer, (3) higher heating rate, and (4) rapid start-up and stopping of the heating,(5) uniform heating with minimal thermal gradients, (6) selective heating properties, (7) reverse thermal effects (heating starting from the interior of the material body), (8) energy savings and (9) higher yields in shorter reaction time.

Microwave heating is based on dielectric heating, the ability of some polar liquids and solids to absorb and convert microwave energy into heat. In this context, a significant property is the mobility of the dipoles by either ionic conduction or dipolar polarization and the ability to orient them according to the direction of the electric field. The orientation of the dipoles changes with the magnitude and the direction of the electric field. Molecules that have a permanent dipole moment are able to align themselves through rotation, completely or at least partly, with the direction of the field. Therefore, energy is lost in the form of heat through molecular friction and dielectric loss. The amount of heat produced by this process is directly related to the capability of the matrix to align itself with the frequency of the applied electric field. If the dipole does not have enough time to realign, or reorient too rapidly with the applied field, no heating occurs [17].

The allocated frequency of 2.45GHz employed in all commercial systems is placed between these two extremes, and offers the molecular dipole time to align in the field, but not to follow the alternating field precisely. The heating characteristics of a particular material under microwave irradiation conditions are dependent on its dielectric properties.

When organic synthesis is performed by an external heat source, for example, an oil bath, heat is conducted from the surface into the interior of the specimen, the reaction will be slow and inefficient for transferring energy into the system, because it depends on the thermal conductivity of the different materials that must be penetrated, and results in the temperature of the reaction vessel is being higher than that of the reaction mixture. In contrast, microwave irradiation produces efficient internal heating (in core volumetric heating) by direct coupling of microwave energy with the solvents, reagents or catalysts that are present in the reaction mixture [17–19]. Microwave activation has also been widely used in various polymerization reactions, such as poly condensation, free and controlled radical polymerizations, ring-opening polymerization and polymer processing (including polymer modification, curing processes and preparation of dental materials) [18-19]. Recently, several excellent books and reviews have been published on microwave- assisted polymer synthesis and processing [20-22].

1.1 Electromagnetic Spectrum

The *electromagnetic spectrum* is the range of all possible frequencies of electromagnetic radiation. The "*electromagnetic spectrum*" of an object is the characteristic distribution of electromagnetic radiation emitted or absorbed by that particular object.

The electromagnetic spectrum extends from low frequencies used for modern radio communication to gamma radiation at the short-wavelength (high-frequency) end, thereby covering wavelengths from thousands of kilometers down to a fraction of the size of an atom (Fig. 2) [23].

