Numerical 3D-FEM-simulation made by COMSOL Multiphysics of a microwave assisted cleaning system for a diesel sooty particle filter and its experimental validation

Ivan Imenokhoyev*[,1], Albrecht Matthes[1], Heiner Gutte[1] and Gerd Walter[2]

[1]TU Bergakademie Freiberg, Department of Energy Process Engineering and Chemical Engineering, Deutsches EnergieRohstoff-Zentrum (DER), Fuchsmühlenweg 9, Reiche Zeche, 09596 Freiberg, Germany

[2]TU Bergakademie Freiberg, Department of Thermal Engineering, Gustav-Zeuner-Str. 7, 09596 Freiberg, Germany

*Corresponding author: Ivan.Imenokhoyev@der.tu-freiberg.de

TU Bergakademie Freiberg, Department of Energy Process Engineering and Chemical Engineering, Deutsches EnergieRohstoff-Zentrum (DER), Fuchsmühlenweg 9, Reiche Zeche, 09596 Freiberg, Germany

Abstract: By means of a numerical 3D-FEM-simulation, some alternatives for the arrangement of the waveguide supplying the microwave energy to a cylindrical ceramic filter are investigated. The different alternatives are compared concerning a homogenous distribution of the electromagnetic field and the resulting microwave heating initiating the combustion of the diesel sooty particles. Based on this comparison, the alternative showing the (most promising) field distribution is chosen. For the chosen arrangement, the temperature distribution in the ceramic filter is calculated numerically based on the electromagnetic field distribution. The results of this simulation are compared and validated with experimental data gathered from a real microwave assisted cleaning system for diesel sooty particles. In summary, the results of the numerical simulation for the distribution of the temperature in the ceramic filter presented a very good correlation with the experimental results.

Keywords: ***Microwave Heating, FEM, Numerical Simulation, Elektrodynamics, diesel sooty particle filter cleaning, COMSOL Multiphysics.***

1. Introduction

For a multitude of industrial processes and mass applications, the generation and transfer of heat is an essential element. For this reason the development of the microwave heating technology is of high economic importance.

The treatment of various materials by microwaves has a number of promising advantages compared to conventional heating technologies, e.g. a better quality of the product, shortage of the processing time, reduction of energy consumption and energy costs by a higher efficiency, relief of the environment, lower installation costs and a higher flexibility of the plant [Ha 2000, Wal 2004, W-P 2006, Feh 2009, Vötsch 2011].

Microwave heating names the process, in which electromagnetic energy with frequencies in the range of 300 MHz to 300 GHz penetrates the material to be heated and is dissipated into heat right in the material (see Fig. 1).

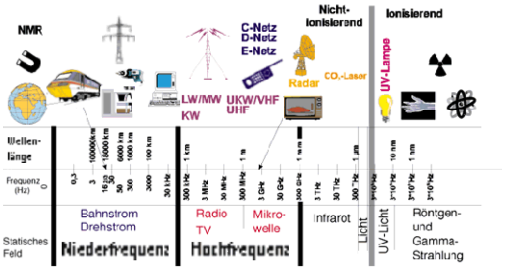

Fig. 1 Frequency ranges for the microwave thermal processing [Vötsch 2011]

For the microwave thermal processing technology, the UHF-band and the SHF-band with frequencies of 2450 ± 50 MHz and 5800 ± 50 MHz are most important [Kum 1986, Wal 2004, Feh 2009].

Because the soot can be oxidized with the residual oxygen from the exhaust gas, the soot oxidation is the predominantly used method of regeneration. In order to initiate the oxidation even below the ignition temperature of the soot (≈ 600 °C), regeneration systems are necessary.

Thereby two systems are differed. The first ones are active systems boosting the soot temperature up to the ignition temperature. The second ones are continuous systems lowering the temperature of the soot oxidation using a catalyst [Str 2008].

The regeneration of diesel sooty particle filters (DPF) using microwaves belongs to the active systems of regeneration (Fig. 2), because depending on the filter load the soot is heated up to the temperature for regeneration. In active regeneration systems, the regeneration takes place discontinuous, as it is required. As the exhaust gas back pressure in front of the filter is the deciding parameter for the necessity of a regeneration, this pressure is measured and as the critical pressure is exceeded, the regeneration is initiated. Therefore, the exhaust gas or the filter are heated up to the ignition temperature of the soot.

