Engineering Aspects of Radio-Wave Heating for Soil Remediation and Compatibility with Biodegradation

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Dielectric heating of soil using radio waves (RW) can be applied to support various remediation techniques, namely biodegradation and soil vapor extraction, under in situ, on site or ex situ conditions. To improve the spatial resolution of energy dissipation, the design of rod electrodes was modified with an air gap around the electrode allowing thermal treatment focused to the desired soil volume. A combination of low- and high-frequency electrical energy was successfully applied to homogeneously heat the capillary fringe, the boundary region of saturated and unsaturated zones. The energetic efficiency of the method was evaluated showing that an efficient transformation of RW energy to heat in the target volume can be achieved. By comparing biodegradation and soil respiration under conventional and electric (low-frequency resistive and dielectric RW) heating, the compatibility of the electric heating methods with bioremediation processes could be proven. Therefore, RW-supported microbial degradation of pollutants is a real option for accelerated soil remediation.

Introduction

The remediation of contaminated soil can be significantly enhanced by increasing the temperature to desorb, mobilize, and evaporate pollutants, to initiate chemical reactions forming nonhazardous products or to support biodegradation. Some obvious effects are related to the state of water in the soil: at low temperature (e.g., under cold-climate or even permafrost conditions) melting of ice leads to an increase in mobility of both water and pollutants, which is a prerequisite of their destruction or removal. The phase transition from liquid water to steam can be utilized for stripping effects due to internal steam production in the temperature range around 100 °C. An enhanced mobility of pollutants might possibly result from a phase transition ("glass transition") in the soil organic matter (SOM) at elevated temperature (*1–3*). Another thermal option is the utilization of thermophilic instead of mesophilic microorganisms for the biodegradation of contaminants. Advantageous physical effects such as increase of vapor pressure, water solubility, and mobility or decrease of the surface tension can again positively influence the bioavailability of pollutants.

While the influence of temperature on physical and chemical properties and processes is well-known and mainly independent of the type of warming, the impact of electromagnetic heating on biological phenomena is not a priori clear. Due to the fact that the number of studies on this topic in the remediation context is very limited, in this study a number of experiments have been applied to reveal possible effects of electromagnetic heating on biological processes.

The spectrum of available methods for in situ soil heating is limited (*4–8*). By introducing heating lances into the soil, very high temperatures can be achieved locally (*9*). This method is comparably simple to realize and robust in use (*6–8*). However, especially in poorly heat-conducting materials such as dry and coarse soils, narrow high temperature zones, and large temperature gradients are unavoidable. Therefore, an enhancement of microbial degradation processes is impossible using this method. Heating by injection of hot air or steam (*10, 11*) requires a sufficiently permeable soil. Furthermore, the heat carrier flow is contaminated and has to be additionally cleaned. Electrical resistive heating (ERH), often technically realized as six-phase heating (*10, 12*), is based on the ohmic losses of the medium. In most cases, power-line frequencies (PLF) of 50 or 60 Hz are used without transformation. It can only be applied in humid soils, i.e. in the temperature range up to 100 °C.

In contrast, dielectric heating using radio waves (RW, frequencies between 1 and 100 MHz) is suitable for heating practically all contaminated media including dry and humid, sandy or tenacious soils with a wide accessible temperature range from below 0 °C up to more than 400 °C. The working principle of RW heating is similar to that of a microwave oven. The temperature increase is due to a fast reorientation of molecular dipoles in the rapidly changing external electromagnetic field. However, much larger penetration depths in the meter-range can be realized with RW heating, which is essential for in situ remediation procedures. With dielectric heating, heat is produced within the soil volume. The attainable heating rates depend on the installed power. Typically some K/h can be achieved.

