MICROWAVE HEATING:
A GENERAL OVERVIEW OF APPLICATIONS

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Summary

Microwave heating has been developed over the last decade into a versatile heating technology that has advantages in many heating processes. The theoretical background of microwave heating is explained and the advantages, especially of the new microwave frequency 5.8 GHz, are shown.
Many different applications from the ceramics, plastics and other industries and research are explained in detail.

1. Microwave Theory

Microwaves are electromagnetic waves such as those used in radio, television and radar technology. The difference consists in the frequency and in the power density. The frequency range 88-108 MHz is used, for example, for VHF radio. Mobile phones use higher frequencies, for example 1800 MHz, whereby the output power is about 2 Watts.

At the moment, three different microwave frequencies are available for industrial microwave heating. 915 MHz, which is mainly used for defrosting and heating of large scale materials. The most widely used is 2.45 GHz; most household and industrial systems apply this frequency. Since early 2002 the new frequency 5.8 GHz is available for industrial use. It is especially advantageous for small pieces and materials that are difficult to heat with the lower frequencies.

The conversion of electromagnetic energy into thermal energy is realized by the electromagnetic characteristics of the materials and depends principally on the material, temperature, and frequency. As generally only one frequency is used for the heating process and the temperature dependency of the characteristics is not known, an observation can only be carried out in terms of the material itself.

Whether a material can be heated up by microwaves or not depends on its molecular structure. Polar molecules, i.e. asymmetrical molecules, as for example water, can be heated up well with microwaves. Thus, the polar molecule gets into rotation through the high frequent alteration of the microwaves and thus converts the electromagnetic energy into heat. As every molecule generates heat and the microwaves penetrate deep into the material (depending on material), all the volume is heated up. This is an essential advantage over conventional heating, where heat is penetrating into the material through the surface only.

It is obvious that a high heat conductivity is not necessarily needed for microwave heating as it is a volumetric heating. The equation (1) shown below describes the process, which is valid for non-magnetic materials only:

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

P: power taken up by the material
f: frequency of the microwaves
ε_0: electrical field constant
ε'': imaginary part of the complex dielectric constant
E: electrical field-strength
V: material volume

At the volumetric heating, every volume element receives the same amount of heat, provided the material is thin compared to the penetration depth of the microwaves. This results at homogeneous materials in the fact that first the body has the same temperature everywhere. As the surface of the material is in contact with the environment which is not heated up by the microwaves and so consequently is colder than the material, the surface releases heat to the ambient atmosphere and is cooled that way. This results in the fact that with microwave heating, the inside of a material is hotter than the surface. Thus the temperature profile is inverse to that for conventional heating. This effect is desirable in many cases, as the surface is protected and the heat can be built up more quickly on the inside.

The microwaves travel at the velocity of light. As soon as the microwave source is switched on, energy penetrates immediately into the body to be heated. An energy conversion immediately starts. When the source is switched off, the heating process is immediately stopped. Therefore long heating up and cooling down cycles are not necessary with a microwave heating system.

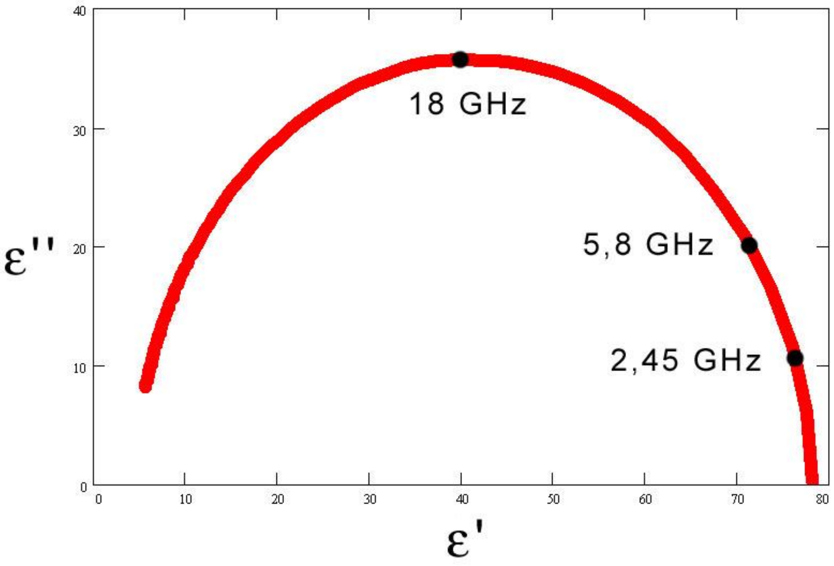
Non-polar materials, (for example air, Teflon, quartz glass) cannot convert microwave energy into heat and therefore do not consume any energy. The microwaves pass through these materials and are not weakened. Basically the material which can do the energy conversion, can be described as „heating element“, as the material itself represents the „heat source“. The metallic microwave chamber is only needed to reflect the microwaves back to the material, in order to prevent microwave leakage and prevent the operator from exposure to microwave radiation.

