Microwave Heating Technology: Potentials and Limits

Abstract: For approximately 50 years, microwave heating technology has been used in industry. In order to outline the advantages of this technology, the theory of microwave heating is presented in detail. In addition, the practical effects are shown by selected examples. Microwave heating devices meanwhile exist in many different designs. Despite the classic chamber system like microwave ovens in kitchens, microwave heating is also used in industrially continuously operated drying and heating furnaces. Long-time experience in microwave area and innovative ideas are the basis of *LINN HIGH THERM's* microwave furnaces. This article shall give an overview of currently available types of industrial low- and high-temperature microwave heating furnaces. The drying- and heating-processes which are possible with these furnaces are as diverse as in the conventional thermoprocessing technology. Microwave heating can often accelerate significantly the drying respectively heating process and thus can safe time, energy and money.
Keywords: microwave heating, microwave technology, microwave furnace, furnace, numeric simulation, FEM, electrical heat, low-temperature application, drying, heat treatment, hardening, baking, debinding, sintering

Introduction

Treatment of materials with microwaves has a variety of promising advantages compared to conventional heating technologies, e.g. better product quality, reduction of process time, saving of energy and energy costs by higher efficiency, environmental relief, lower investment costs and higher flexibility of the furnace [1–5]. Microwave heating is a process where electromagnetic energy with a frequency from 300 MHz to 300 GHz gets into a heating product as electromagnetic wave with wavelengths in the range from 1 m to 1 mm and which is transferred into heat inside the product (Fig. 1).

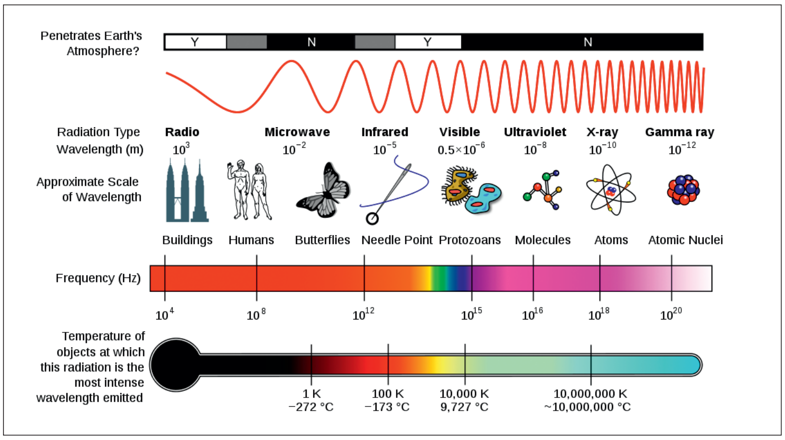

Fig. 1 Spectrum of electromagnetic radiation [6]

Basically, 4 ISM-frequencies (Frequencies for Industrial, Scientific and Medical radio-frequency equipment) are available for microwave technology which can also deviate depending on country specific rules. The highest frequency is 28 000 respectively 30 000 MHz although an industrial and cheaper use in a larger scale is not yet in sight. The low frequency of 915 MHz is subject to a certain technical requirement which only justifies a use for certain cases. The most economic "frequency" is 2450 ± 50 MHz which is used for household microwaves all over the world. From the point of microwave thermo-process technology, the SHF-band with the frequency 5800 ± 75 MHz is used in the industry [5].

Theoretical basic principles

Before the detailed discussion of the physical principle of microwave technology, the authors first give a quick look at the conventional heating process. Resistance- or infrared-heating elements serve as heating sources whereby they are placed near the material to be heated. By heat radiation and convection, their energy is transferred to the surface of the material and has to flow from there to the inner part to enable a complete heating of the material. Heat conductivity, adsorption and the specific heat capacity of the material hereby basically determine the heating process.

Sensitive materials may not allow high temperatures. And if the material also has low thermal conductivity, a long process is inevitable so that there are strong limits for the production of certain products regarding conventional heating technology. In order to avoid these limits, physics doesn't have to be redeveloped. "High frequency technology respectively radar engineering" only have to attract more interest.

Microwave heating differs from conventional heating systems regarding the fact that heat doesn't have to be brought into the heating product by heating the ambient gas and subsequent heat transfer but it can be directly coupled into the material volume. It has the potential of an extremely energy efficient heating method so that there have already been published a variety of research papers concerning microwave heating [1–3, 5, 7–8].

The transformation from electromagnetic energy to heating energy is realized on the basis of the electromagnetic characteristics of the materials and is basically independent of material, temperature and

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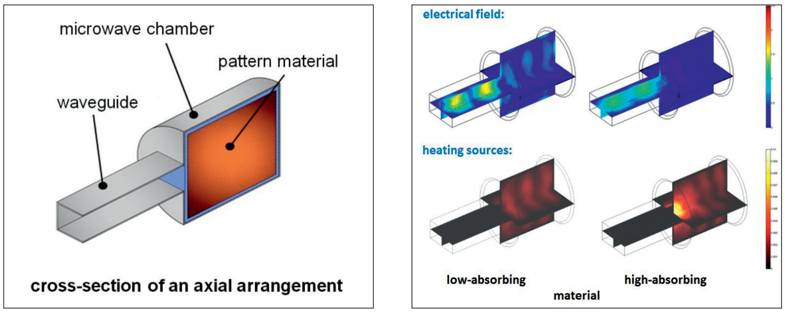

Fig. 2
FEM simulation: distribution of the electric field and of the heating source in cylindrical multi-mode-applicator [4]

frequency. As generally only one frequency is used during the heating process and as temperature dependence of electrodynamic characteristics is not clear, consideration is done only depending on material properties.