RW heating (typically in the frequency range between 1 and 27 MHz (*13*)) was initially applied to exploit residual hydrocarbons from oil shale or other rock formations more efficiently (*14*). In the 1980s, the technology was increasingly introduced into remediation to eliminate hazardous hydrocarbons preferentially by soil vapor extraction (*15, 16*). Basically, two electrode designs have been applied: coaxial antennae (*17, 18*) and rod electrodes, often arranged in three parallel sets thus representing a capacitor-like geometry with so-called "hot" and "cold" grounded electrodes (*16, 19*). In the first case, heating is concentrated around the coaxial dipoles and special combinations of antennae are used to obtain more homogeneous temperature profiles (*20*). Rod electrodes suffer from attenuation of the electric field strength along the rods. This limits the accessible depths of treatment. For thermally enhanced soil vapor extraction, a combined function of the introduced rods as both electrodes and extraction wells has been described (*13, 16, 19*). Alternatively, the extraction via the surface of the ground can be realized (*21*). Volatile and semivolatile organic compounds are the main target compound classes to be eliminated using the RW technology. An overview of projects using RW heating techniques is given in several EPA papers and books (*4, 22, 23*).

The flexibility of the RW method provides a number of options for soil remediation: thawing of frozen soil, thermally enhanced microbial remediation, thermally enhanced soil vapor extraction (T typically $\leq$200 °C), cleanup procedures on the basis of steam-distillation ($T \approx 100$ °C, internal stripping), disinfection of soil and waste materials, thermally

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supported chemical reactions of the pollutants (e.g., hydrolysis and oxidation), conversion of contaminants adsorbed on pyrogenic carbon (*24*) up to high temperature vitrification (e.g., for radio nuclides).

However, there are also significant disadvantages of the method which caused its limited utilization in remediation practice (*6–8*). The necessity of transformation of PLF into RW energy leads to an energy loss of 40−50% when compared with ERH. Additionally, RW heating is a comparably sophisticated method requiring experience and time for establishment. The investment costs are relatively high.

In the present paper, some basic engineering aspects of RW heating such as the optimization of the electrode design, the combination with resistive heating and the energy efficiency are addressed. Special attention is also paid to the compatibility of RW heating and thermally supported bioremediation of contaminated soils.

Experimental Section

Electrical Power Sources and Radio-Wave Heating Module. At the laboratory and the pilot-plant scales as well as in some preliminary field tests, commercial RW generators PFG 1000 RF and PFG 5000 RF (both from Hüttinger, Freiburg, Germany) having a maximum RW power of 1 and 5 kW, respectively, have been applied. They operate at a fixed RW frequency of 13.56 MHz.

The high-frequency energy was transferred by coaxial cables from the generator to an electronic network (so-called matchbox) consisting of coils and capacitors. From the matchbox the energy was transmitted by means of thin copper bands (thickness approximately 1 mm) to the electrode system. The matchbox allowed the total impedance of the tuned circuit, including the soil, to be fitted optimally to the RW generator. Therefore, in contrast to microwave application, electromagnetic energy can be guided into the soil efficiently, without significant reflection. PFM 3000A and PFM 6000A matchboxes (also from Hüttinger) were used in combination with the 1 and 5 kW generators, respectively.

Temperature Measurement. To continuously measure the temperature within the heated soil volume, nonmetallic sensors have to be applied. It is well-known that in strong electromagnetic fields conventional sensors (thermocouples or resistance thermometers) cannot be used reliably, safely, and without disturbance of the process to be monitored (*25*). Therefore, fiber optical sensors from Nortech Fibronic (Quebec, Canada) and OPTOcon (Dresden, Germany) exhibiting an accuracy of about ±0.3 K were used (*26*).

Experimental Setup in the Laboratory and at the Pilot-Plant Scale. Reactors with volumes between 0.3 L and 2 m^3 having plane or coaxial electrodes were used. An experimental setup for microbiological studies under low- and high-frequency electrical heating consisted of the RW equipment with the soil reactor (parallel plate electrodes), flow controllers for the purge gas, absorbents for the removal of CO_2 prior to the soil reactors, an installation for establishing a defined humidity of the gas flow and measuring devices for multi-channel gas analysis.

Microbial respiration was quantified by purging the soil samples and analyzing the composition of the effluent gas with respect to oxygen and carbon dioxide contents. For this purpose, Multor 610 and V130 gas analyzers from Maihak (Hamburg, Germany) and Saxon Junkalor (Dessau, Germany), respectively, were applied. The gas flow (air with defined humidity) was established by digital gas flow controllers. The water content was measured using humidity sensors (Rotronic, Ettlingen, Germany).