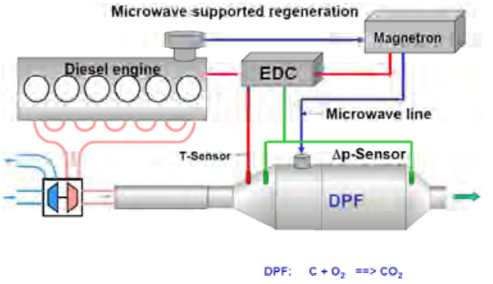

Fig. 2 Concept for DPF-system [Str 2008]

The microwave regeneration differs from conventional systems in the point of heat introduction. In conventional systems the heat is transferred to the filter indirect by heating the exhaust gas. In the microwave regeneration system the heat is coupled directly into the soot. This working principle is holding a high potential for an energy efficient method for regeneration, as shown by a couple of research work about microwave regeneration.

2. Numerical Model

In the last two decades, huge advances were denoted in the development and utilization of numerical methods for the calculation of electromagnetic field and temperature distributions. Because of the rapid development of the computer science at the same time, today it is possible to compute electromagnetic and thermal fields even for complex geometries and nonlinear material behavior in three-dimensional cases.

The modeling of microwave heating plants has often been highlighted in literature [Ha 2000, LBM 2003, Im 2007, Feh 2009].

But the numerical simulation of microwave applicators is still subject of numerous publications and scientific research, because the results of other authors are not directly transferable to other configurations and therefore hardly applicable (Fig. 3-4).

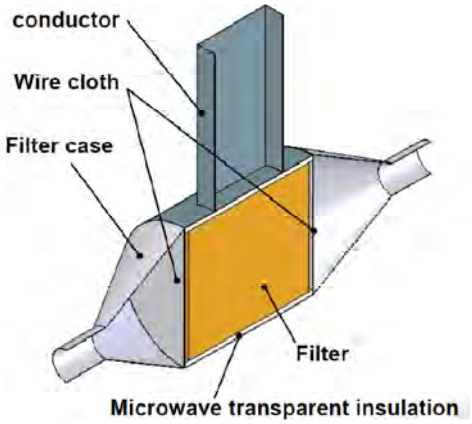

Fig. 3 Construction of a microwave supported DPF-regeneration system [Str 2008]

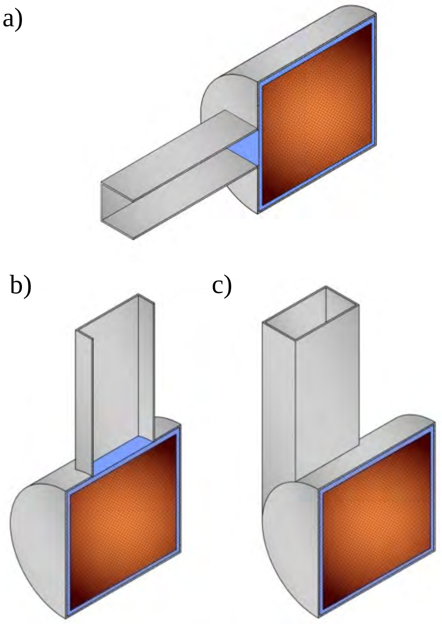

Fig. 4 Arrangement variants for a microwave line: a) axial; b) radial; c) tangential

The FEM is the most common and a widely spread method for simulation in different areas of technique. For the computing of wave propagation the FEM is rarely used. The reason therefore is less the poor fitness of the FEM for computing the formation of waves in closed areas like wave guides and resonators, but the establishment of the finite difference method (FDM), which is more common for this application.

