3 Dielectric heating

Horst Linn, Malte Möller

3.1 Physical and Technical Basis

Dielectric heating is based on the use of microwaves or radio frequency (RF) waves for heating of insulating material.

3.1.1 Microwaves and Radio Frequency Waves

Microwaves and RF waves are electromagnetic waves, comparable to light or radar waves. The frequency spectrum most commonly used for dielectric heating is in the range of 3 MHz to 30 GHz, corresponding to a wavelength of 100 m to 1 cm.
The heating effect of high frequencies is based on the interaction of the electric and magnetic field, generated by the high frequency, with the insulating material. The applied field results in a displacement of charged particles in the insulating material, giving rise to induced dipoles. Dipoles (either induced dipoles or permanent dipoles like the water molecule) respond to the electric field, which results in a transfer of power from the electric field to the insulating material. This dissipated power results in a temperature increase of the material.
The factors that influence the dielectric heating can be found in equation (1) [1].

$$P = 2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon'' \cdot E^2 \cdot V \qquad (1)$$

P = power taken up by material; f = frequency of high frequency wave; ε_0 = electric field constant; ε“ = imaginary part of complex dielectric constant; E = electric field strength; V = material volume

The main factors that influence the high frequency heating are: the frequency of the waves, the dielectric properties of the material, the incident high frequency power and the material volume. For a specific application where the material properties and the volume are given, the induced power can only be influenced by the frequency and the incident power.

The dielectric properties of the material determine the interaction of the high frequency waves with the material. The interactions can be: reflection, transmission and absorption.
Electrical conductive materials, like metals, do reflect most of the waves. The waves cannot penetrate deeply into the material and, therefore, the dissipated power in the material is low. For technical applications, these materials cannot be heated by microwaves.
Some materials have a very low interaction with the high frequency waves, resulting in a transmission of most of the wave energy. Therefore the absorption is low, resulting in practically no heat-up of the material. Common materials that show this effect are for example: quartz glass, and PTFE.
Most materials belong to the group of lossy dielectrics, which absorb high frequency waves. Depending on their dielectric properties, these materials absorb most of the incident waves, converting them to heat. The waves can penetrate some distance into the material, resulting in a volumetric heating. The penetration depth is defined by equation (2) [4].

$$\mathrm{PD} = \frac{\lambda_0}{2\pi} \cdot \frac{\sqrt{\varepsilon'}}{\varepsilon''} \qquad (2)$$

PD = penetration depth; λ_0 = vacuum wave length; ε‘ = real part of complex dielectric constant; ε“ = imaginary part of complex dielectric constant

The penetration depth is defined as the depth at which the incident wave intensity is reduced to 1/e (about 36,8%). This means that even in depths below the penetration depth, a certain wave energy is still present, resulting in some heating. The penetration depth of most technically interesting materials as a minimum is in the range of 5 cm to 10 cm, allowing for a homogeneous heating of most industrial size products.

Plate 1: Dielectric properties and penetration depths of chosen materials at 25°C and 2.45 GHz [10]

Material	**ε´**	**ε´´**	**Penetration Depth**
Aluminium Oxide	9	0,004	1460 cm
Silicon Carbide	10,4	0,9	7 cm
PTFE	2,1	0,0006	4700 cm
PVC	2,9	0,016	200 cm
Wood (40% H_2O)	5,1	1,12	4,0 cm
Water	77,4	9,2	1,8 cm

3.1.2 Frequency Bands (ISM bands)

In the frequency spectrum of high frequency waves, certain frequency bands are allocated for industrial use. These so-called ISM bands (**I**ndustrial, **S**cientific and **M**edical) are free to be used by high frequency heating units without requiring special permissions by the national telecommunication authorities. Equipment using high frequency waves of the ISM bands must comply to EN 55011 / IEC 11 [7] and for microwave frequencies also to EN 60519-6 / IEC 519-6 [8].

