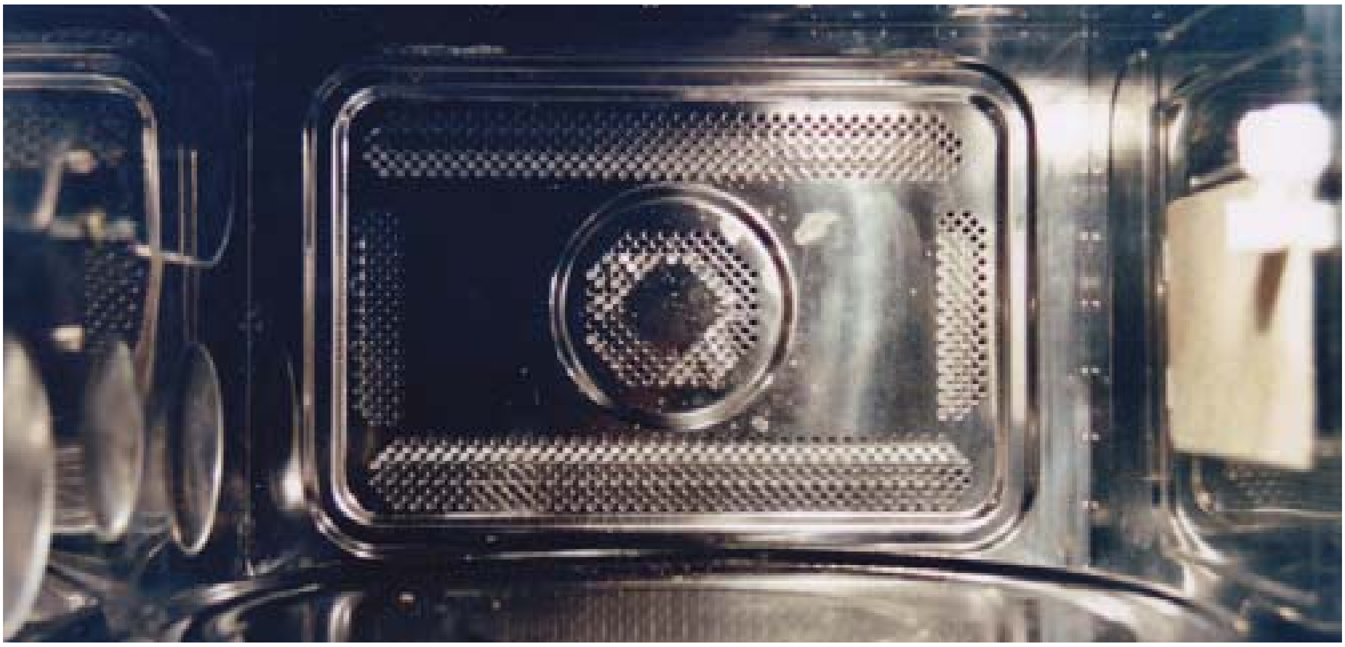
Use of microwaves and MRI

MANY HOUSEHOLDS ALL OVER THE WORLD USE MICROWAVE OVENS WHILE INDUSTRIAL MICROWAVE APPLICATIONS, IN PARTICULAR FOR BAKED GOODS, ARE SPARSELY SPREAD



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The reasons for this discrepancy between potential application and actual industrial utilization in the food industry are a number of drawbacks: These include high investment and operating costs, low willingness of the industry to take a risk, and last but not least problems with the process which are often due to lack of understanding the process. One main reason is the complex interaction between electromagnetism, heat and mass transfer. Up to now these interactions could only be simulated insufficiently. Design and optimization of microwave processes currently are still based on trial and error. The fact that measuring temperature distributions in the sample during microwave treatment was so far only possible invasively with insufficient resolution is a further reason.
However, there is a new approach for the simulation of microwave processes in the food area as well as an MRI-based method for non-invasive determination of three-dimensional temperature distributions.

Simulation of microwave heating

The new approach is based on the coupling of two commercial software programs to yield a custom-made own program. One software package (QuickWave-3DTM) calculates