The basic principle for the FEM modeling are Maxwell's equations in the frequency domain. In Comsol Multiphysics these equations are rephrased and further treated as Helmholtz equations (1)-(2).

$$\nabla^2 \underline{\vec{E}}(\vec{r}) = \omega^2 \mu \varepsilon \cdot \underline{\vec{E}}(\vec{r}) \tag{1}$$

$$\nabla^2 \underline{\vec{H}}(\vec{r}) = \omega^2 \mu \varepsilon \cdot \underline{\vec{H}}(\vec{r}) \tag{2}$$

The complex dielectric permittivity is defined as equation (3). For the permeability equation (4) is valid.

$$\underline{\varepsilon}_{ges} = \varepsilon_0 \cdot \left[\varepsilon_r^{/} - j\,\varepsilon_r^{//}\right] = \varepsilon_0 \cdot \underline{\varepsilon}_r \tag{3}$$

$$\underline{\mu}_{ges} = \mu_0 \cdot \left[\mu_r^{/} - j\mu_r^{//}\right] = \mu_0 \cdot \underline{\mu}_r \tag{4}$$

By the definition of the complex dielectric permittivity and the complex permeability, the treatment of Maxwell's equations in the frequency domain is considerably relieved [Kum 1986, Im 2007].

The energy transmitted from the electromagnetic waves can be derived from Maxwell's equations leading to the well-known Poynting's theorem in the frequency domain:

$$P_{\text{in}} = \frac{1}{2}\int_F \left[\underline{\vec{E}} \times \underline{\vec{H}}^*\right] \cdot \vec{n}^0\, dF = \frac{1}{2}\int_F \underline{\vec{S}} \cdot \vec{n}^0\, dF \tag{5}$$

This theorem says that the mean energy imparted P_{in} is depending in absolute value and phase on the amplitude, the distribution and the particular phase of the electric and magnetic field. Converting the surface integral into a volume integral, see equation (6), by means of the Gauss' theorem, you get the definition of the losses in the dielectric medium [Püsch 1964, Sim 1989].

$$P_{\text{abs}} = \frac{1}{2}\,\omega\,\varepsilon_0\,\varepsilon_r^{//} \cdot \iiint_V \left|\underline{\vec{E}}\right|^2 dV \tag{6}$$

The result is the three-dimensional heat source density distribution in a dielectric.

A heat source density distribution and an electromagnetic field intensity distribution for an axial arrangement are shown in Fig. 5.

Fig. 6 shows the heat source density distribution for a radial arrangement comparing diesel sooty particle filters made of Cordierite and SiC.

For a better comparability all values in Fig. 5-7 are shown as reference values as they are divided by P_{Max} and E_{Max}.

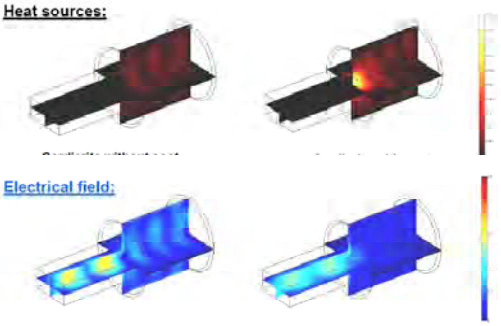

Fig. 5 Distribution of heat sources and electric field intensity (for axial arrangement)

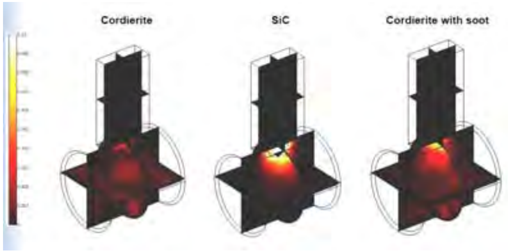

Fig. 6 Comparison of the filter materials: Cordierite and SiC (heat sources, radial arrangement)

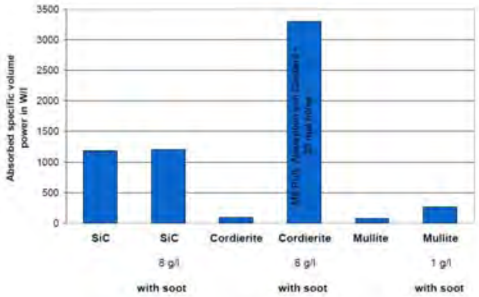

Fig. 7 Microwave absorption of the loaded filter materials at the critical working point [Str 2008]

As can be seen in Fig. 6, SiC carriers produce a very high field inhomogenity independently of the amount of soot. A heating of the complete filter is thus only heavily possible.

For the development of microwave heating plants, the distribution of the electromagnetic field is important. But an electromagnetic analysis alone will not be sufficient for the design of such a microwave heating plant.