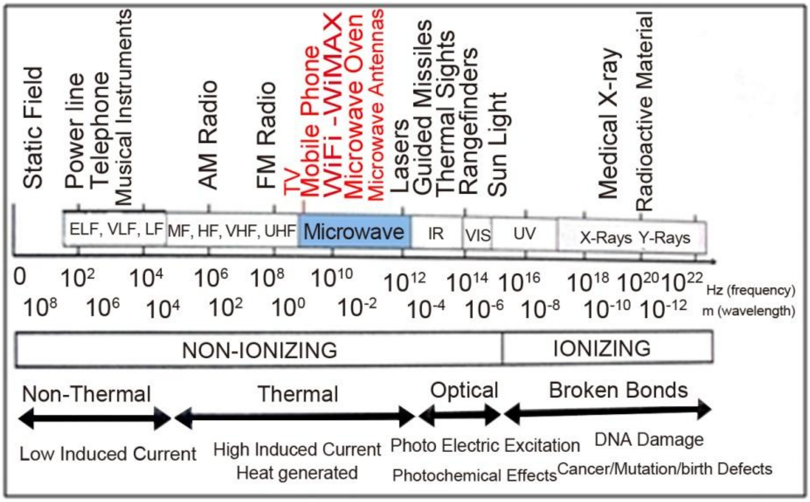

Fig. 2. *The electromagnetic spectrum.*

Table I. *Main interactions of electromagnetic radiation with matter [23].*

Region of the spectrum	**Main interactions with matter**
Radio	Collective oscillation of charge carriers in bulk material (plasma oscillation). An example would be the oscillation of the electrons in an antenna.
Microwave	Plasma oscillation, molecular rotation.
Near infrared	Molecular vibration, plasma oscillation (in metals only).
Visible	Molecular electron excitation (including pigment molecules found in the human retina).
Ultraviolet	Excitation of molecular and atomic valence electrons, including ejection of the electrons (photoelectric effect).
X-rays	Excitation and ejection of core atomic electrons, Compton scattering (for low atomic numbers).
Gamma rays	Energetic ejection of core electrons in heavy elements, Compton scattering (for all atomic numbers), excitation of atomic nuclei, including dissociation of nuclei.
High-energy gamma rays	Creation of particle-antiparticle pairs. At very high energies a single photon can create a shower of high-energy particles and antiparticles upon interaction with matter.

1.2 Fundamentals of Microwaves

Microwave frequencies occupy the electromagnetic spectrum between radio frequencies and infrared radiation with the frequencies of 300 GHz to 300 MHz, (as mentioned before) which corresponds to the wavelengths of 1 mm to 1 m, respectively (Fig.3).Their major applications fall into two categories, depending on whether they are used for transmission of information (telecommunication) or transmission of energy. However, the extensive application of microwaves in the field of telecommunication (e.g., most of the wavelengths in the range of 1 cm to 25 cm are used for mobile phones, radar, and radar line transmissions) has caused only specially assigned frequencies to be allocated for energy transmission (i.e., for industrial, scientific, or medical applications). Currently, to minimize interferences with telecommunication devices, these household and industrial microwave applicators are operated only at a few precise frequencies with narrow tolerance that are allocated under international regulations. For example, the most common microwave applicators (i.e., domestic microwave ovens) use the frequency of 2.45 GHz. This is probably why most commercially available microwave reactors devoted for chemical use operate at the same frequency; however, some other frequencies are also available for heating [24].

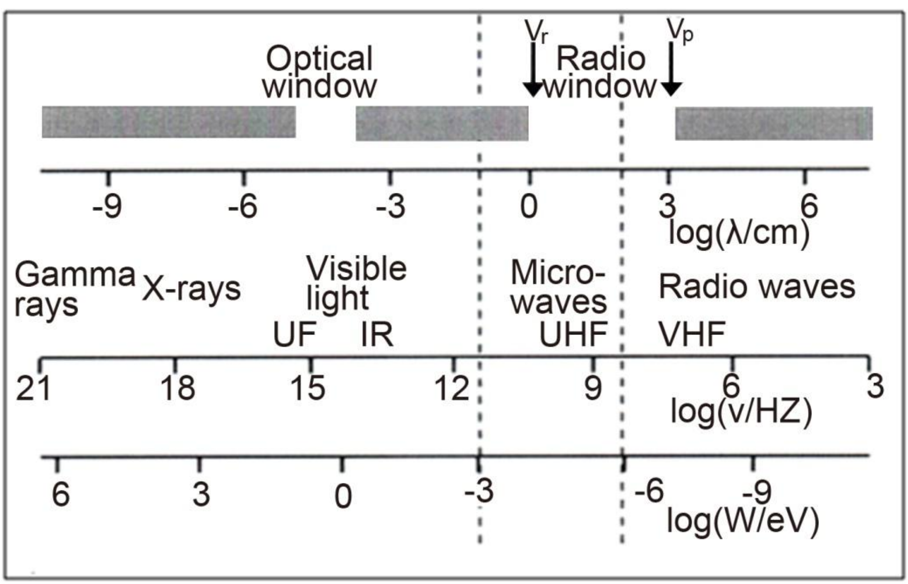

Fig. 3. *Spectrum of electromagnetic radiation: λo, wavelength in free space; W, hν quantum energy;* ν_r*, lowest resonance frequency in the rotational spectrum of water; and* ν_p*, plasma frequency of the ionosphere.*

1.3 Interaction of Microwaves with Materials[24]

When a piece of material is exposed to microwave irradiation, microwaves can be:

a) Reflected from its surface if it is an electrical conductor (e.g., metals, graphite, etc.),
b) Penetrate the material without absorption in the case of good insulators with good dielectric properties (e.g., quartz glass, porcelain, ceramics),
c) Absorbed by the material if it is a lossy dielectric (i.e., a material that exhibits so-called dielectric losses, which in turn results in heat generation in a quickly oscillating electromagnetic field, such as water).