Characterization of Soil Samples. Soil samples (clean and contaminated) from various origins were used in the framework of this study. Since the work was focused on the practicability, the effects and the potential of dielectric soil heating, the description of soil properties and constituents is restricted to the relevant information here. The corresponding data are given in the descriptions of the experiments.

The carbon content of the various soils was determined by heating to 900 °C in air with IR detection of the CO_2 formation (after total oxidation over CuO at 750 °C), using a commercial carbon analyzer C-MAT 5500 from Stroehlein (Karst, Germany). Soil humidity was determined gravimetrically by quantifying the weight loss after heating to 105 °C for 4 h.

Results and Discussion

Basic Engineering Aspects of Radio-Wave Heating. *Energy Efficiency of the Process.* Since dielectric heating is based on the application of high-grade electrical energy, the efficiency of heat formation in the soil is an essential parameter for evaluating the economic aspect of this technology. The transformation from PLF energy (50 or 60 Hz) to RW energy is realized with an efficiency of only 50−60% by commercially available RW generators which is obviously a disadvantage in comparison to ERH. Taking into account the additional energy consumption of peripheral devices (cooler, pumps etc.), the total energetic effectiveness starting from PLF electric energy is in the range between 35 and 50%. These conditions (which are comparable with microwave applications) represent the present state of the art for dielectric heating technologies.

The transformation of RW energy into heat in the desired soil volume is a key step of the process, which has to be optimized. To determine this efficiency value, the obtained energy input for heating is calculated according to eq. 1.

$$\Delta Q = m_{soil} \times c_{soil} \times \Delta T \text{ or } \dot{Q} = m_{soil} \times c_{soil} \times \dot{T} \quad (1)$$

The required amount of energy (ΔQ [J]) is determined by simple physics and is related to the desired temperature increase (ΔT [K]) as well as to the mass and specific heat capacity of the material (weighted mean values m_{soil} [g] and c_{soil} [J g^{-1} K^{-1}], respectively) to be heated. $\dot{Q}$ [W] and $\dot{T}$ [K s^{-1}] are the corresponding heat flux and heating rate, respectively.

When an initially frozen material is continuously heated until a temperature of more than 100 °C is reached, two temperature plateaus are usually observed. They are due to the required heat for melting and vaporization of water (ΔH_M = 334 J g^{-1} and ΔH_V = 2257 J g^{-1}), only the latter being relevant, of course, when starting above 0 °C. The latter value clearly shows the large energetic effect of this phase transition which is used in particular for stripping of contaminants from soils. On the basis of the theoretical energy demand as described above, the efficiency of RW heating was estimated by measuring the heating rate and the amount of melted ice or evaporated water under various experimental conditions (*27*). To quantify this secondary effectiveness, the measured heating rates at the beginning of the heating process when heat losses to the environment are still relatively small, were extrapolated. In a variety of experiments in the laboratory as well as at the pilot-plant scale the secondary effectiveness was found to be ≥90%. Considering the estimated values for both primary and secondary effectiveness, a total efficiency of energy transformation in the range between 30 and 50% was usually achieved (*27*).

On this basis, the order of magnitude for the necessary energy input can be demonstrated with two typical examples. A first case, where a soil with 15 wt-% humidity shall be heated from 10 to 35 °C, is related to thermally enhanced biological remediation. Under these conditions, a theoretical specific energy input of 10 kWh t^{-1} is required. Assuming a total efficiency of only 20% (which is very pessimistic), the specific energy consumption is 50 kWh t^{-1} (corresponding to only 6 Euro/t with 0.12 Euro/kWh). Additionally, further