In order to describe any material, the three parameters electrical conductivity, permeability and permittivity are necessary. For the latter, the former description dielectric constant (DC) respectively relative permittivity and loss factor are used.

A complex dielectric constant is described by eq. (1). Eq. (2) is valid for the permeability constant:

$$\underline{\varepsilon}_{ges} = \varepsilon_0 \cdot \left[\varepsilon_r^{/} - j\,\varepsilon_r^{//}\right] = \varepsilon_0 \cdot \underline{\varepsilon}_r \qquad (1)$$

$$\underline{\mu}_{ges} = \mu_0 \cdot \left[\mu_r^{/} - j\mu_r^{//}\right] = \mu_0 \cdot \underline{\mu}_r \qquad (2)$$

The influencing factor for energy transformation is the imaginary part of the permittivity constant $\varepsilon_r^{//}$ = loss factor ($\tan\delta$) x relative permittivity ($\varepsilon_r^{/}$). This part is often confused with the loss factor by mistake. This connection is shown in eq. (3).

$$\varepsilon_r^{//} = \tan\delta \cdot \varepsilon_r^{/} \quad \text{and} \quad \tan\delta = \frac{\varepsilon_r^{//}}{\varepsilon_r^{/}} \qquad (3)$$

With:

- $\underline{\varepsilon}_{ges}$ = complex dielectric constant (DC);
- $\underline{\mu}_{ges}$ = complex permeability constant;
- ε_0 = $8{,}85418 \cdot 10^{-12} \frac{A \cdot s}{V \cdot m}$ = electric field constant;
- μ_0 = $4 \cdot \pi \cdot 10^{-7} \frac{V \cdot s}{A \cdot m}$ = magnetic field constant;
- $\varepsilon_r^{/}$ = real part of DC;
- $\mu_r^{/}$ = real part of permeability;
- $\varepsilon_r^{//}$ = imaginary part of DC;
- $\mu_r^{//}$ = imaginary part of permeability;
- $\underline{\varepsilon}_r$ = relative dielectricity number;
- $\underline{\mu}_r$ = relative permeability;
- $\tan\delta$ = loss factor and δ = loss angle.

With this description of the complex dielectricity constant and the complex permeability constant, the treatment of *Maxwell's* equations in the frequency range in form of *Helmholtz* equations (4) and (5), which are the basis of microwave technology, is facilitated considerably. These equations are further treated for numeric simulation in the frequency range [2, 7].

$$\nabla^2 \underline{\vec{E}}(\vec{r}) = \omega^2 \cdot \underline{\mu}_{ges} \cdot \underline{\varepsilon}_{ges} \cdot \underline{\vec{E}}(\vec{r}) \qquad (4)$$

$$\nabla^2 \underline{\vec{H}}(\vec{r}) = \omega^2 \cdot \underline{\mu}_{ges} \cdot \underline{\varepsilon}_{ges} \cdot \underline{\vec{H}}(\vec{r}) \qquad (5)$$

The energy which is transmitted by the electromagnetic waves can be deduced by Maxwell's equations and leads to the famous *Poynting* vector in the frequency range [7, 9]:

$$P_{ein} = \frac{1}{2} \int_F \left[\underline{\vec{E}} \times \underline{\vec{H}}^*\right] \vec{n}^0 \, dF = \frac{1}{2} \int_F \underline{\vec{S}} \cdot \vec{n}^0 \, dF \qquad (6)$$

This vector says that the average energy P_{in} which flows into an enveloping surface depends on the amplitude, the distribution and the corresponding phase of the electric and magnetic field. If one transfers the surface integral in eq. (6) to a volume integral following *Gauss'* theorem, the efficacy loss in any dielectric is determined:

$$P_{abs} = \frac{1}{2} \omega \, \varepsilon_0 \cdot \iiint_V \varepsilon_r^{//} \cdot \left|\underline{\vec{E}}\right|^2 dV \qquad (7)$$

This way, a 3D-heat source density distribution in case of non-magnetic material can be calculated. Fig. 2 shows electromagnetic field strength and heating source density distributions as an example of a numeric 3D-Finite-Element-Method (FEM) simulation. It deals with a cylindrical multi-mode applicator (microwave chamber, Fig. 2, left) which has an axial arrangement of the rectangular waveguide and which is filled with modeling material. Low absorbing and highly absorbing materials with different values of DC $\underline{\varepsilon}_{ges}$ are used as modeling material [4].

As the whole volume of the object is heated simultaneously, a higher temperature develops in the inside as the surface adjoins to the "cold environment" and is thus cooled. However, the inside insulates the heat as the neighbouring molecules have the same approximate temperature. Thus, the temperature curve is inverse compared to conventional heating methods. In many cases, this effect is desired as the surface is prevented from thermal damage and heat inside the object is generated faster.