1.1 Theoretical Advantages of 5.8 GHz

Considering only the variable parameters of equation 1, the absorbed power depends on the frequency, dielectric constant, and electric field strength. Comparing both frequencies 2,45 GHz and 5,8 GHz, it can be deduced that the absorbed power increases with frequency at constant microwave power and therefore constant electric field strength. As a result , in theory, a material absorbs approximately twice the energy at 5,8 GHz than at 2,45 GHz at the same incident microwave power

In addition, the dielectric constant is, in most cases, not really a constant for materials. It depends on both temperature and microwave frequency. In most materials, the dielectric constant increases with frequency. An example of frequency dependency of the dielectric constants for water is shown in a Cole-Cole curve in picture 1, and for some other materials in table 1.

The maximal imaginary part of complex dielectric constant for water at 25°C is at about 18 GHz. The two discussed frequencies are shown in the diagram and it can be observed, that the value at 5,8 GHz is higher than that at 2,45 GHz. Therefore, water can absorb up to four times the microwave power at 5,8 GHz in comparison with 2,45 GHz, theoretically.



Picture 1: Cole-Cole curve for water at 25 °C.

	915 MHz		**2.45 GHz**		**5.8 GHz**	
	ε'	**ε''**	**ε'**	**ε''**	**ε'**	**ε''**
Water	78	4.3	76	10.9	71	22.9
Methanol	31.5	7	24	13.5	12	13
Brick, wet	21.7	1	22	3.5	20	4.8

Table 1: comparison of microwave frequencies

2. Applications and Equipment

2.1 Drying of grinding wheels

The conventional drying process of industrial grinding wheels is very time consuming due to the large dimensions of the wheels. Especially the thickness of some grinding wheels prevents a fast heating and drying, as the heat conductivity of the grinding material is typically low. With microwave heating, the drying speed can be increased and thus the total drying time is decreased. Picture 2 shows a microwave chamber drier used for this application. Grinding wheels are placed on racks inside the chamber. Microwave is applied from both sides of the chamber and ensures an even heating of the whole load. Drying air is introduced from the sides of the chamber, where the direction of the air flow is constantly changed to ensure an even drying.

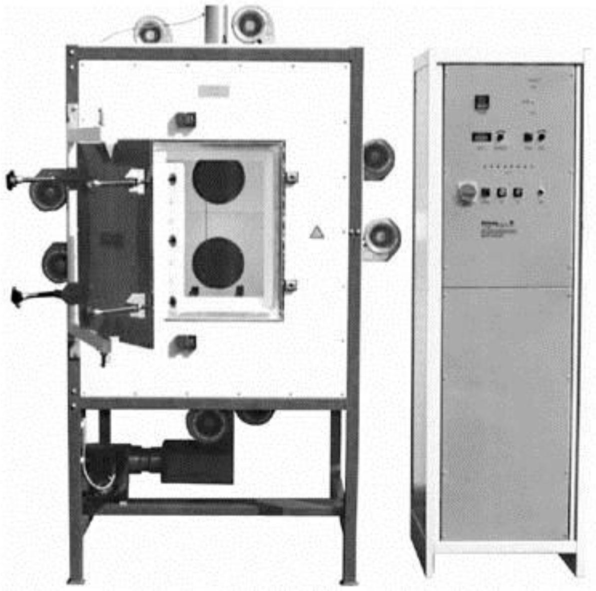
Picture 2: microwave chamber drier, chamber size 21 m³, 30 kW

2.2 Debinding of injection-moulded ceramics (CIM)

Injection moulding of ceramics is a relatively new shaping method, which was derived from the plastics production. A ceramic is injected into a mould with high pressure and can then be removed. The ceramic keeps the shape of the mould due to some organic binder that gives it a certain green toughness. With this shaping method even complicated shapes can be generated.

The organic binder has to be removed before sintering of the ceramic bodies. With conventional thermal methods, typically temperatures of 500°C to 700°C and debinding times of some hours to a few days are needed.

Microwave hybrid debinding, a combination of microwave and hot-air heating, can reduce the debinding temperature and get the debinding time down to 10-20% of the conventional time. The actual savings depend on the binder used and specifics of the ceramic. This otherwise expensive and time-consuming shaping method can be made cheaper and the process can be shortened by microwave heating. A laboratory/small-production sized hybrid debinding furnace is shown in picture 3.



Picture 3: microwave hybrid debinding furnace 6,4 kW / 550 °C

2.3 Curing of glass-fiber reinforced plastic rods

Rods made of glass-fiber reinforced plastics are manufactured by pultrusion process and used, for example, for fishing rods. The resin that covers the glass fibers has to be cured in order to obtain its final toughness. It is especially important to cure the rods in its whole volume to get optimal product characteristics. This was not guaranteed with conventional methods as the core of the rods was not entirely hardened in some cases because of the low thermal conductivity of the rods.