When a strongly conducting material (e.g., a metal) is exposed to microwave radiation, microwaves are largely reflected from its surface. However, the material is not effectively heated by microwaves; in response to the electric field of microwave radiation, electrons move freely on the surface of the material, and the flow of electrons can heat the material through a resistive (ohmic) heating mechanism (Fig. 4a). In the case of insulators (e.g., porcelain), microwaves can penetrate the material without any absorption, losses, or heat generation. They are transparent to microwaves (Fig4b). For some dielectrics, the reorientation of either permanent or induced dipoles during passage of microwave radiation, which is electromagnetic in nature, can give rise to absorption of microwave energy and heat generation due to the so-called dielectric heating mechanism (Fig. 4c).

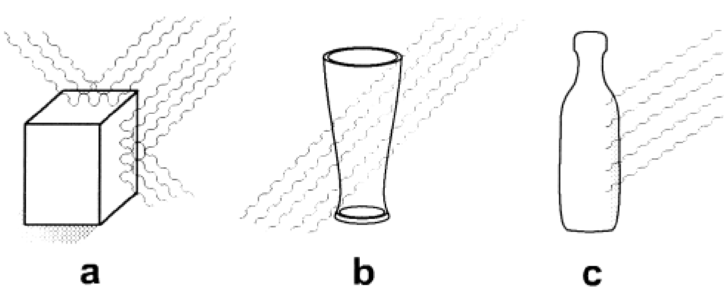

Fig. 4. *Interaction of microwaves with different materials: (a) electrical conductor, (b) insulator, and (c) lossy dielectric.*

Dependent on the frequency, the dipole may move in time to the field, lag behind it, or remain apparently unaffected. When the dipole lags behind the field (polarization losses), interactions between the dipole and the field lead to an energy loss by heating (i.e., by dielectric heating mechanism), the extent of which is dependent on the phase difference of these fields (Fig.5b).

In fact, the electric field component of microwave radiation is responsible for dielectric heating mechanisms because it can cause molecular motion by either migration of ionic species (conduction mechanism) (Fig. 5a) or rotation of dipolar species (dipolar polarization mechanism) (Fig 5b).

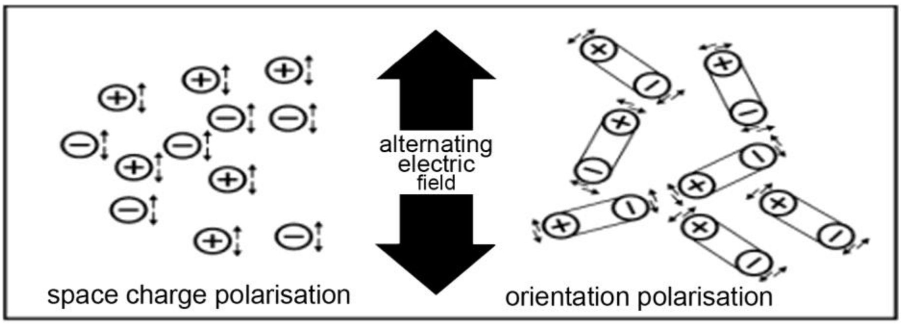

Fig. 5. *Interaction of charge particles and dipolar molecules with electromagnetic radiation: space charge polarization (a) and orientation-polarization (b), respectively.*

In a microwave field, the electric field component oscillates very quickly (at 2.45 GHz, the field oscillates 4.9 x 10^9 times/sec), and the strong agitation, provided by cyclic reorientation of molecules, can result in an intense internal heating that can lead to heating rates in excess of 10 ℃/sec when microwave radiation of a kilowatt-capacity source is used [25].

In practice, most good dielectric materials are solid and examples include ceramics, mica, glass, plastics, and the oxides of various metals, but some liquids and gases can serve as good dielectric materials as well. For example, deionized water is a fairly good dielectric; however, possessing polar molecules (i.e., a dipole moment) can couple efficiently with microwaves to lead to heat generation due to polarization losses. Thus, such substances that are counted among dielectrics but exhibit some polarization losses that result in dielectric heating are also called dielectric lossy materials or in general lossy materials. On the other hand, n-hexane, having a symmetrical molecule, does not possess a dipole moment and does not absorb microwaves.