There is a number of excellent specialist books on heat transfer discussing the mechanism of heat transfer with the known mathematical methods. Out of this plenty the books of Metaxas [Met 1996] as well as Kramer und Mühlbauer [KM 2002] shall be mentioned representative. Especially for the subject of heat transfer in microwave heating processes, the papers of Metaxas and Meredith [MM 1993], Zhao and Turner [ZT 1996] and Feher [Feh 2009] have to be named.

In microwave heating thermal processes play a major role beside the dissipation of electromagnetic field energy. In order of further examination of the heating process different heat transfer mechanism plus corresponding effects shall be regarded as well [Ha 2000, Wal 2004, Feh 2009].

Both thermal and electromagnetic temperature-dependent properties of the examined materials are available in literature [Dan 2001]. But measurements of temperature-dependent material properties are associated with high efforts and often contradictory [Ni 2001]. This is a major challenge for science and technique, which is only unsatisfactorily solved at the moment [Pohl 1996, W-P 2006].

3. Experimental Results

For the validation of the FEM-simulation by the experiment, a cylindrical multimode applicator with a soot loaded Cordierite diesel sooty particle filter (Cordierite-DPF) is regarded. The transport of the microwave power from the magnetron to the applicator is realized by an open wave guide of type R26. In this kind of line entry, the feeding rectangular wave guide leads tangential into the cylindrical microwave applicator. The applicator itself consists of a cylinder with 155 mm in diameter and a length of 162 mm made of 8 mm thick steel. The metal grid (see Fig. 8) serves as an electromagnetic shielding from undesirable microwave leakage radiation.

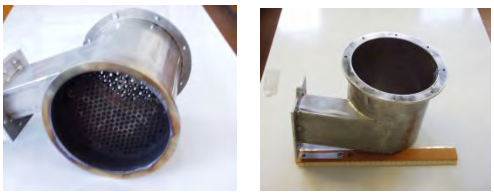

Fig. 8 Cylindrical multimode applicator

The cylindrical filter is 143.76 mm in diameter, has a length of 152.4 mm and a mass of 1255.5 g. The chosen filter medium is Cordierite ($Mg_2Al_4Si_5O_{18}$) (see Fig. 9).

The soot load amounts to 18.4 g, so the soot loaded DPF has a mass of 1273.9 g. The soot is scattered all over the Cordierite-DPF. In macroscopic scale the soot loaded Cordierite-DPF can be regarded as a heterogeneous medium consisting of six identifiable homogenous zones (see Fig. 9)

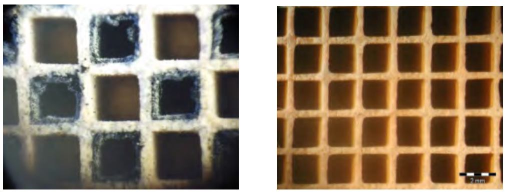

Fig. 9 Structure of the Cordierite-DPF. On the left figure loaded with soot particles, on the right without load.

Section 1 is 13 mm long and the layer thickness of the soot (German: **R**uß**s**chicht**d**icke - RSD) amounts to 250 µm. In the mid-section of the filter, section 2, the RSD is 50 µm and has a length of 30 mm. In the next mid-section, section 3, the RSD is 75 µm and 66.4 mm long. Section 4 is about 30 mm long and the RSD amounts to 125 µm. In the rearward section, section 5, no soot particles are settled. This section has a length of 13 mm and consists only of Cordierite. On the outside margin of the Cordierite filter a cylindrical section, section 6, is found having a thickness of 10 mm and the RSD amounts to 250 µm. These proven facts found in the experiment are incorporated in the 3D-FEM-simulation.