Plate 2: ISM frequencies and corresponding wavelengths [7]

ISM frequency	**wavelength**
6,78 MHz ± 15 kHz	4424,8 cm
13,56 MHz ± 7 kHz	2212,4 cm
27,12 MHz ± 0,163 MHz	1106,2 cm
40,68 MHz ± 0,02 MHz	737,5 cm
433,92 MHz ± 0,87 MHz	69,14 cm
915 MHz ± 25 MHz	32,79 cm
2,45 GHz ± 50 MHz	12,24 cm
5,8 GHz ± 75 MHz	5,17 cm
24,125 GHz ± 125 MHz	1,36 cm

Some of the ISM frequencies given in plate 2 may differ in certain countries. For example, in the UK the frequency 896 MHz is used instead of 915 MHz.
For industrial microwave heating units the frequencies 915 MHz and 2.45 GHz are most commonly used. For special applications the frequency 5.8 GHz is increasingly used.
For radio frequency applications, the frequencies 13.56 MHz and 27.12 MHz are most commonly used.

3.1.3 Microwave Generators (Magnetron)

The type of microwave generator most frequently used is the magnetron. Magnetrons were developed in the 1950s for radar applications and have been used for microwave heating since the discovery of this application for high frequency waves.
Magnetrons are produced with an output power ranging from 200 W to 60 kW or even higher. The majority of the magnetrons are produced with an output power between 800 W and 1200 W for household microwave ovens. Those magnetrons with very low power are commonly used in medical applications, while those with high power are used for industrial heating and research applications.
Due to the mass production of magnetrons with a power of about 800 W to 1200 W, the price for these magnetrons is comparatively low. Therefore, these magnetrons are also used for industrial heating applications.
During operation the magnetrons must be cooled to prevent overheating. Magnetrons with a power up to about 2 kW are usually air-cooled, while those with a higher power are usually water cooled, requiring water re-circulation units. Those magnetrons also require the use of special protection equipment against reflected power that could overheat and destroy the magnetron. Low power magnetrons are more robust and can be operated without the protection equipment.

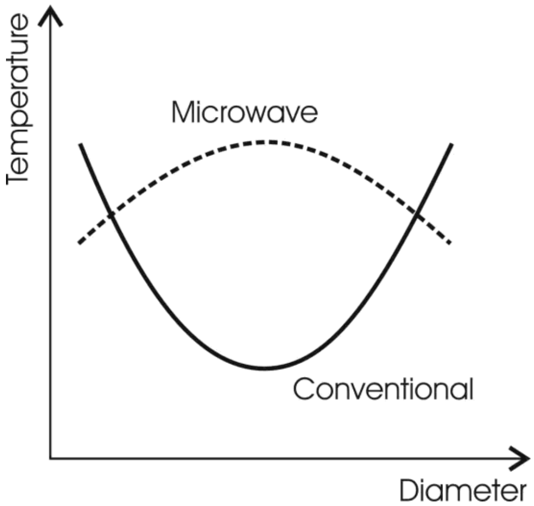
There are many other types of microwave generators, like klystrons or traveling wave tubes. None of these generator types are used for industrial microwave heating as the costs are too high compared to magnetrons.

3.1.4 Radio Frequency Generators

Radio frequency waves are usually generated by tube or semiconductor generators. Tube generators use a vacuum tube for generating the high frequency waves. Semiconductor generators are a comparatively new development for industrial heating and have only a limited output power. Tube generators can have an output power of several 100 kW.

3.1.5 Microwave- and Radio Frequency Heating

In a high frequency heating process, the high frequency waves heat the lossy dielectric in the complete volume by penetrating into the material, depending on the penetration depth of the waves. Provided the material is not too thick, the high frequency waves transfer more or less the same amount of energy to every volume element of the material, resulting in a homogeneous temperature increase of the material. Theoretically this would give every volume element the same temperature. In a practical situation the surface of the material would loose heat to the ambient atmosphere, which is not heated by the high frequency waves. Therefore the surface temperature is reduced, resulting in a temperature profile where the highest temperature is in the inside, while the lowest temperature is on the surface of the material. This temperature profile is inverse to the one of conventional heating processes.