To apply microwaves to carry out chemical processes, it is most important to find at least one component that is polarizable and whose dipoles can reorient (couple) rapidly in response to changing electric field of microwave radiation. Fortunately, a number of organic molecules and solvents fulfill these requirements and are the best candidates for microwave applications.

The first step is to analyze the reaction components together with their dielectric properties, among which the most important is dielectric constant (ε_r), sometimes called electric permeability. Dielectric constant (ε_r) is defined as the ratio of the electric permeability of the material to the electric permeability of free space (i.e., vacuum), and its value can derived from a simplified capacitor model (Fig. 6).

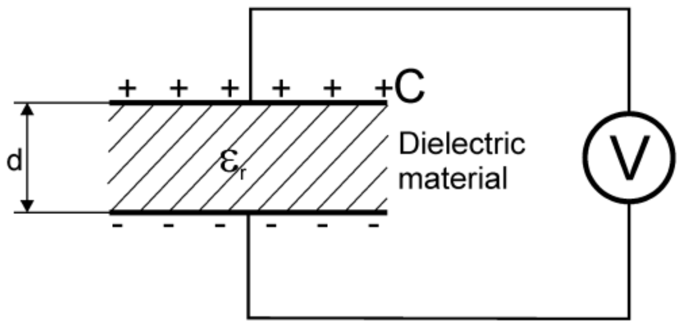

Fig. 6. *An electrical capacitor consisting of two metal plates separated by an insulating material called a dielectric.*

When the material is introduced between two plates of a capacitor, the total charge (C_0) stored in the capacitor will change (C) (Eq. 1.1). The change depends on the ability of the material to resist the formation of an electric field within it and, finally, to get polarized under the electric field of the capacitor.

$$\varepsilon_r = C/C_0 \tag{1.1}$$

where C_0 is the capacitance of the capacitor with vacuum and C is the capacitance of the capacitor with the material.

Thus, dielectric constants (ε_r) that determine the charge holding ability of the materials are characteristic for each substance and its state and vary with temperature, voltage, and, finally, frequency of the electric field. Dielectric constants for some common materials are given in Table II.

Table II. *Dielectric constants (ε_r) of some common materials at 20 ℃.*

Material	**Dielectric constant (ε_r)**	**Material**	**Dielectric constant (ε_r)**
Vacuum	1	Titanium dioxide	100
Air (1 atm)	1.00059	Water	80
Air (100 atm)	1.0548	Acetonitrile	38
Glass	5-10	Liquid ammonia(-78 ℃)	5
Quartz glass	5	Ethyl alcohol	25
Porcelain	5-6	Benzene	2
Mica	3-6	Carbon tetrachloride	2
Rubber	2-4	Hexane	2
Nylon	3-22	Plexiglass	3
Paper	1-3	Polyvinyl chloride	3
Paraffin	2-3	Polyethylene	2
Soil (dry)	2.5-3	Teflon	2
Wood(dry)	1-3	Polystyrene (foam)	1.05

Air has nearly the same dielectric constant as vacuum (ε_r = 1.00059 and 1.00000, respectively). Polar organic solvents (i.e., water, acetonitrile, ethyl alcohol) are characterized by relatively high values of dielectric constants and, in turn, can be heated by dielectric heating mechanism under microwave irradiation. Nonpolar organic solvents (i.e., benzene, carbon tetrachloride, *n*-hexane) have low dielectric constants and, in fact, show negligible heating effects under microwave irradiation. Most plastics range in the low values of dielectric constants (i.e., between 2 and 3); therefore, some of these materials, besides glass and quartz glass, are used to manufacture reaction vessels for microwave application due to their good chemical as well as temperature resistance (e.g., Teflon, PEEK). Thus, heating a material in microwave ovens is based upon the ability of some liquids as well as solids to absorb and to transform electromagnetic energy into heat.