The diffusion speed of microwaves is the velocity of light in vacuum respectively in air. If microwave source is activated, its energy is directly present in the object to be heated and immediately also starts with energy transformation. If the source is switched off, the heating process is stopped immediately. There are no long heating-up and cooling-down processes of the furnace.

Nonpolar materials (e.g. air, Teflon, quartz glass) cannot transform energy and thus cannot be heated. Microwaves penetrate these materials and are not dissipated. Generally, the material to be heated which is able to make the heat transformation can be seen as "heater" as the material itself represents the heating source. The metallic furnace housing, i.e. the microwave chamber, only serves for reflecting back the microwaves to the material so that no energy gets lost and that the operating personnel is not exposed to microwave radiation.

Drying as example for industrial low temperature application has a special status in the production process and determines in certain cases even the production rate respectively the cycle time. In case of optimization of the whole process, thus the drying process is examined carefully. Regarding ceramic industry, drying times of 10–14 days and in case of big parts even up to several months are no rarity. As shorter delivery times and smaller stock capacities are the aim, microwave drying will play a more and more important role. The reason for that is the physics of microwave technology respectively the propagation and characteristics of electromagnetic waves. In special cases, even a material improvement can be achieved by microwave treatment.

In case of microwave drying, the inverse temperature profile is advantageous, as a higher vapour pressure develops inside the material and drying is effected from the inside to the outside. In the colder outer layers, a part of the steam condenses and keeps the surface humid and permeable until there is no more steam from the inside and the surface con-

sequently starts to dry. As water generally transfers the most microwave energy due to its high loss factor, lower energy transformation (microwaves go on without being weakened) is effected depending on drying substance and drying rate in the inside although this energy can be used in other areas.
That way, effective drying with removing all water nests is possible. Because of different energy input of the materials to be dried, in principle different processes are possible although there is no essential difference above a humidity content of approximately 15 %. In this case, water determines the process. In the range from 5–15 %, the drying substance itself can play a more and more important role. If the material itself can transform microwave energy into heat, the temperature of the material can increase although the temperature dependence of the dielectric constant determines the process. In case of certain chemicals, the chemically bonded water can be split off that way. Below 5 %, microwave drying can become ineffective with decreasing humidity content. However, it is recommended to examine the material before for ensuring that the necessary temperatures can be reached.

Microwave continuous belt dryer MDBT-range

At the beginning of the 1990s, *LINN HIGH THERM GmbH (LHT)* started their activities in the area of microwave heating together with *Riedhammer GmbH.* In order to meet the demand for industrial dryers, a modularly designed microwave continuous belt dryer was developed [10]. Due to the easy and flexible concept like modular design, it was possible to manufacture a cost-effective microwave continuous belt dryer (MDBT) which can be used for various applications. The main application in many manufacturing processes is drying.
The microwave continuous belt dryer type MDBT offers the following advantages compared to conventional heating furnaces:

- Faster, reproducible and homogeneous heating
- Immediate readiness for operation respectively control of the heating power without delay
- Good suitability for process automation
- No storage heat losses
- Low specific energy consumption
- Shorter production times
- Faster heating of thicker layers.

In case of thicker materials or bigger bulk densities, the penetration of microwaves into the material and the immediate transformation of the microwave energy into heat result in a faster drying compared to conventional drying technology. The drying time of several materials of several hours or even days is reduced considerably. In addition to that, there is the possibility to achieve an improved product quality. As the heating of the material depends on the volume, overheating is mostly avoided. In case of insulation materials which have a low thermal conductivity, the drying process takes long until the conventionally produced heat has reached the inside and until drying starts there. In case of microwave drying, heat conductivity of the material only plays a minor role.
The applications of microwave continuous belt furnaces are of course not only limited to the drying process. In food industry, microwave heating has been used for approximately 50 years. An example for this is the production of sliced bread. Microwave heating is used for pasteurization [11]. Furthermore, baking of bread without crust by microwaves has proved to be very energy-saving – more than 40 % less energy requirement by decreasing the baking process compared to the conventional baking oven – baking time with microwaves approximately 10 min and with conventional baking oven approximately 24 min. The production of fast-cooking rice by microwaves saves up to 90 % of the energy in case of the same gustatory characteristics and avoids the usage of water in the production (Fig. 3). As the subsequent drying is not necessary, a lot of energy can be saved [12]. Moreover, this heating principle is used for thawing, calcination, hardening, tempering and synthesis acceleration.
Older microwave continuous furnaces are based on the concept of less generators (magnetrons) with high power on a rectangular microwave chamber. This implies that it is difficult to generate a homogeneous microwave field in such furnaces. High power is transferred on the supply points of the magnetrons which, however, cannot disperse evenly in the chamber volume. Additionally, the reflection of the microwaves is lead back to the magnetrons due to the rectangular design of the chamber. All these facts lead to a comparatively irregular microwave field distribution.