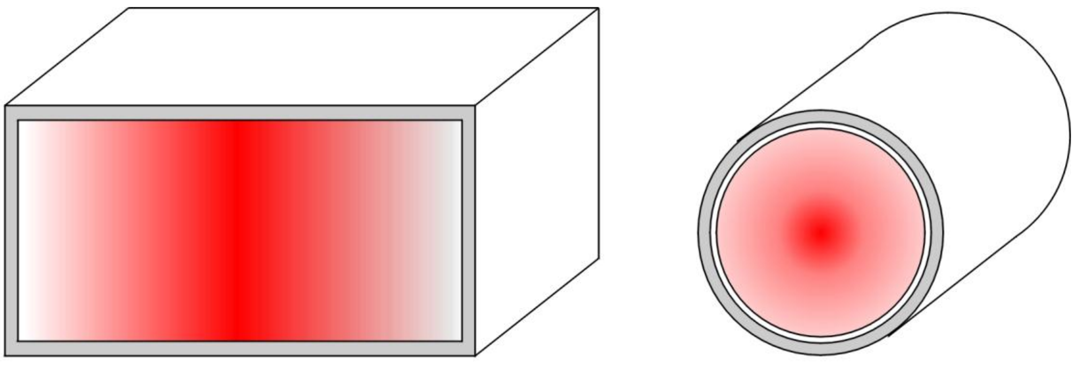
Picture 1: Temperature profile for conventional and dielectric heating

High frequency heating is governed by the dielectric properties of the material. The dielectric properties depend on the frequency, and temperature.
The dielectric properties of some materials are mainly dependent on temperature, whereby the coupling is increased as the temperature increases. These materials are prone to a thermal runaway effect that is initially caused by low temperature differences in the material. Those areas that have a slightly higher temperature than the surrounding material take up more energy due to better coupling to the high frequency waves. This results in a faster temperature increase, which in turn leads to even better coupling and increased energy take-up, and so on. This thermal runaway can result in local destruction or even melting of the material.

3.2 Design, Construction and Application

3.2.1 Microwave Chambers

In genera, two different types of microwave chambers or cavities can be distinguished. In Single Mode cavities a single standing wave pattern is generated, while in Multi Mode cavities a large number of resonant modes is supported.

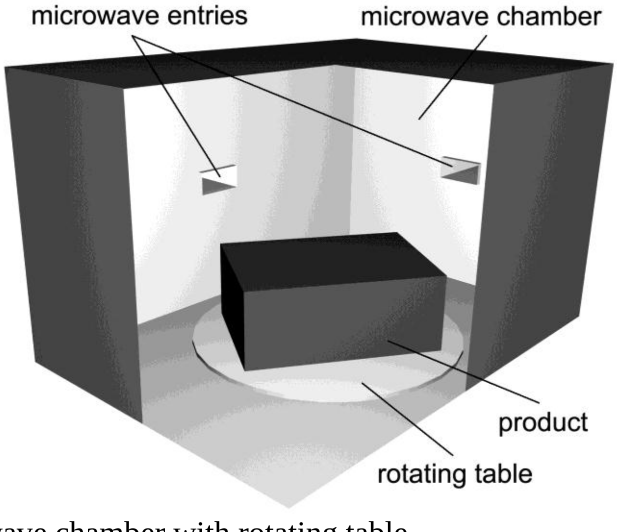


Picture 2: Wave pattern in different Single Mode cavities
left side: TE_{10} mode, right side: TM_{01} mode

The standing wave that is supported by a Single Mode cavity depends on the frequency and the dimensions of the cavity. Various wave patterns exist and are differentiated by the number and position of the maxima of the electric and magnetic field.