The heating rate (i.e., temperature increase) of the material under microwave irradiation also depends on the shape and size of the sample. Eventually, the sample size, penetration depth, and heating rate are strongly coupled during microwave irradiation and may finally result in more homogeneous or heterogeneous heating of the material, which in turn can result in overheating of the material and creation of so-called hot spots in the latter case [23].

It is worth stressing that microwaves in comparison with conventional heating methods are the means of volumetric heating of the material that gives rise to a very rapid energy transfer into the material being heated. In conventional heating, heat flow is initiated on the material's surface and the rate of heat flow into the center is dependent on the material's thermal properties and the temperature differentials. A conventional oven is required to be heated to temperatures much higher than is required by the material itself (Fig. 7).

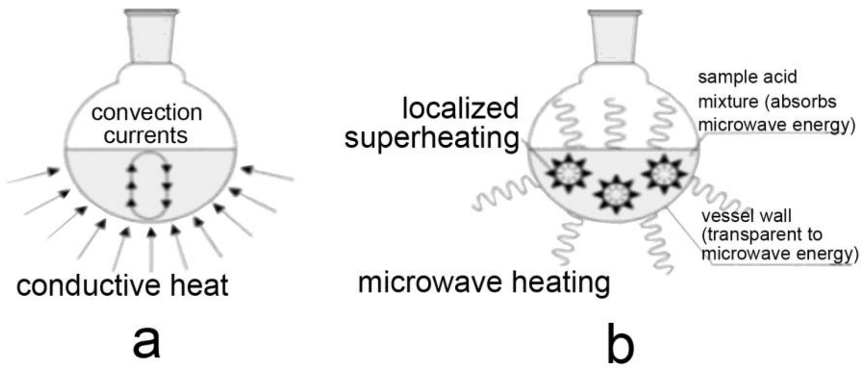

Fig. 7. *Different heating mechanisms for conventional (a) and microwave heating (b).*

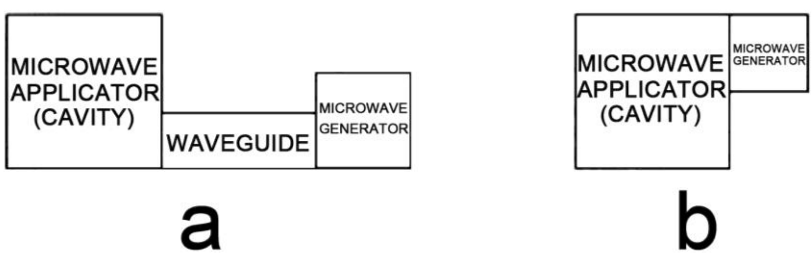

Fig. 8. *Schemes of microwave devices with (a) and without (b) transmission line.*

1.4 Microwave Equipment

Microwave devices that are dedicated to carry out chemical processes are similar to other microwave systems that consist of (Fig.8):

1) Microwave power source (generator),
2) Transmission line (waveguide) that delivers microwaves from the generator into an Applicator,

3) Microwave applicator (cavity).

1.4.1 Microwave Generators

The main types of microwave power sources are magnetrons and klystrons. Magnetrons, which are commonly used in microwave ovens, are mass produced and thus are cheap and easily available on the market. Therefore, it is common practice to use the same magnetrons for laboratory and industrial microwave processing. In general, magnetrons are vacuum devices consisting of an anode and a cathode, and the anode is kept at a higher potential than the cathode. As soon as the cathode is heated, electrons are emitted from it and are accelerated toward the anode by the electric field. At the same time, external magnets mounted around the magnetron anode block create the magnetic field parallel to the axis of the cathode. This magnetic field forces the electrons to rotate around the cathode before they can reach the anode. The rotating electrons form a rotor moving around the cathode synchronously in the way that they decelerate and thus transform their energy into microwave oscillations in the cavities cut in the anode blocks. A typical anode block consists of an even number of small cavities that form a series of microwave circuits, which are tuned to oscillate at a specified frequency dependent on the dimensions and shape of the cavities. Finally, microwave energy from one of the resonant cavities is coupled to the output transmission line, usually terminated with an output antenna (Fig. 9).