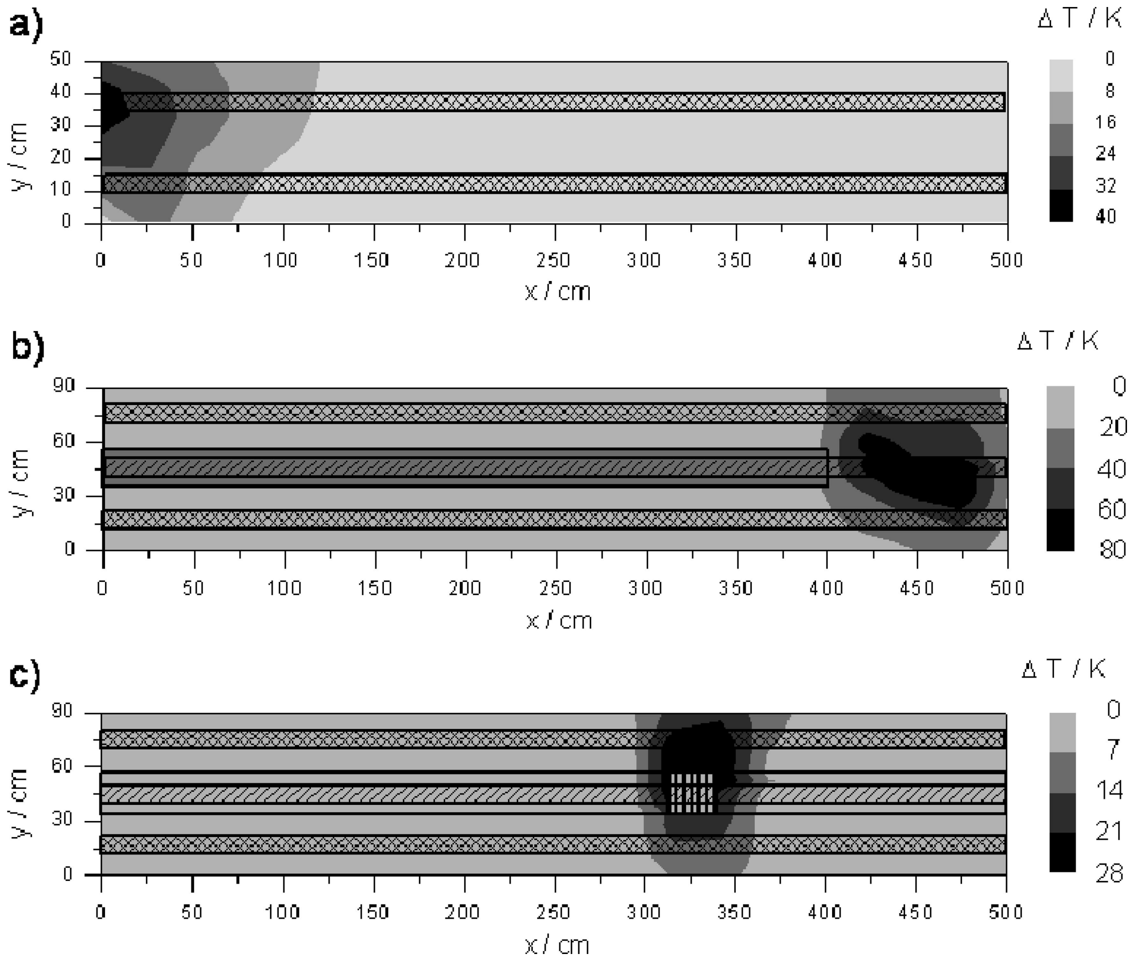

FIGURE 1. Temperature profiles along parallel rod-shaped electrodes in soil (horizontal arrangement at a depth of 0.5 m, electrical connection to matching network and RW generator at $x = 0$, RW frequency 13.56 MHz, initial soil temperature between 15 and 17 °C, sandy soil with a humidity of about 8 wt-%): (a) after 4 h heating with an RW power of 1.65 kW using electrodes in direct contact with the soil, (b) after 90 min heating (RW power 1.7 kW) with a modified hot electrode with a 5 cm air gap in the range from 0 to 4 m, and (c) after 75 min heating (RW power 0.8 kW) using air-gap-modified hot electrode with a water reservoir at $x = 3.25$ m to realize coupling of RW into the soil.

energy is necessary to stabilize the desired temperature and to compensate for the heat flow to the environment. Operating costs are mainly determined by the quality of thermal insulation. In a second case, a soil with 10 wt-% initial humidity shall be heated to a final temperature of 150 °C to thermally enhance soil vapor extraction. During this process, the water is assumed to be completely evaporated. In this case, the energy input would be 105 kWh t^{-1} under ideal conditions and 525 kWh t^{-1} with a conservative secondary energetic efficiency of only 20% (approximately 60 Euro/t). Due to the fact that most of the energy consumption (60%) is due to the evaporation of water, the application of final temperatures above 100 °C should be carefully evaluated.