The technically most important wave patterns are the TE_{10} and TM_{01} mode (picture 2). The TE_{10} mode is supported in a rectangular cavity, having the maximum of the field intensity in the middle of the cavity.
In a cylindrical cavity, the TM_{01} mode is supported, having the maximum of the field intensity in the axis of the cavity.
Single Mode cavities have the advantage that very high electric field strengths can be achieved. Also the knowledge of the electromagnetic field configuration enables the dielectric material under treatment, to be placed in the position of the maximum electric field. This results in a high absorption of the incident wave.
Despite these advantages, the use of Single Mode cavities in technical applications is limited due to size restrictions of the cavities. The cross section of the cavities for a specific wave pattern depends on the frequency. For a certain frequency, the cross section is fixed and may not be altered without changing the wave pattern. Therefore Single Mode cavities are mainly used for comparatively small products.

In a Multi Mode cavity the superposition of the large number of resonant modes that are supported by the cavity is used to generate a comparatively even microwave field in the useful volume of the cavity. Therefore it is advantageous to generate as many different resonant modes as possible to improve the homogeneity of the electromagnetic field.
Multi Mode cavities are not limited in their dimensions and therefore very large heating chambers can be realized. The advantage of the Multi Mode chamber is the even microwave field that enables the heating of large or complex shaped products. In comparison to Single Mode cavities the Multi Mode systems have a relatively low electric field strength, resulting in lower heating rates.



Picture 3: Multi Mode microwave chamber with rotating table

3.2.2 Radio Frequency Units

In a radio frequency heating unit, the high frequency field is generated between two or more electrodes. The shape of the electrodes determine the shape of the generated field. Although many electrode shapes are possible, two types of electrodes are most commonly used. These are rod electrodes and plate electrodes.
For heating, the lossy dielectric is placed between or over the electrodes. The electric field strength is determined by the frequency, the applied voltage and the distance of the electrodes. The technically reasonable distance of the electrodes is limited by the applied voltage. With increasing electrode distances the required voltage to maintain the electric field strength also

increases. The maximum electrode distance and thus the maximum product thickness is determined by the necessity to avoid arcing between the electrodes.

3.2.3 Chamber Designs

Batch Units

Microwave Batch Units

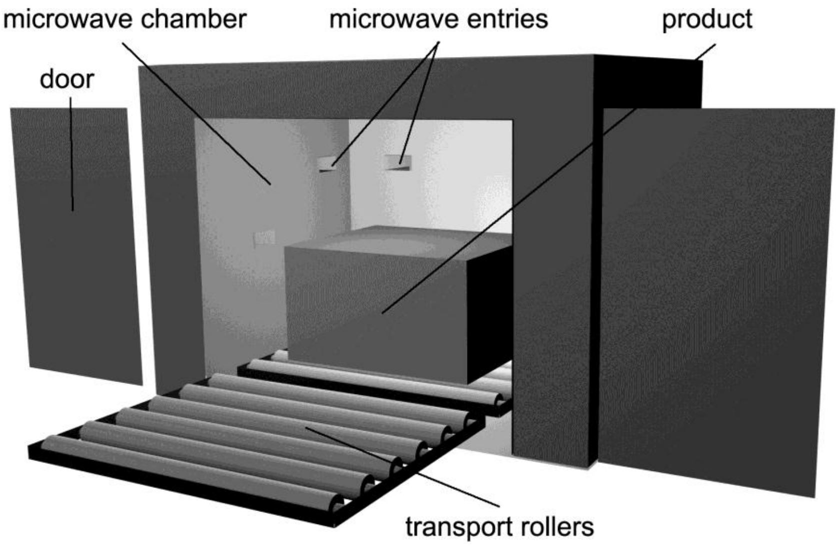
The basic design of a microwave batch unit is a metallic cavity to which one or more microwave generators are connected, having at least one opening for loading/unloading closed by a kind of closure.

For technical applications the cavity is usually a Multi Mode design, while Single Mode designs are mostly used for high temperature research applications. The Multi Mode chambers usually cover the range of some litres to several cubic meters. For industrial applications the chamber is often especially designed for the product to be treated. As a rule of thumb, the chamber volume should be several times the volume of the product. This is required for the homogeneous heating of the product.

The microwave generators may be connected to the cavity in different ways. For industrial batch units, a common method is to place the magnetron on the chamber wall, so that the antenna is inside the cavity. Another option is to connect the magnetron to the chamber with a short waveguide, called launcher. For high power special applications it is not uncommon to separate the cavity from the microwave generator and connect both by a longer piece of waveguide.