Fig. 3 MDBT-furnace in fast-cooking rice production (installed microwave power 21 kW, throughput approximately 300 kg/h)

LHT's microwave continuous furnaces are based on the concept of many small magnetrons and a cylindrical microwave chamber. An equal supply of many small microwave powers results of the distribution of a number of magnetrons on the chamber walls. Thus, a more homogeneous microwave distribution is achieved. This effect is furthermore supported by the curved chamber which diffusively reflects the striking microwaves into the chamber volume.
An example for such a furnace with new design is below microwave continuous belt dryer MDBT 70+24/1040/210/16300 which is used for heating and drying pulses. This furnace has a heated length of approximately 16,3 m and a belt width of approximately 1 m (Fig. 4). In case of this furnace, a modular construction was chosen. This offers the possibility to modify the furnace afterwards without much effort. The microwave generators (magnetrons) are installed spiral-like around the longitudinal axis of the cylinder chamber so that a more equal field distribution is achieved. The conveyor belt is lead over bottom plates which are equipped with secondary beams (slotted antennas) so that further field influence (concentration) takes place. The inlet and outlet openings are lined out with special absorbing materials for attaining the permitted leak radiation values.
Depending on the size of the opening, additional absorbing zones are integrated which effect further reduction of the leak radiation. In case of much bigger openings, additional absorber curtains, e.g. manufactured from carbon fibers, are installed. The used magnetrons are cooled by air although the heated cooling air flows into the furnace and is able to take up humidity. The humid air is then exhausted from the furnace by an exhaust system. This microwave continuous belt furnace can be equipped with a microwave power of up to 100 kW.

Fig. 4 Microwave continuous belt dryer MDBT 70+24/1040/210/16300 of LINN HIGH THERM in production (installed microwave power 70 kW, hot air power 24 kW, throughput approximately 2000–3000 kg/h)

Microwave chamber vacuum dryer MKST-range

The patented microwave furnace of the MKST range (Fig. 5) is used for vacuum drying. It is a universal test unit which can be adapted to various applications e.g. for drying wood, ceramics, chemicals, food, building materials, for hardening of fiber reinforced composite materials and more. The microwave furnace consists of a cylindrical microwave chamber with an inner diameter of approximately 550 mm and a length of approximately 3485 mm. The microwave furnace is designed for operation under normal pressure, rough vacuum (10 mbar) and slight protective gas overpressure. It is equipped with 12 magnetrons á 800 W/2,45 GHz (totally 9,6 kW). The power of these magnetrons can be adjusted continuously in a range from 15–100 %.

Microwave in drum drying MIDD-range

As the result of a long collaboration with the German nuclear industry (*Nukem*), LHT patented a process which vaporizes liquid waste by microwaves. The original application background was drying/crystallization of slightly radioactive saline solutions, decommission sludge, cooling and washing liquids which were presented in numerous publications [1]. The microwave in drum drying process (MIDD-process) is a drying process controlled by evaporation. The most important characteristics and advantages of the MIDD process compared to resistance heated systems are:

- Heat is directly produced in the solution over the complete volume.
- In this process, only minimal temperature gradients develop and thus the most possible homogeneous drying/solidification.
- Compared to resistance heated systems, the process time is shortened significantly.

Fig. 5 Microwave chamber dryer MKST-9,6 200/2500

The MIDD-furnace is operated semi-continuously. At the beginning, a defined quantity of liquid waste is pumped into the final storage container while it is pre-heated by inductive heating. Subsequently, microwave heating starts and liquid waste is supplied continuously. The final storage container and the microwave applicator are held at an absolute pressure of approximately 900 mbar. The developing steam is absorbed by a fan. A droplet separator filters dust and carried away water drops from steam flow before it is condensed out in a plate heat exchanger. The condensate is collected in a separate container.

At the end of the process, the supply of liquid waste is stopped and the remaining liquid in the final storage container is evaporated with adjusted microwave power. After container has cooled down, it is replaced by a new final storage container and the cycle starts again. The condensate can be used further on or it can be recycled and the solid, dry residual can be finally stored in the container. During the process, a cooling water recooler ensures that the cooling liquid of the plate heat exchanger is below a defined temperature limit for guaranteeing a complete condensation. The MIDD-furnace is operated by a programmable logic controller (PLC). Apart from all mass flows, temperature, filling levels as well as difference pressures are controlled and measured in order to draw back the conclusion over the total mass balance to the thickness of the liquid layer above the already dried material. The layer is important for the automatic operation of the furnace. All measured data are visualized and documented by a separate data recorder. The process is visualized by a touch panel, all notifications are documented.

As the result of numerous tests and further development work on this process, LHT built a ready for series production prototype of a MIDD-furnace (Fig. 6).The new furnace was developed and built for a permanent industrial use. The safety devices which are required by nuclear regulations, were implemented in collaboration with a partner of the German nuclear industry. For the process it is important to achieve the best possible efficiency as well as the most homogeneous electromagnetic field. This is realized by nine 900 W standard magnetrons which do not only have a long lifetime but also significantly lower maintenance and repair costs. All materials which are in contact with the components are made of stainless steel, Teflon or silicone. During designing, it was also put emphasis on the fact that all components can be cleaned, maintained and changed easily [1].

Microwave chamber dryer MKT-range

In case of microwave drying, a rule of thumb can be used for determining the necessary microwave power which says that a microwave power of approximately 1 kW is necessary for the evaporation of 1 kg water/h.