This problem can be avoided by microwave heating, because the microwaves heat the rods from the inside out, so that a complete curing of the material, even in the core, is ensured. The microwave systems, which are used, are very compact and provide the necessary heat at a heating length of appr. 30 cm, as shown in picture 4.

Picture 4: microwave heating chamber MEK 1,2 kW

2.4 Preheating of casting resins

Plastic insulators for high voltage installations are manufactured by curing casting resin in a heated metallic mould. Time for curing of the resin inside the mould, the so-called gelling time, determines the productivity of a system. To reduce the gelling time and thus increase the productivity, it is possible to preheat the casting resin before it is put into the mould. Heating up to approx. 100 °C has shown to be perfect for the process, whereas the gelling time can be reduced by up to 40 %. In order to obtain an evenly cured product in this short time, it is necessary to heat the casting resin homogeneously to the pre-heating temperature. If the resin is not heated evenly, it cannot be cured completely at the reduced gelling time. Homogeneous heating cannot be obtained with conventional heaters that heat a tubing through which the resin flows. Therefore, only parts of the resin that are in contact with the wall of the tube are heated.

During microwave heating, the casting resin flows through a microwave transparent Teflon tube. Therefore, the microwaves can heat the resin from outside through the tube. As the microwaves can penetrate into the resin, a uniform heating of the whole volume is obtained. A microwave flow heater used for this process is shown in picture 5.

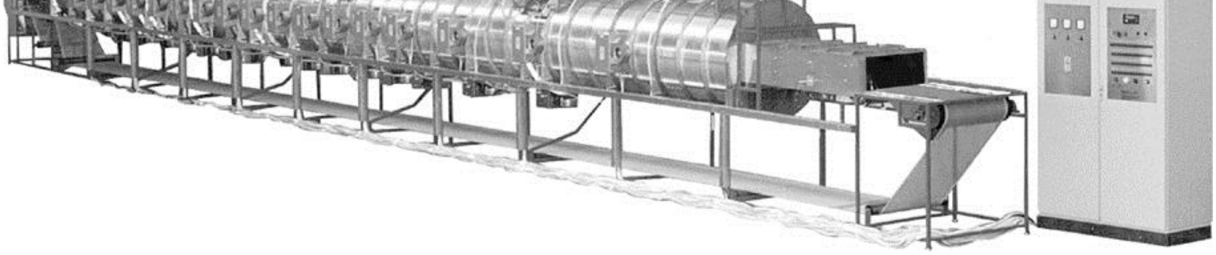
Picture 5: microwave flow heater MFH 3,6 kW

2.5 Drying of heat insulation materials

Heat insulation materials have a very low heat conductivity by design. Therefore any conventional heating for drying or other purposes takes a long time until the core of the material reaches the desired temperature.

Conventional drying is done mostly in chamber driers, with drying times of 4 hours and up. This requires much space for the driers and manpower for loading and unloading.

With the microwave drying, this problem can be avoided. The microwaves penetrate into the complete volume of the insulation material, which results in a fast heating and drying. Thus, continuous microwave driers, like the one shown in picture 6 can be used to dry this material in less than one hour, depending on the thickness.



Picture 6: microwave continuous belt drier MDBT 55 kW / 20 m

2.6 Heating of ceramic fibers

For a coating process, ceramic fibers are pre-heated by a rotary tube microwave shown in picture 7. This unit has the advantage, that only the fiber material is heated by the microwaves, as the tube is made of quartz-glass which is transparent to microwaves. Thus the required energy is comparatively low.

Picture 7: microwave rotary tube furnace MDRT 6,4 kW

2.7 Comparison test with 2.45 GHz and 5.8 GHz

As the 5.8 GHz frequency is new for industrial heating, there is a lack of available data for this frequency. Thus it is necessary to compare the behavior of materials at 2.45 GHz and 5.8 GHz to see the advantages/differences of the two frequencies.
A laboratory sized test unit for this purpose is shown in picture 8. This unit has one microwave generator of each frequency. Thus tests under identical conditions with variations in the frequency only can be conducted.

Picture 8: microwave dual frequency furnace, 800 W/2.45 GHz and 600 W/5.8 GHz

2.8 Other Applications

Other applications for microwave heating are: Heating and drying of wood; Heating, drying and sterilization of foodstuff; Pre-cooking of rice; Drying and curing of foundry cores; Drying of porcelain figures; Curing of rubber; Sterilization of bottle corks; and many, many more.

3. Summary

Industrial microwave technology is available for a broad variety of applications, of which only a few could be discussed here. In general, microwaves are best used where conventional heating and drying technology has reached its limits. Microwaves excel by reducing heating and drying time and improving quality tremendously.