The opening of the cavity is usually closed by a kind of metallic door. This door may be sliding or hinged doors or alternatively flexible rolling curtains made of metal lamellas. The door must be protected against excessive microwave leakage. Usually this is done by ensuring that there is a conductive contact between the door and the chamber frame. Alternatively a so called “choke structure” may be used that terminates the microwaves without needing a metallic contact.

To increase the homogeneity of the microwave field it is possible to use active elements like mode-stirrers or to move the product (i.e. rotating table).



Picture 4: Microwave Multi Mode batch unit for large products

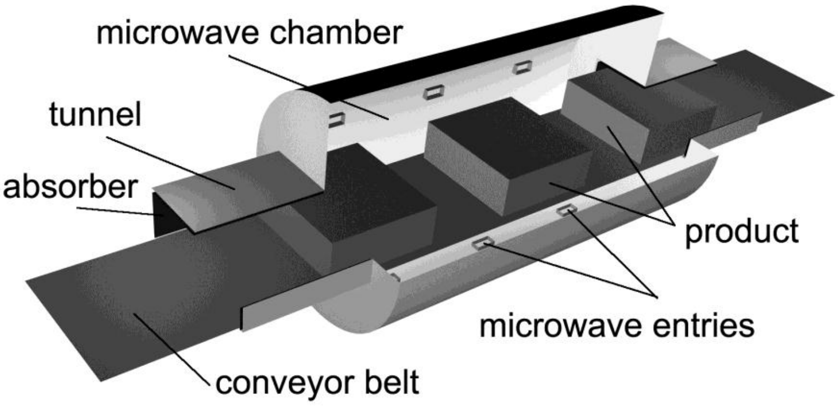
Radio Frequency Batch Units

In RF batch units the heated area is defined by the shape and placement of the electrodes. The product is placed between the electrodes for heating. Usually the distance of the electrodes may be adjusted to match the product. A chamber or cage around the electrodes is usually required only for protection against RF leakage.

Continuous Units

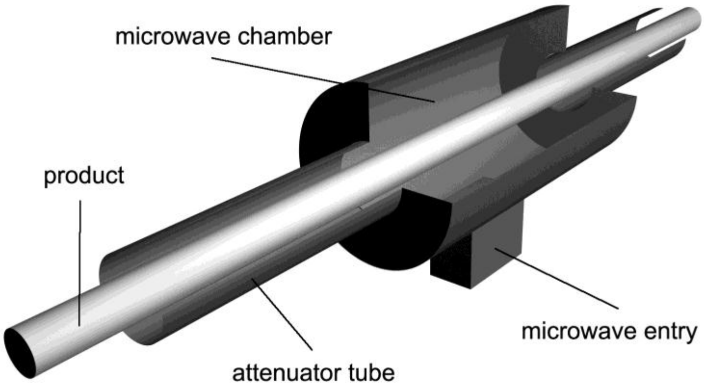
Microwave Continuous Units

A continuous microwave heating unit is defined by the more or less continuous movement of the product through the heating area. It is possible to use either Single Mode or Multi Mode cavities as continuous units.
In Multi Mode units, the product transport is usually accomplished by a transport belt or, in some cases, by transport rollers. The microwave chamber is usually adjusted to the product and may be rectangular, circular or polygonal in cross-section. As in batch type units it is necessary that the volume of the microwave chamber is higher than the product volume. The connection of the microwave generators to the cavity may be done in the same way as in batch units.
A continuous unit usually has two openings in the microwave chamber, one at each end of the unit. The openings must be protected against excessive microwave leakage by either an absorbing tunnel or doors. For truly continuous operation, absorbing tunnels are used at each opening. They are lined with a special material that absorbs the microwave leakage. The required length of the absorbing tunnel depends on the opening size and the microwave power of the unit.
If doors are used to close the openings at both ends, the process will be intermittent as the microwave power must be switched off when the doors are opened.