The calculation of the real and imaginary part of the relative dielectric permittivity for the *i*th section of the DPF including the soot load is based on the following equations:

$$\varepsilon'_{r\,Section\,i} = K_{air} \cdot \varepsilon'_{r\,air} + K_C \cdot \varepsilon'_{r\,C} + K_{i\,S\,real} \cdot \varepsilon'_{r\,S} \quad (7)$$

$$\varepsilon''_{r\,Section\,i} = K_{air} \cdot \varepsilon''_{r\,air} + K_C \cdot \varepsilon''_{r\,C} + K_{i\,S\,imag} \cdot \varepsilon''_{r\,S} \quad (8)$$

This includes:

$K_{air} = \frac{V_{air}}{V_{DPF}} = 0.74$ as the volume ratio coefficient of air,

$\varepsilon'_{r\,air} = 1$ as the real part of the dielectric permittivity of air,

$K_C = \frac{V_{Cordierite}}{V_{DPF}} = 0.16$ as the volume ratio coefficient of the Cordierite honeycomb structure,

$\varepsilon'_{r\,C} = 2.873$ as the real part of the dielectric permittivity of Cordierite,

$$K_{i\,S\,real} = \frac{V_{Soot}}{V_{DPF}} = -5 \cdot RSD^2 + 5 \cdot RSD + 1{,}2 \quad (9)$$

the volume ratio coefficient of the soot for the real part of the dielectric permittivity in the *i*th section of the DPF (Section 2, 3 and 4),

$$K_{iS\,real} = -0.5\cdot RSD^2 + 0.5\cdot RSD + 1.0 \qquad (10)$$

the volume ratio coefficient of the soot for the real part of the dielectric permittivity in the *i*th section of the DPF (Section 1, 5 and 6),

$\varepsilon^{/}_{rS} = 10.695$ is the real part of the dielectric permittivity of soot,

$\varepsilon^{//}_{r\,air} = 0$ is the imaginary part of the dielectric permittivity of air,

$\varepsilon^{//}_{rC} = 0.138$ is the imaginary part of the dielectric permittivity of Cordierite,

$$K_{iS\,imag} = -1.8\cdot RSD^2 + 1.8\cdot RSD + 0.016 \qquad (11)$$

the volume ratio coefficient of the soot for the imaginary part of the dielectric permittivity in the *i*th section of the DPF (Section 2, 3 and 4),

$$K_{iS\,imag} = -1.9\cdot RSD^2 + 1.9\cdot RSD + 0.003 \qquad (12)$$

the volume ratio coefficient of the soot for the imaginary part of the dielectric permittivity in the *i*th section of the DPF (Section 1, 5 and 6),

$\varepsilon^{//}_{rS} = 3.561$ imaginary part of the dielectric permittivity for soot and

$V_{DPF} \approx 2.5\ l = 2.5\cdot 10^{-3}\ m^3$ the volume of the Cordierite filter.

As can be seen the volume ratio coefficient of the soot depends on the layer thickness of the soot (RSD) and can be expressed in a second-degree polynomial. The polynomial coefficients in equation (9)-(12) are indentified empirical from experimental data for a determination of actual soot distribution within the Cordierite DPF.

Further details and physical parameters necessary for a modeling are described elaborately in the paper [Im 2007].

Fig. 10 and 11 show the experimental equipment and the results of the experimental verification of the cylindrical multimode applicator.

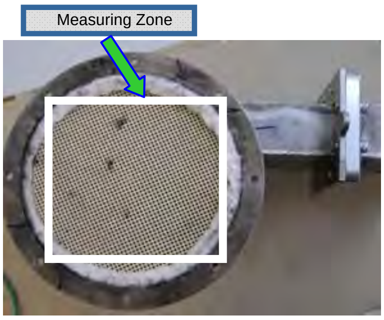

Fig. 10 Cylindrical multimode applicator with a Cordierite-DPF and soot load

As can be seen in Fig. 11, the numerically computed and experimentally measured temperature field distributions show an excellent consistency in quality and quantity.

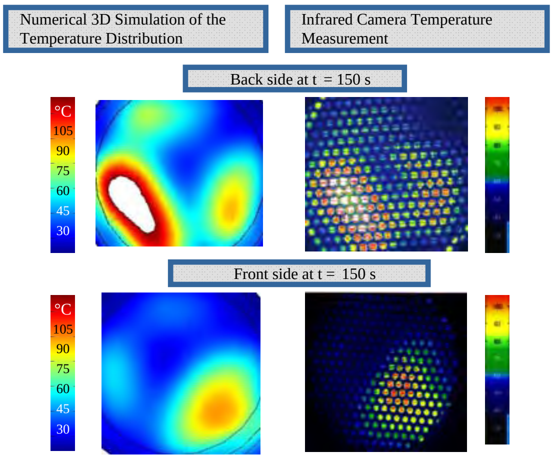

Fig. 11 Results of the experimental validation [Im 2007]