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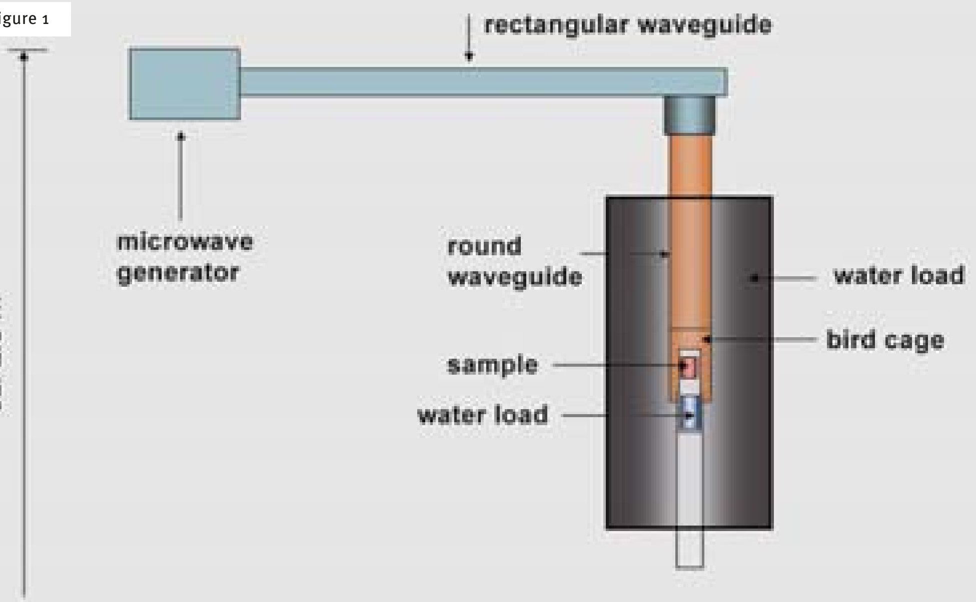
++ figure 1
Schematic depiction of the microwave equipment for integration of microwaves in the MRI tomograph and in-line observation of microwave processes

++ figure 1



the distribution of the power density pv dissipated within the product by solving Maxwell's equations in combination with material (constitutive) equations. The other software package (COMSOLTM) uses the result from QuickWave-3DTM, the calculated pv-distribution, as source term to determine the temperature distribution in terms of time and location, solving the energy balance with included Fourier term. Based on different data (e.g. processing time, material parameters, iteration steps), the new developed program controls both software packages via a graphical user interface. Supported by a further new developed program it is then possible to download the simulation results and to analyze the (time-varying) three-dimensional temperature distributions, temperature curve in discrete points as well as the homogeneity of the heating.

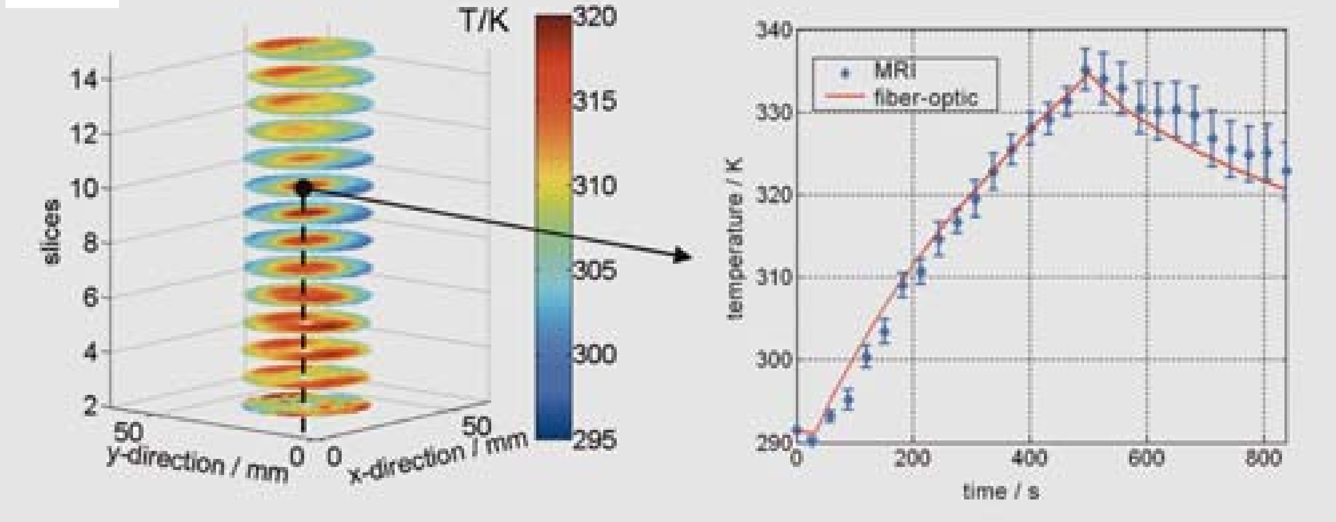
In-line observation of the microwave heating