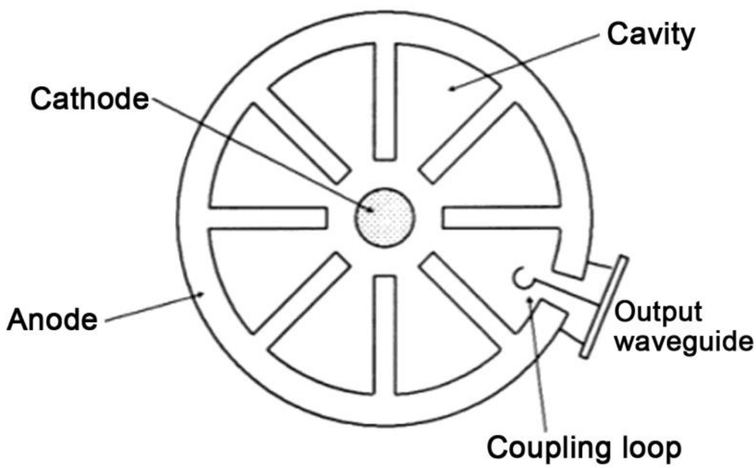

Fig. 9. *Schematic diagram of a magnetron shown in cross section. Reprinted from National Academy Press {26}. Microwave Processing of Materials. National Academy Press, with permission.*

1.4.2 Transmission Lines (Waveguides)

Microwaves can be easily transmitted through various media. Hence, an applicator can be remote from the power source and connected to it via the transmission line, in which microwaves can be propagated using three types of modes:

1) Transverse electromagnetic mode (TEM).
2) Transverse electric (TE).
3) Transverse magnetic (TM).

1.4.3 Microwave Applicators (Cavities)

Microwave applicators may appear in many different shapes and dimensions, and in fact their design is critical to processes run under microwave conditions since within applicators the microwave energy must be efficiently coupled to the material.

Every efficient application of microwave energy to perform chemical syntheses requires reliable temperature measurement as well as continuous power feedback control, which enable heating of reaction mixtures to a desired temperature without thermal runaways. Moreover, power feedback control systems that are operated in most microwave reactors enable a synthesis to be carried out without knowing the dielectric properties and/or conductive properties of all the components of the reaction mixture in detail. On the other hand, temperature control during microwave irradiation is a major problem that one faces during microwave-assisted chemical reactions. Maintaining good thermal contact with the material being heated is crucial when heating using microwave irradiation and it is important that temperature probes produce a minimum perturbation to the existing field in a microwave cavity. In general, temperature in microwave field can be measured by means of:

- Fiberoptic thermometer
- Shielded thermocouple
- Pyrometer (infrared sensor)

Fiberoptic thermometers can be applied up to 300 ℃ but are too fragile for real industrial applications. In turn, optical pyrometers and thermocouples can be used, but pyrometers measure only surface temperatures, which can be lower than the interior temperatures in reaction mixtures. Application of thermocouples, which in the case of microwaves are metallic probes, screened against microwaves, can result in arcing between the thermocouple shield and the cavity walls, leading to failures in thermocouple performance.

The temperature of microwave-irradiated samples can be also measured by inserting either a thermocouple or thermometer into the hot material immediately after turning off microwave power. This rather simple procedure may sometimes help if no other means of temperature measurements is provided. However, it must be stressed that the temperature of many materials can drop quickly as soon as microwave power is switched off [23,26].

1.5 Methods for Performing Reactions under Microwave Irradiation

Two pioneering works for the synthesis under microwave conditions that were published almost 20 years ago described several organic syntheses that were completed in household microwave ovens with high yield when conducted in sealed vessels [27,28]. They used commercially available screw-up pressure vessels made of glass, Teflon, and PTFE (i.e., being transparent for microwaves). This strategy has been successfully applied to a number of syntheses, but it always generates a risk of hazardous explosions. Later, there were reported 45 different reaction procedures with a commercial microwave oven and poly(ethylene terephthalate) vessels designed for acid digestion. Since then, different techniques have been developed.