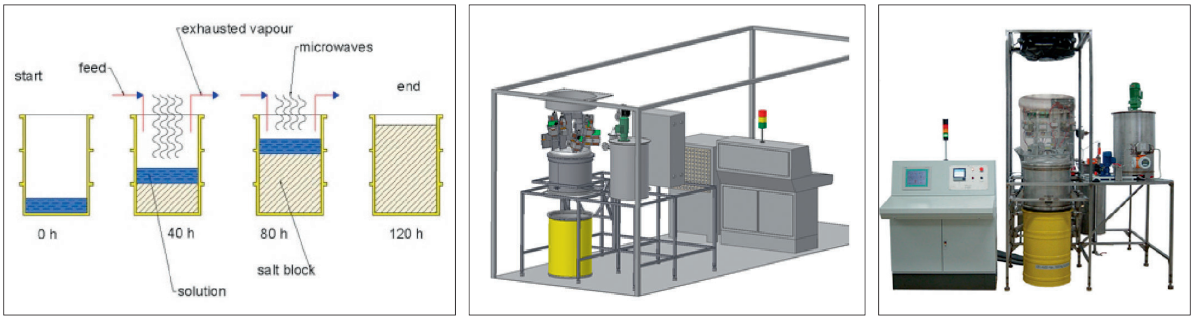

Fig. 6 Schematic diagram of MIDD-process (l.) and new MIDD prototype (r.)

This rule is valid as long as there is a sufficient starting humidity. Multi-mode batch furnaces consist of the microwave chamber which is closed by a door. The microwave power is mostly introduced on the sides and/or the ceiling and the rear wall. As shown in the picture, the furnaces can be equipped with a roll transport system. In such furnaces, the insert good is mostly not moved. That is why a very homogeneous microwave distribution is necessary in the chamber for avoiding an irregular heating. Such furnaces are mostly used for drying or heating products which are too big, too heavy or too sensitive for being transported in a continuous furnace. Even for long drying times it is often advantageous to use a batch furnace. An example for a multi-mode batch furnace is the below shown microwave chamber dryer with a microwave power of 30 kW and a chamber volume of approximately 21 m³ (Fig. 7).

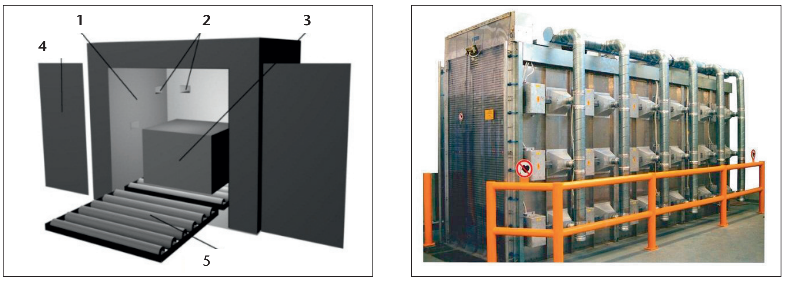

Fig. 7 Basic scheme of a multi-mode batch furnace (l.) and microwave (MW) chamber dryer MKT-30 (r.); 1 = MW chamber, 2 = MW inlet openings; 3 = heating good; 4 = door, 5 = transport rolls

The microwave chamber dryer is used for drying industrial ceramic or resin bonded grinding wheels which can be moved into the furnace by metal racks. The microwave energy is produced by 38 magnetrons which are placed on both sides of the furnace for assuring a uniform heating. The ventilation system is also installed on both sides so that a homogeneous drying of all parts can be ensured. For microwave tightness, the rolling door is pressed on pneumatically in case of microwave operation [13].

Another application is heating of natural and synthetic rubber. So far, the state of the art for the cold season of the year was the preheating of natural rubber based on big heating chambers in which the standard rubber plates were preheated for days until weeks. Especially during winter months, the pre-heating times are very long as the plates exhibit low temperatures of –10 °C or lower. The low thermal conductivity of the rubber and the big volume of the plates inevitably result in long preheating times as heating is effected by warm air with maximum 60 °C.

Microwave technique enables preheating of single plates within 0,5–2 h depending on requirement. The advantage of microwaves is that they can penetrate into the material and that heat is also produced in the inside of the rubber. That is why a complete pallet can be heated homogeneous and fast. Thus a big heat hall (several 1000 m³) can be saved when using two microwave furnaces. Consequently, stock requirement and investment can be reduced considerably as rubber for e.g. one week production does not have to be stored in the heat halls.

Microwave laboratory furnaces MKE-range

Due to the variety of materials and production processes, it first has to be investigated how the material specific microwave process can be used optimally. For this purpose, special test microwave furnaces are available with which the corresponding tests can be made on the premises of LHT.

The multi-mode furnace type MKE is equipped with two magnetrons. They can be operated individually or together and provide each 800 W heating power in case of a frequency of 2,45 GHz. The microwaves are directly introduced into the cylindrical microwave chamber. Control of microwave power is effected by potentiometers.

For heat insulation, a rectangular housing of fiber insulation plates with a useful volume of one liter is used. The sample surface temperature is measured contactless by a pyrometer. The data is recorded and analysed by software. The furnace is designed for use in laboratory especially for low temperature range. With this furnace, first general knowledge about microwave behavior of different materials can be found out (Fig. 8).