Picture 5: Microwave Multi Mode continuous belt unit

In Single Mode chambers the product must be placed at the maximum of the wave pattern. For the TM_{01} mode in cylindrical cavities this is in the axis of the chamber and for TE_{10} in rectangular cavities this is along the axis through the broad side of the cavity. Due to the high field strength in Single Mode systems, these are usually comparatively small. As discussed in chapter 3.2.1, the product size is very limited for these units.
For these small products it is usually possible to use attenuation tubes for leakage protection. These are based on a certain relation between diameter and length of the tube to prevent microwave leakage.



Picture 6: Single Mode TM_{01} continuous operation unit

Radio Frequency Continuous Units

A continuous RF unit is very similar to a batch system with the only exception that the material move over or between the electrodes. Due to the highly concentrated electric field between the electrodes this setup is especially suitable for fast heating of thin sheets.

Special Units

Theoretically most designs of conventionally heated furnaces can also be adapted to high frequency heating if special care of the requirements of the high frequency waves is taken. For example, a microwave rotary tube furnace has been realized, using a microwave transparent tube through which the microwaves heat the product inside the tube.

3.2.4 Areas of Application

High frequency waves are used for heating in those areas where the heating process can benefit the most from the advantages of high frequency heating.
In general these advantages are: fast heating, volumetric heating, high efficiency, good control, and better product quality.
The advantages of fast and volumetric heating are the most important. Most conventional heating processes are limited by the heat conductivity and physical alterations of the product (i.e. evaporation of liquids, phase transformations). As high frequency heating is independent of the heat conductivity of the product and is a volumetric heating, the heat-up time is much shorter than for conventional heating. Due to its inverse temperature profile, dielectric heating can also improve the drying speed of a product without risking damages to the material.

The actual areas of application for dielectric heating are simply too many to be listed here. The next chapter will give some examples of applications. Most of the high frequency heating units are used for drying, the remainder being divided into curing, sterilization, high temperature applications, research and special applications.
The industry branches were dielectric heating is mostly used are: ceramic, food, rubber, chemistry and building materials.

RF heating is used in some areas of applications where the special advantages of this heating method can be realised, but most high frequency heating is done by microwaves due to its higher flexibility.

3.2.5 Examples of Dielectric Heating

Microwave Drying of Heat Insulation Materials

Conventional drying of heat insulation plates is done in batch dryers, having drying times of 12 to 24 hours, depending on the thickness of the product. This is the result of the low heat conductivity of these materials and the high water content.
The microwave drying process is accomplished in a continuous microwave belt drier with a drying time of 30 to 45 minutes. Due to the continuous drying process, the space requirements for the microwave dryer are much lower and loading/unloading of the batch driers is avoided.

Microwave Treatment of Cork Stoppers

Conventionally produced natural cork stoppers for wine bottles have a high risk of bringing the so called cork taste to the wine. The cork taste is actually a chemical product of micro-organisms living inside the cork stopper. Conventional sterilization processes are ineffective against this problem as the natural cork is a very good heat insulator, making it nearly impossible to reach sterilization temperatures inside the stopper without destroying the material.
A special microwave process will sterilize the complete volume of the stopper and at the same time remove the taste from the cork. The treatment is done in continuous microwave belt units, each treating about 1.5 million cork stoppers per day.

Picture 7: Microwave continuous belt unit for treatment of cork stoppers (Picture Linn High Therm/Ohlinger)

Microwave Drying of Grinding Wheels

For the fast drying of ceramic grinding wheels large microwave batch driers with chamber volumes of about 20 m³ are used. The large industrial grinding wheels are placed on drying racks, which in turn are placed in the microwave chamber. Compared to conventional hot-air drying, the microwaves allow much faster drying, which gives more flexibility to the production process and reduces the space requirements for the drying chambers.

Picture 8: Microwave chamber dryer for drying of ceramic grinding wheels (Picture Linn High Therm)

Microwave Curing of FRP Material

Special Single Mode microwave units are used for the curing of fibre reinforced plastics (FRP) of rod or cable shape,. Due to the special field pattern in the cavity, the field is concentrated in the product, resulting in very fast heating of the FRP. Therefore a heating zone of only 30 cm is sufficient to heat the product. Contrary to conventional heating from the surface, the microwaves heat the complete volume, giving better curing results.