Different factors can lead to inhomogeneous heating patterns in microwave applications. This results in significant variations of the temperature distributions in different products. For industrial microwave applications it could be that quality and safety (e.g. in pasteurization processes) of the products might be affected. For optimization of microwave processes or for monitoring already used processes, it is very important to know the three-dimensional temperature distribution of the heated products.
The construction of a microwave device for integration of microwaves in the MRI tomograph (see fig. 1) allows for the observation of microwave processes in-line regarding the time-varying inhomogeneous temperature distribution for the first time. The simultaneous temperature measurement by means of a fiber-optic sensor allowed for the validation of the temporal resolution of the MRI temperature measurement method. The correlation of the temperature curves in discrete points, determined by two independent measurement methods, was good (see fig. 2). Here again, a software has been developed, which allows for an evaluation of the MRI data in terms of temperature distributions, curves, and inhomogeneities via a graphical user interface. This measurement method in combination with the newly designed equipment allows for monitoring the course of the microwave treatments for the parameters temperature, water content, and structural changes (for example during a baking process) inside the sample.

Validation of simulation

The validation of the simulated data became possible by combining the evaluations programs from simulation and measurement. This validation was done qualitatively visually using false-color coded three-dimensional temperature distributions (see fig. 3) as well as quantitatively using discrete temperature curves and comparison of entire layers (see fig. 4). The results reveal a good quantitative correlation of simulation and measurement.

++ figure 2



++ figure 2
left: 3D temperature distribution of a cylindrical food sample heated by microwaves (d = 31 mm, h = 30 mm) including depiction of the fiber-optic sensor
right: Temperature curve of the spot where the fiber-optic sensor is located, measured by MRI and fiber-optic sensor

Control of the microwave heating

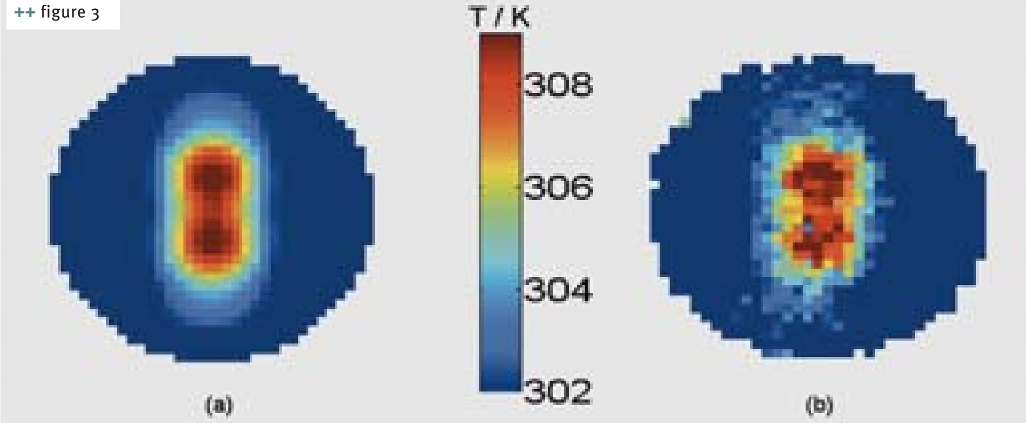
In order to optimize a pasteurization process in terms of treatment time (minimal time temperature treatment) and to guarantee the safety of the treated product, the treatment must be controlled. For microwave pasteurization, the parameter to be controlled is the microwave power. It is controlled based on the time varying minimum and maximum temperature in the product.
Here an ON/OFF control has been implemented into the new developed code controlling the simulation software packages which determines the minimum and maximum temperature inside the product at any time interval. The pre-set microwave power is delivered until the temperature in the hot spot has reached a pre-defined maximum temperature. When this value is exceeded, the power is turned off. As soon as the maximum temperature then falls below this value, the power is turned on again. This process is repeated in a loop until the temperature in the cold spot has reached the previously defined minimum temperature. After the temperature has been kept for a defined time, the simulation is stopped. The simulations (see fig. 5) showed that just a microwave heating alone without additional heating of the resonance chamber is not sufficient to achieve the required pasteurization temperature. Combining both technologies, microwave heating and conventional heating, in one unit will allow reaching the minimum temperature in the critical spot. The time required to achieve this temperature is clearly below the time needed for a pure conventional heating without microwave at higher ambient temperature.