The simplest method for conducting microwave-assisted reactions involves irradiation of reactants in an open vessel. Such a method, termed microwave-organic reaction enhancement (MORE), was developed [29]. During the reaction, reactants are heated by microwave irradiation in polar, high-boiling solvent so that the temperature of reaction mixture does not reach the boiling point of a solvent. Despite the convenience, a disadvantage of the MORE technique consists in limitation to high boiling polar solvents such as DMSO, DMF, *N*-methylmorpholine, diglyme, etc.

Microwave heating has been proved to be of benefit particularly for the reactions under “dry” media in open vessel systems (i.e., in the absence of a solvent, on solid support with or without catalysts) [30]. Reactions under “dry” conditions were originally developed in the late 1980s [31]. Solvent less systems under microwave irradiation offer several advantages. The absence of solvent reduces the risk of explosions when the reaction takes place in a closed vessel. Moreover, aprotic dipolar solvents with high boiling points are expensive and difficult to remove from the reaction mixtures [23].

1.5.1 Microwave Irradiation vis-a-vis to Conventional Heating

In conventional or surface heating, the process time is limited by the rate of heat flow into the body of the material from the surface as determined by its specific heat, thermal conductivity, density and viscosity. Surface heating is not only slow, but also non-uniform with the surfaces, edges and corners being much hotter than the inside of the material. Consequently, the quality of conventionally heated materials is variable and frequently inferior to the desired result.

Imperfect heating causes product rejections, wasted energy and extended process times that require large production areas devoted to ovens. Large ovens are slow to respond to needed temperature changes, take a long time to warm up and have high heat capacities and radiant losses. Their sluggish performance makes them slow to respond to changes in production requirements making their control difficult, subjective and expensive [32-35].

Conversely, with microwaves, heating the volume of a material at substantially the same rate is possible. This is known as volumetric heating. Energy is transferred through the material electro-magnetically, not as a thermal heat flux. Therefore, the rate of heating is not limited and the uniformity of heat distribution is greatly improved. Heating times can be reduced to less than one percent of that required using conventional techniques [32, 34, 36].

1.5.2 The Advantages of Microwave

Because volumetric heating is not dependent on heat transfer by conduction or convection, it is possible to use microwave heating for applications where conventional heat transfer is inadequate. One example is in heterogeneous fluids where the identical heating of solids and liquids is required to minimize over-processing. Another is for obtaining very low final moisture levels for product without over-drying. Other advantages include [37]:

- Microwaves generate higher power densities, enabling increased production speeds and decreased production costs;
- Microwave systems are more compact, requiring a smaller equipment space or footprint. Microwave energy is precisely controllable and can be turned on and off instantly, eliminating the need for warm-up and cool-down;

- Lack of high temperature heating surfaces reduces product fouling in cylindrical microwave heaters. This increases production run times and reduces both cleaning times and chemical costs;
- Microwaves are a non-contact drying technology. One example is the application of IMS planar dryers in the textile industry, which reduce material finish marring, decrease drying stresses, and improve product quality;
- Microwave energy is selectively absorbed by areas of greater moisture. This results in more uniform temperature and moisture profiles, improved yields and enhanced product performance;
- The use of industrial microwave systems avoids combustible gaseous by-products, eliminating the need for environmental permits and improving working conditions.

1.5.3 Disadvantages of Microwave

1) Limited transmission capacity;
2) Certain topographical conditions must be observed and in certain circumstances erection of special structures (pylons) is required;
3) Relay stations necessary for long distances;
4) Disruptions can be caused by the weather.

1.5.4 Harmful Effects of Microwave

In its interaction with matter, microwave energy may be:

- Reflected as in case of metal;
- Transmitted as in case of glass;
- Absorbed as in case of living tissues.

The latter case is the most important consequence of human exposure to microwave radiation. If the environmental temperature and humidity are too high, the person’s body temperature will increase. Thus, the biological thermal stress from whole body exposure at power densities on the order of 1-10 mW/cm^2 depends strongly on the environmental temperature and humidity [37, 38]. Most of the documented harmful biological effects on man from microwaves are attributed to hyperthermia. These include damage mainly to the eyes and to the testicles which are not able to efficiently dissipate absorbed energy at a rate greater than 10 W/m^2.

Among the symptoms which may be observed for workers chronically exposed to microwaves are: increased fatigability, periodic or constant headaches, extreme irritability, sleeping during work and decrease in olfactory sensitivity.