Microwave furnaces MEK- and MFH-range

Microwave flow furnaces are used as special furnaces for heating liquid, highly viscous materials. The liquid flows in a microwave transparent Teflon tube (PTFE tube) through the heating zone and is heated by

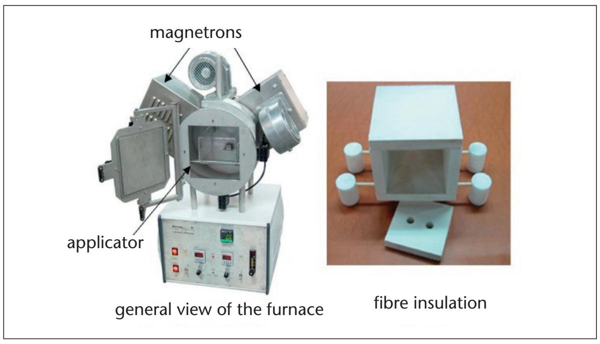

Fig. 8 Microwave laboratory furnace MKE-1,6

Fig. 9 Microwave flow furnace of type MEK (l. and middle) and MFH (r.)

microwaves. Thus, the liquid can be heated homogeneously in the complete volume without getting in touch with the walls of the microwave heating chamber (Fig. 9).

Pre-heating of cast resin is another industrial application of interest [14]. Plastic insulators for high voltage furnaces are produced by bringing cast resin into a heated metal mould. The time the resin needs for hardening in the form, the so called gel time, determines the productivity of the furnace. For reducing the gel time and thus increasing the productivity, it is possible to pre-heat casting resins with Al_2O_3 or SiO_2 filler contents of up to 50 mass-% before being filled into the form mould. Heating up to approximately 100 °C thereby proved to be optimal. Gel time could be reduced by up to 40 %.

For achieving this effect, it is necessary to heat up the cast resin evenly to the temperature. If this is not the case, the resin cannot harden completely due to the reduced gel time. An equal heating could not be achieved with conventional heaters which heated a metallic tube line through which the resin was lead as only the parts of the resin which get in touch with the tube are heated.

In case of microwave heating, cast resin flows through a microwave transparent PFTE-tube. Thus, the microwaves can heat the resin from the outside of the tube. As the microwaves can penetrate into the cast resin, the whole volume of the resin is heated evenly. Apart from reduction of the gel time, microwave heating had other advantages: the colour fastness and the strength had been increased.

Another application is the hardening of glass fiber composite rods. Rods made of glass fiber reinforced plastic are produced in a pultrusion process and are e.g. used as cores for glass fiber cable fishing rods. The glass fibers which are soaked with synthetic resin have to be hardened for achieving their final strength. It is especially important to harden the rods completely for achieving optimal product characteristics.

With conventional methods, this was not always guaranteed as the core of the rods was not completely hardened due to its low thermal conductivity. With the help of microwave heating, this problem could be solved as microwaves heat the rods from the inside such that it is guaranteed that they are heated completely.

The microwave furnaces which are used for this process are very compact and achieve the necessary heating in the passage with a heated length of only approximately 30 cm. In case of load carriers for glass fiber cables, for example, a conventional tube furnace with a length of 6 m is replaced by this unit.

Microwave rotary tube dryer MDRT-range

Microwave rotary tube furnaces of type MDRT are used as special furnace for powder and granules [15]. The material is lead through the heating zone by a rotating PTFE or quartz glass tube and is being heated by microwaves. The furnace can be operated under vacuum or protective gas. The microwave rotary tube furnace can be used for heat treatment and coating of granules, powders and fibers. In case of this furnace, the material also doesn't get in touch with the heating zone (Fig. 10).

Microwave hybrid furnaces MHT-range

This furnace is a microwave hybrid furnace which is designed for high temperature operation. Heating can be done by resistance heating respectively by microwaves or both in combination. The microwave chamber is rectangular and is made of stainless steel. Heating insulation is made of 3 respectively 4 layers of special ceramic fiber plates and is installed inside the microwave chamber wall.

The insulation of these microwave hybrid furnaces is suitable for an operation up to maximum 1800 °C. It is equipped with 8 magnetrons which provide each 900 W heating power in case of a frequency of 2,45 GHz and which can be switched on separately. The total available microwave heating power is thus 7,2 kW.

The magnetrons are directly fixed on the microwave chamber so that there is a direct radiation of the microwaves into the chamber. There are each two magnetrons on the rear wall, on both side walls and on the floor of the microwave chamber. The microwave inlets are arranged in a shifted way for improving the uni-

Fig. 10 Microwave rotary tube dryer type MDRT (microwave power 2,7 kW respectively 5,4 kW)

Fig. 11 Position of the magnetrons on the microwave chamber (l.) and microwave hybrid furnace MHT-1600 (r.)