The reflected power P_{ref} is in accordance to

$$P_{ref} = P_{in} - P_{abs} \qquad (13)$$

defined as the difference of the incoming power P_{in} and the absorbed power P_{abs}. The efficiency factor is defined in the common ratio according to equation (14).

$$\eta = \frac{P_{abs}}{P_{in}} = \frac{P_{in} - P_{ref}}{P_{in}} = 1 - \frac{P_{ref}}{P_{in}} \qquad (14)$$

According to equation (15) also the value of the factor of reflection is determined [Kum89].

$$R_0 = \sqrt{\frac{P_{ref}}{P_{in}}} = \sqrt{1 - \frac{P_{abs}}{P_{in}}} = \sqrt{1-\eta} \qquad (15)$$

Afterwards the *Voltage Standing Wave Ratio* VSWR is calculated by means of equation (16).

$$VSWR = \frac{1+R_0}{1-R_0} \qquad (16)$$

Further results of the FEM-simulation and the experimental measurements are summarized in Table 1.

As in the data presented in Fig. 11 and Table 1 is obvious, the results of the 3D-FEM-simulation is in excellent agreement with the reality [Im 2007]

Table 1 Results of the experimental Validation of the 3D-FEM-simulation

Physical Values	COMSOL®-Simulation	Experiment
	Electromagnetic Parameter	
E_0 , V/m	18 097	-
E_{max} , V/m	29 845.8	-
P_{max} , W/m^3	1.3×10^6	-
P_{in} , W	572	572
$P_{abs\ total}$, W	532	545
$P_{abs\ housing}$, W	0.02	-
$P_{abs\ DPF}$, W	531.98	-
$P_{ref\ total}$, W	40	27
R_0	0.2644	0.2173
η	0.9301	0.9528
VSWR	1.719	1.5551
	Thermal Parameter	
T_0 , °C	20	20
$T_{max\ (t=150\ s)}$, °C	165.6	≈170

4. Discussion

In the course of the validation done for the FVV-project No. 832; AiF 139 ZBR „Verwendung von Mikrowellen zur Regeneration von Dieselpartikelfiltern“ (Utlization of Microwave Radiation for the Regeneration of Diesel Soot Particle Filters) in the Department of Thermal Engineering, the correct functioning of the numerical simulation done with COMSOL Multiphysics is experimentally verified.

In the process the high efficiency of the microwave heating plant was proven (measured $\eta = 0.9528$, computed $\eta = 0.9301$).

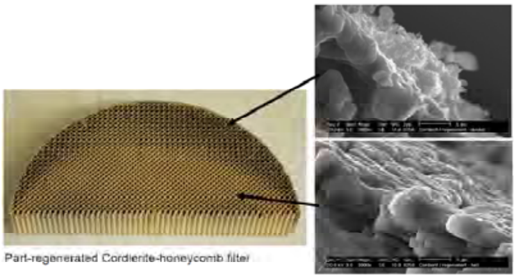

Fig. 12 By microwave radiation regenerated loaded filter [Str 2008]

However the heating of the soot loaded DPF and the temperature field distribution in this arrangement are very inhomogeneous making a further optimization of the microwave field necessary including field and heat source distribution.

5. Conclusions

The results of the validation lead to the following conclusions:

- The numerically and experimentally determined temperature field distributions match excellent in quality and quantity.
- The 3D-FEM-models created with COMSOL Multiphysics provide practice-orientated results.
- They can be used for a computer-assisted modeling and optimization of microwave heating plants and even for coal processing purposes like preheating of coal, pyrolysis and gasification.

6. Acknowledgements

The authors acknowledge the financial support of the BMBF (Federal Ministry of Education and Research) Germany, in this research.