Future applications in (industrial) bakeries

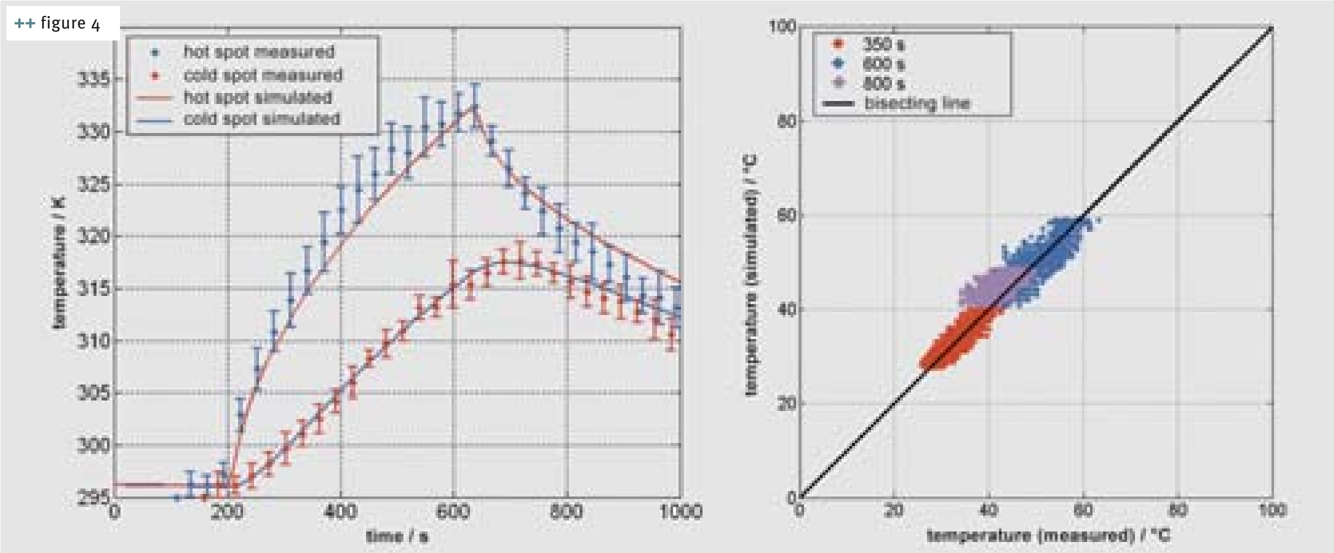
Simulation of microwave processes
Up to now microwaves are hardly used in industrial bakeries. Some few exceptions are thawing processes for frozen, par-baked goods in mobile bakeries. This application is the first step into the right direction but the application potential of microwave processes is utilized to a very limited extent only. Nevertheless, even this fairly simple application also raises problems due to the inhomogeneous

++ figure 3
Depiction of the simulated (a) and measured (b) temperature distribution in the medium layer of a cylindrical food sample heated by microwaves (h = 32 mm, d = 34 mm) at a discrete time (t = 250 s) and a microwave power of 19 W

++ figure 3



++ figure 4



field distribution inside the ovens with the result that the rolls have already been thawed at some spots (inside) while other parts are still frozen. Based on the new developed approach for the simulation of microwave processes it is now possible to optimize the oven geometry and the product arrangement "manually" in order to minimize the formation of hot spots. Furthermore, a treatment program can be developed by the previously described feed-back simulation, which can be implemented in the oven's control allowing an almost uniform heating during the thawing process. The homogeneity of the heating could be further improved by combining microwave, hot air and radiation (IR) heating which could be simply implemented in the developed interface and calculated simultaneously. It can also be imagined to develop this approach further or to expand it by neural networks (ANN) which would be able to vary the oven's geometry independently for optimum field distribution.

Magnetic resonance imaging for process control

For a number of process engineering problems, the magnetic resonance imaging has the potential to offer insights in the details of the processes, to increase the knowledge about the processes and thus promote their advances.

Even the measurement of the three-dimensional spin density distribution alone is able to provide a number of information. It is possible to determine water distributions; but even more important is the determination of three-dimensional structures. In a subsequent analysis, the pore size distribution can be determined and the pore growth can be monitored in processes in-line. The new developed method for in-line determination of three-dimensional temperature distributions allows for controlling the process in terms of maximum and minimum temperatures to be achieved. When using such process control feature, overheated and thus carbonized spots in baked goods would no longer occur. Currently, the use of this technology on industrial level is still too expensive. But the use of simplified MRI measuring systems (NMR mouse) can be imagined for the near future. +++

++ figure 4
left: Comparison of the simulated and measured temperature curves at a microwave power of 19 W in a hot spot and a cold spot in the same layer. The error bars state the standard deviation referred to the mean value from three identical experiments
right: Comparison of simulated microwave heating and measured microwave heating (P_{MW} = 19 W) of the layer of the cylindrical samples which contains the hot spot

++ figure 5
Example of a simulated heating of a cylindrical food sample
(a) Microwave heating
(P = 38 W, $T_{environment}$ = 296 K)
(b) Hot air heating
($T_{environment}$ = 333 K)
(c) Combination of microwave and hot air heating
(P = 38 W, $T_{environment}$ = 296 K)

++ figure 5