Radio Frequency Drying of Wood Glue

The gluing of wood is conducted under pressure to ensure good contact of the gluing faces. The pressure is applied vertically to the gluing face. Depending on the position of the product, the pressure may be applied directly by the RF electrodes or by a separate system. Two different methods are distinguished: parallel- and transverse heating.
For parallel heating, the gluing face is parallel to the electric field lines and, therefore, vertical towards the electrode plates. The pressure is applied parallel to the electrode plates.
For transverse heating, the gluing face is parallel to the electrode plates and transverse to the electric field. The pressure can be applied directly by the electrode plates.

3.3 Process Technology and Process Control

3.3.1 Control of Microwave and RF Units

Depending on the application microwave heating units may have pulse-, phase- or non-controlled magnetrons. For pulse controlled magnetrons, the microwave power is constantly switched on and off to achieve an average power of the desired value. Phase controlled magnetrons can be adjusted continuously between typically 15% and 100% of its maximum power. Non-controlled magnetrons are either switched on at full power or off.
The choice which kind of control is used depends on the application. For applications that require good control of the incident power, like laboratory applications or those with fast changing throughputs, either pulse- or phase-control is used. For industrial applications with

constant throughputs, it is usually sufficient to use non-controlled magnetrons. The number of activated magnetrons is set during process development and saved in the PLC program.

Control of RF units is usually done by a radio frequency matching element to adjust the generator and the incident power to the product.

3.3.2 Measurement Techniques

The most important parameter to be measured in thermo processing units is the temperature. While it is usually sufficient for the control of conventional process to know the furnace temperature, for dielectric heating, the product temperature is usually much higher than the furnace temperature. Therefore, it is usually necessary to measure the product temperature for control of dielectric heating units. Either contact- or non-contact measurement techniques may be used to measure the product temperature

Probably the most common contact temperature measurement method is the thermocouple. Unfortunately the application of thermocouples in dielectric heating is limited as the electric field of the units may interfere with the measurement. It is possible to shield the thermocouple to reduce the problem, but for certain applications with high electric field strengths, the shielded thermocouple may still be unsuitable.

A contact temperature measurement method that was specially developed for dielectric heating and similar applications is the so called optical fibre thermometer (OFT). This technology is based on a special sensor material that emits or reflects light depending on its temperature. The sensor material is placed on the tip of a glass fibre that transmits the emitted or reflected light to a control unit which calculates the temperature of the sensor. Due to the optical measuring principle, the measurement is not affected by the electromagnetic field of dielectric heating.

The most common non-contact temperature measurement method is the pyrometer. These units detect the infrared light that is emitted by any material and calculate the surface temperature based on the adjusted emission factor. Unlike the contact measurement techniques, pyrometers can only measure the surface temperature.

When comparing temperature measurements of conventional and dielectric heating processes, the inverse temperature profile of dielectric heating has to be considered for correct interpretation of the results.

3.4 Design Criteria, Limitations

3.4.1 Design Criteria

The choice of the basic cavity design, and/or type of electrode (Single Mode or Multi Mode and rod or plate electrodes) and the basic process (batch or continuous) depends on the production process and the product and is usually limited. The actual design of the dielectric heating unit is, therefore, based on the adaptation of the basic cavity and/or electrodes to the product and the calculation of the required heating power.
Prior to the actual design, a test with the product is usually conducted in a suitable test to verify the desired heating process.
For Single Mode microwave cavities the possibilities for adapting the cavity to the product size are very limited as discussed in chapter 3.2.1. As far as microwave Multi-Mode cavities

are concerned, there are hardly any limitations in adjusting the chamber to the product size. In general, the chamber volume should be several times the product volume and the product should not be too close to the chamber walls.
In RF heating units, the dimensions of the electrodes must be adjusted to the product and the location of the product.
For industrial applications the calculation of the required heating power is usually accomplished by calculating the energy required for the heating process (based on heat-up of the product and the evaporation energy of the water for drying). This value is modified by an efficiency factor that is based on experience with the type of cavity used. Although equation (1) in chapter 3.1.1 could be used for the power calculation, the practical use of the equation is very limited as usually the exact values for the dielectric constant and the electric field strength are not known.