Generally, the possible health hazard due to exposure to microwaves is highly dependent on the field strengths, frequencies and likely duration of exposure. On the other hand, metallic implants in human bodies may act as antennas in microwave radiation field and possibly cause adverse health effects by heating local tissues. For example, microwave radiation may interact with cardiac pacemakers and steps have to be taken to prevent this interference.

1.5.5 Microwave Safety

Using patented applicator design geometries and a unique slotted choking mechanism, IMS technology reduces microwave leakage from system entry and exit points to virtually non-detectable levels for both their planar and cylindrical heating systems. This poses no threat of electro-magnetic radiation to the health and safety of equipment operators. IMS heaters and dryers operate at a twenty times higher level of electromagnetic emission safety than that specified by the FDA for domestic microwave systems. As a further precaution, all IMS control systems are supplied with safety interlocks and leakage detectors that shut down power instantaneously in the event of equipment malfunction or misuse.

1.5.6 Economical Aspects

A common misconception is that microwave heating is always more expensive than heating by conventional techniques. The actual answer depends on the application. In some cases, microwaves can be 50% more efficient than conventional systems, resulting in major savings in energy consumption and cost.

When used as a Pre-Dryer in combination with conventional gas or oil heated air dryers, IMS microwave systems allow overall production capacities to be increased by 25 to 93%. This is because the pre-dryer performs three functions, namely:

- Removes residual moisture;
- Preheats moisture to the evaporative temperature;
- Equalizes the moisture level of product to the conventional dryer;
- With current energy costs, the return on capital invested in an IMS

pre-dryer can vary from 12 to 24 months.

When used as a Post-Dryer in combination with conventional gas or oil-heated dryers, IMS microwave systems are disproportionately more efficient than conventional dryers at achieving final moisture levels of less than 20%. This is because the lower the moisture level, the more difficult it is to drive moisture from the center of material to the surface by conventional heat conduction and convection processes. An IMS post-dryer provides:

- Uniformity of moisture control and surface temperature of the final product;
- Higher production efficiency due to increased process speeds;
- Improved product quality resulting from reduced surface temperatures, compared with conventional post-dryer designs;
- Return on capital invested in an IMS post-dryer usually varies from 12 to 24 months.

In addition to the applications above, IMS planar units are often used as Stand-Alone Dryers.

These may be the most economical solution where minimal equipment floor space or footprint is available for a new application, or when expansion of existing production facilities would require building modifications to accommodate a conventional drying system.

In the case of liquid heating, the production cost of providing sensible heat transfer from microwave energy is approximately one third higher than using steam in a conventional heat exchanger. However, this is offset by several factors, including:

- The reduced capital investment in steam boilers, steam trains, condensate collection and water treatment plant;
- The ability to use high power densities enables microwave heaters to substantially increase production rates;
- Uniform energy distribution minimizes fouling depositions in even the most viscous products. This is particularly important with thermally sensitive materials such as chemical polymers, food ingredients, nutraceuticals, biotech products & pharmaceuticals;
- With volumetric heating of multiphase products, solids loadings of 70% or higher can be processed since the carrier fluid is not used as the primary

heat delivery medium;

- The shorter residence times achievable with microwave heating improve product quality. Compared to conventional heating, IMS heated food products tend to retain a higher percentage of flavors and nutrients.

1.5.7 Maintenance

In addition to downtime for cleaning and inspection, conventional dryers and heat exchangers need periodic servicing with an expensive inventory of parts and a highly trained labor force. Apart from periodic examination for wear on the belt of a planar system or the tube in a cylindrical heater, the only part that requires maintenance on an IMS system is the magnetron. In the event of a malfunction or misuse through incorrect operation, this can be replaced and often repaired.

Although the operating life of a 915 MHz commercial magnetron can be greater, IMS recommends that the magnetron be replaced after 8,000 hours of operation. This translates to a maintenance cost of about US$1 per operating hour.

Low power 2,450 MHz magnetrons cannot be repaired, but larger units usually can be. A typical operating life for magnetrons at this frequency is 6,000 hours, although some vendors limit their warranty to 6 months or 500 hours.