Fig. 12 Recycling of carbon fibres (l. and r.) and microwave hybrid continuous belt furnace (middle)

formity of the microwave field. Alternatives with an insert temperature of up to 1400, 1600 and 1800 °C respectively are available.
The control of the complete microwave power can be made by either a potentiometer or a program controller. 6 resistance heating elements serve for the conventional heating, e.g. made of molybdenum disilicide with a total heating power of 9 kW (Fig. 11).
In case of microwave hybrid heating, the microwave is combined with a conventional heating method. The most common heating methods are hot air and resistance heating but others are also possible, e.g. gas-firing and infrared-heating. Microwave hybrid heating with an additional hot air heating achieves high conventional temperature homogeneity by circulation of the air in the chamber. Insulation is necessary for protecting the metallic microwave chamber and for reducing heat losses.
Hot air is mostly used in case of medium temperatures as they are for example necessary for debinding of ceramic parts. In case of microwave hybrid heating with an additional resistance heating, heating elements are used for achieving high preheat temperatures, e.g. for sintering. An insulation of the chamber is necessary as well. Due to the additional resistance heating, materials which only absorb microwave energy at elevated temperatures can be preheated. In the low temperature range, an almost conventional type of heating with hot air or resistance heating takes place, microwaves only contribute to heating at of higher temperatures.
The additional introduction of hot air can also be of advantage in case of low temperature processes like drying, e.g. in order to accelerate the humidity extraction. The applications for both hybrid heating processes are mainly debinding and sintering of ceramics and powder metals.

LHT manufactures specific special microwave hybrid continuous belt furnaces for recycling of carbon fibers, production waste and end of life components in the high temperature range (Fig. 12).

Modeling of microwave heating furnaces

During the last two decades, huge progress was achieved in the development and application of numerical methods for calculating electromagnetic field as well as temperature distributions. Due to the simultaneous rapid development of computer technology, it is currently also possible to calculate electromagnetic and thermal fields in technical problems even in case of complicated geometry and non-linear material behavior for three-dimensional geometries.
The modeling of microwave heating furnaces has often been dealt with in literature [2–4, 16]. However, the numeric simulation of microwave applicators is still subject of many works, as the results of other authors cannot be transferred to other configurations which have to be investigated and thus are hardly suitable for application. When developing microwave heating furnaces, the distribution of the electromagnetic field is important. However, an exclusively electromagnetic simulation will not be sufficient for designing microwave heating furnaces. Apart from dissipation of electromagnetic energy, the thermal process plays an important role in case of microwave heating. In order to determine the heating process exactly, various heat transfer mechanisms as well as the effects resulting thereof have to be considered as well.
There are a number of excellent reference books which treat the heat transfer mechanism with well-known mathematic methods. The books of *Metaxas* [17] as well as *Kramer* and *Mühlbauer* [18] have to be mentioned. The books of Metaxas and *Meredith* [19], *Zhao* and *Turner* [20] and *Feher* [3] are especially dedicated to the topic of heat transfer in the case of microwave heating.
The thermal and electromagnetic characteristics of the considered materials which depend on temperature can be found in literature [21]. Measurements of material characteristics which depend on temperature are very complex and often contradictory [22]. They are a huge scientific and technical problem which currently is only solved unsatisfactorily [23].
An example for the FEM validation by the experiment is a cylindrical multi-mode applicator with a soot-loaded cordierite diesel particulate filter (cordierite DPF). An open waveguide is used for the transport of the microwave power of a magnetron into the applicator. In this type of supply, the tangentially installed,

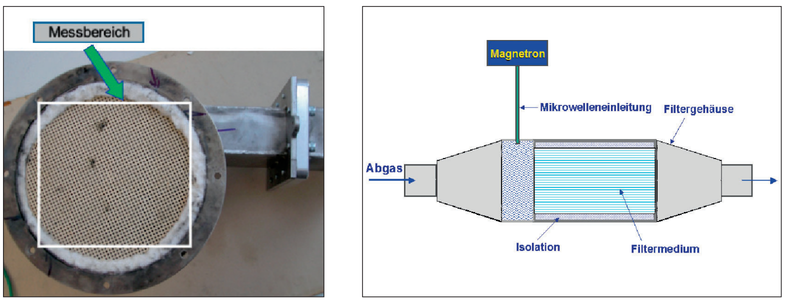

Fig. 13 Experimental setup (rear side) and test assembly for experimental validation of the 3D-FEM-simulation [4]

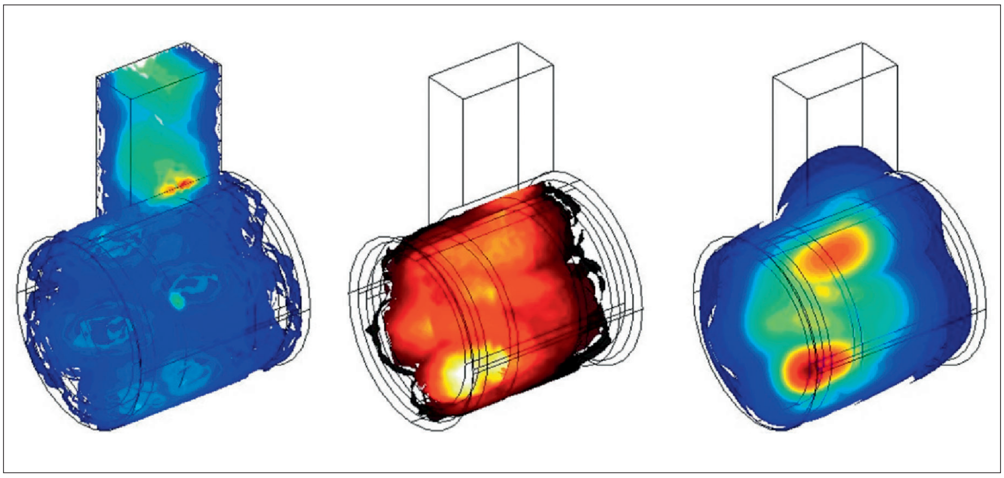

Fig. 14 Results of FEM-simulation: a) electrical field distribution, b) heating source density distribution and c) temperature distribution [4]