3.4.2 Limitations

Limitations for the application of dielectric heating are based on the material, the product size, the power density and the installed power.
As described in chapter 3.1.1, only lossy dielectric materials can be heated by dielectric heating. Transparent or reflective materials do not couple to the high frequency.
Depending on the penetration depth of the high frequency into the product material, those products with a thickness of significantly more than 2 times the penetration depth (penetration from both sides) may not be heated homogeneously.
The microwave power in a certain cavity volume, i.e. the power density, is limited due to the fact that the electric field strength may not exceed the breakdown voltage, to prevent arcing and plasma generation.
The microwave power installed in a single unit is usually not more than a few 100 kW, depending on the frequency. Usually lower frequency microwaves can have higher powers than higher frequency units.
RF heating units may have a power of up to 1000 kW in a single unit.

3.5 Future Developments

For industrial microwaves the future developments will include high temperature applications with hybrid systems, higher frequency microwaves and the application in chemical processes.

High temperature microwave applications, i.e. sintering, in an industrial scale will probably only be successful using hybrid systems. In a hybrid unit, microwave heating is combined with a conventional heating method (usually resistance heating or hot air heating). This combination can reduce some of the difficulties of pure microwave heating, i.e. strong influence of the product material on the heating, requirement of susceptor pre-heating, and so on. Especially for large volume batch furnaces and continuous furnaces, the hybrid concept is the most promising technology available.

Higher frequency microwaves have better heating efficiencies and better coupling than lower frequency waves. This makes higher frequency microwaves especially suitable for low volume products and low coupling materials. Although the recent development of a 5.8 GHz magnetron has been a step into this direction, there is still a huge potential for further development into higher frequencies.

The use of microwave to improve or alter chemical reactions is the topic of many research groups around the world. Despite some promising results for certain applications, the adaptation to industrial use is still very limited. Therefore it is expected, that in a short to medium term, industrial microwave applications in chemistry will see increasingly widespread demand.

3.6 Literature

[1] Lange, K.; Löcherer, K.-H.; Meinke-Gundlach Taschenbuch der Hochfrequenztechnik, 4. Auflage 1986, Springer Verlag Berlin

[2] Roussy, G.; Pearce, J.A.; Foundations and industrial applications of microwaves and radio frequency fields, 1995, John Wiley & Sons

[3] Thuery, J.; Microwaves: Industrial, Scientific and Medical Applications, 1992, Artech House Inc.

[4] Metaxas, A.C.; Meredith, R.J.; Industrial Microwave Heating, 1988, Peter Peregrinus Ltd.

[5] Suhm, J., Rapid Wave Microwave Technology for Drying Sensitive Products, American Ceramic Society Bulletin, May 2000, p. 69-71

[6] Gast, H., Hochfrequenz in der Holzverarbeitungstechnik, Holz. Zentralblatt Messeheft 1979, Ligna/Interzum Nr. 54

[7] DIN EN 55011/ IEC 11 Industrielle, wissenschaftliche und medizinische Hochfrequenzgeräte (ISM-Geräte) – Funkstörungen – Grenzwerte und Messverfahren

[8] DIN EN 60519-6/ IEC 519-6 Sicherheit in Elektrowärmeanlagen – Teil 6: Sicherheitsanforderungen für industrielle Mikrowellen-Erwärmungseinrichtungen

[9] Gefahrt, J., Hochfrequenzerhitzung im Holz, Holz Zentralblatt Verlags-GmbH, Stuttgart, 1963

[10] Buffler, C.R., A new, low power 915 MHz microwave system for efficient industrial scale-up prototyping, Microwave Industrial Food Processing, Chicago, 1998