7. References

[Dan 2001] Daneke, N. Zur Anlagentechnik von multimoden Mikrowellen Sinteranlagen – von der Wellenausbreitung in Hohlleiter bis zum erwärmten Gut. Freiberg, TU Bergakademie Freiberg, Dissertation, 2001

[Ha 2000] Haala, J. Analyse von Mikrowellenheizprozessen mittels selbstkonsistenter finiter Integrationsverfahren. Karlsruhe, Universität Karlsruhe (TH), Dissertation, 2000

[Feh 2009] Feher, L. Energy Efficient Microwave Systems, Springer Verlag, 2009

[Im 2007] Imenokhoyev, I. Computergestützte 3D-Modellierung von Mikrowellen-Erwärmungsanlagen. Berichte aus der Verfahrenstechnik. Aachen: Shaker Verlag, zugl. Freiberg, TU Bergakademie Freiberg, Dissertation, 2007 – ISBN 978-3-8322-6604-2

[KM 2002] *Praxishandbuch Thermoprozess-Technik* / Carl Kramer/Alfred Mühlbauer (Hrsg.) *1. Grundlagen und Verfahren*. Essen: Vulkan-Verl., 2002 – ISBN 3-8027-2922-6

[Kum 1986] Kummer, M. Grundlagen der Mikrowellentechnik. 1. Auflage, Berlin: Technik, 1986 – ISBN 3-341-00088-7

[LBM 2003] Leuca, T.; Bansici, L. ; Molnar, K. „The Numerical Modeling of the Electromagnetic Field with the Finite Element Method in a Parallelipipedical Cavity“. In: *48. Internationales Wissenschaftliches Kolloquium*, TU Illmenau, September 2003

[Ma 1997] Ma, J., Fang, M., Li, P., Zhu, B., Lu, X., Lau, N. T. Microwave-assisted catalytic combustion of diesel soot. In Applied Catalysis A: General 159, 1997, S. 211 - 228

[Mer 98] Meredith, R. Engineers Handbook of Industrial Microwave Heating. London: The Institution of Electrical Engineers, 1998 – ISBN 0852969163

[Met 1996] Metaxas, A.C. Foundations of electroheat. Chichester (u.a.): Wiley, 1996 – ISBN 0-471-95644-9

[MM 1983] Metaxas, A.C.; Meredith, R.J.: Industrial Microwave Heating. Power Engineering Series. London: Peter Peregrinus Ltd. on behalf of the JEE, London, 1983, reprinted 1993

[Ni 2001] Nimtz, G. *Mikrowellen: Einführung in Theorie und Anwendungen*. München; Bad Kissingen (u.a.): Richard Pflaum Verlag GmbH & Co KG, 2001 – ISBN 3-7905-0849-7

[Pohl 1996] Pohl, V. Messung von temperaturabhängigen Permittivitäten im Mikrowellenbereich. Fortschr.-Ber. VDI Reihe 8 Nr. 585. Düsseldorf: VDI Verlag, 1996 – ISBN 3-18-358508-1

[Püsch 1964] Püschner, H. *Wärme durch Mikrowellen: Grundlagen, Bauelemente, Schaltungstechnik*. Eindhoven: Philips, 1964 http://www.pueschner.com/

[Sim 1989] Simonyi, K. *Theoretische Elektrotechnik*. 9., durchges. Aufl., Berlin: Dt. Verl. d. Wiss., 1989 – ISBN 3-326-00045-6

[Str 2008] Strack, J. Regeneration von Dieselpartikelfiltern durch Mikrowellen. Freiberg, TU Bergakademie Freiberg, Dissertation, 2008

[Vötsch 2011] Vötsch Industrietechnik GmbH, Mikrowellensymposium in Reiskirchen am 04.05.2011

[Wal 2004] Walter, G. „Industrielle Anwendungen im Überblick“. In: *OTTI-Profiforum Mikrowellen-Thermoprozesstechnik*, Würzburg, November 2004, S. 89-108

[W-P 2006] Willert-Porada, M. Advances in Microwave and Radio Frequency Processing / Monika Willert-Porada (Ed.) Berlin (etc.): Springer, 2006 – ISBN-10 3-540-43252-3

[ZT 1996] Zhao, H.; Turner I. W. „An Analysis of the Finite-Difference Time-Domain Method for Modelling the Microwave Heating of Dielectric Materials within a Three-Dimensional Cavity System“. In: *Journal Microwave Power and Electromagn. Energy*, Vol. 31, Nr. 4 (1996) , S. 199-214