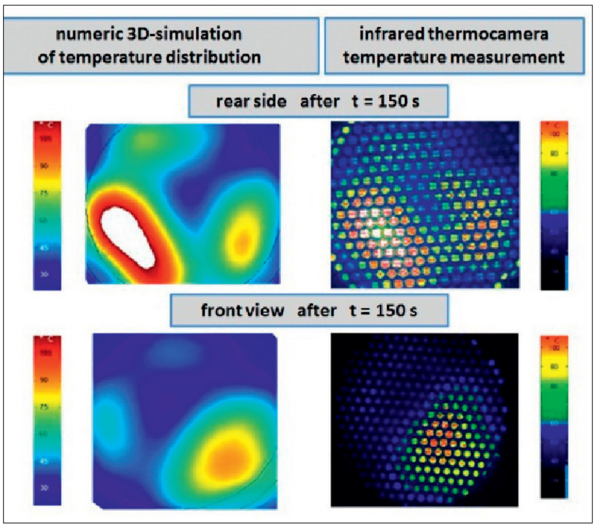

Fig. 15 Results of experimental simulation validation [4]

Parameter	*Modell*	*Experiment*
P_{ein}, W	572	572
P_{abs}, W	532	545
P_{ref}, W	40	27
$P_{abs\ Wand}$, W	0,02	-
η, %	93	95,3
R_0	0,26	0,22
VSWR	1,72	1,56
T_0, °C	20	20
T_{max}, °C	165,6	~170

supplying rectangular waveguide leads to the cylindrical multi-mode applicator. The housing of the applicator consists of the metallic cylinder (diameter = 155 mm, length = 162 mm) with steel walls which are 8 mm thick. The metal grids serve as shields against undesired microwave leak radiation.
The cylindrical filter is manufactured with a diameter of 143,76 mm and a length of 152,4 mm and has a mass of 1255,5 g. The filter medium is cordierite ($Mg_2Al_4Si_5O_{18}$).
Soot load is approximately 18,4 g. The soot loaded DPF has a mass of 1273,9 g. Soot is spread unequally in the cordierite DPF. From macroscopic view, the cordierite DPF is a heterogenic medium with six recognizable homogeneous areas. Further details and physical parameters which are necessary for the modeling can be found elsewhere [2, 4].
Fig. 13–15 show the experimental setup and the results of experimental validation of 3D-modeling of the cylindrical multi-mode applicator [4]. Fig. 13–15 show very good agreement regarding quality and quantity of numerically calculated and experimentally measured temperature field distributions. The reflected power is determined by eq. (8)

$$P_{ref} = P_{ein} - P_{abs} \tag{8}$$

as difference between incident power P_{ein} and absorbing power P_{abs}.
The efficiency can then be calculated following eq. (9):

$$\eta = \frac{P_{abs}}{P_{ein}} = \frac{P_{ein} - P_{ref}}{P_{ein}} = 1 - \frac{P_{ref}}{P_{ein}} \tag{9}$$

The reflection factor is:

$$R_0 = \sqrt{\frac{P_{ref}}{P_{ein}}} = \sqrt{1 - \frac{P_{abs}}{P_{ein}}} = \sqrt{1-\eta} \tag{10}$$

which leads to the so-called Voltage Standing Wave Ratio (VSWR) [7]:

$$VSWR = \frac{1+R_0}{1-R_0} \tag{11}$$

The achieved results of the experimental validation show the following:

- The numerically and experimentally determined temperature field distributions show very good consistency regarding quality and quantity.
- The experimentally tested microwave test unit is energy-efficient, the net efficiency is approximately 95,3 %.
- However, field distribution stays homogeneous (Fig. 14–15) when using only one magnetron.
- It is obvious that the concept of LHT provides better field distribution by using many magnetrons and that it is thus resulting in the homogeneous heating of various materials (see microwave continuous belt furnaces MDBT-range).
- The 3D-FEM-models provide practically robust results.
- Generally, they offer the possibility to visualize the development of local hot-spots and to optimize them more by a fast furnace design adaptation.
- The 3D-models of microwave heating furnaces can be used for computer-aided optimization of industrial microwave heating furnaces.
- Ideally, the simulation results should be checked experimentally in any case.

Conclusions

This article gives a review of the innovative microwave heating furnaces for applications in low- and high-temperature ranges for different industrial sectors which are developed by LINN HIGH THERM GmbH based on long-time experience for laboratory and production and which are used successfully all over the world. Specific examples show the efficiency and the savings potential of microwave heating technology. The topic of computer aided 3D-FEM-simulation of industrial microwave heating furnaces is addressed as well.

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