Influence of the Electrode Geometry on the Temperature Profiles. It is obvious that the type and arrangement of the electrodes have a crucial importance for the homogeneity and the characteristics of the temperature profile. From the theoretical point of view and also according to our experimental experience, parallel plate electrodes are most suitable for homogeneous heating. Homogeneous temperature profiles with minimal overheating around the heating tools are especially necessary for biological applications because the optimum of microbial activity is within a relatively narrow temperature range. For example, a variance of temperatures as low as ±5 K throughout a soil reactor of 20 m^3 size at a mean temperature of 35 °C could be achieved in a field application using parallel plates as electrodes (*28*).

However, under the practical conditions occurring for in situ remediation tasks, the installation of parallel plates (e.g., as sheet piles) is difficult, costly, and in some cases, totally infeasible. In the field, the introduction of rod-shaped electrodes (often with diameters between 5 and 10 cm) into boreholes is usually the most appropriate method. The length of the vertical rod electrodes depends on the depth of the contaminated soil layer to be treated, leading to values of more than 10 m in some cases. When rod-shaped electrodes are used, two factors restrict the evenness of heating: first, the electric field strength radially decreases with increasing distance from the electrode axis. This strongly affects the radial temperature profile since the heating rate is proportional to the square of the electric field strength. Second, the voltage decreases along the rod electrode due to energy coupling into the soil. This behavior is significantly different from that of metal electrodes in the low-frequency range. It usually leads to a decrease of the local heating rate along the electrode length. The magnitude of this phenomenon depends on the properties of the soil and is most pronounced for humid materials with large dielectric losses. An example for these effects originating from own field experiments is shown in Figure 1a. where two parallel rod electrodes have been installed horizontally in a sandy soil at a depth of 0.5 m.

To reduce the decay of the field strength along the electrode, an air gap of approximately 5 cm width was subsequently established between the electrode and the soil. For this purpose, a plastic tube was coaxially introduced around the central rod electrode. This gap significantly reduced the undesired energy transfer into the upper soil layers for a vertical arrangement. Consequently, the electromagnetic field could be focused on the desired segment of the electrode where it was in direct contact with the soil. The effect of the air gap can be clearly demonstrated with data presented in Figure 1b. The attenuation of the field along the electrode could be largely avoided by this simple variation of the design. The "isolating effect" of the air gap was completely lost when the gap was filled with a medium having a high relative dielectric constant (ϵ_r) such as water. In this case, water realized coupling of the electromagnetic waves into the soil leading to heating in the respective zone. An example for the effect is shown in Figure 1c. The water was filled in a polyethylene bag placed around the inner rod electrode. Interestingly, the water phase itself was not directly heated to a significant extent. The soil temperature was higher than the water temperature, proving that the soil heating was not due to simple heat transfer through the water phase. This can be explained by the fact that the electric field strength is reduced in the water phase ($\epsilon_r \approx 80$) in series to the soil (ϵ_r much lower) (*29*). For the air gap, the conditions are vice versa: the field strength in air ($\epsilon_r \approx 1$) is larger than in the soil. However, the dielectric loss factor of air is negligible. To maintain utmost flexibility in the field application, a modified rod electrode with separate chambers forming the gap along the electrode can be applied. These chambers can be filled with either air or water to select the soil segments along the electrode which are to be heated.

The homogeneity of the temperature distribution can be enhanced by arranging the electrodes in parallel lines simulating the parallel plates of a capacitor. A preferential option is a three-row arrangement with the so-called "hot" electrodes in the middle and two sets of "cold", i.e. grounded, electrodes on the two opposite sides (*16, 19*).

In contrast to systems with two types of separated electrodes, the electromagnetic field can also be established using RW antennae. In our tests, a relatively simple design which is appropriate for rapidly heating up "hot spots" having a small spatial extension (≤ 1 m^3) was used (Supporting Information (SI) Figure S1a). In this case, the RW energy is transferred from the matchbox to the heated zone via a coaxial cable. The radiation is then focused to the antenna part without significant heating along the transfer line. However, the temperature profile is inhomogeneous and the heated volume is comparably small (penetration depth typically <0.5 m) as also can be seen from an experiment carried out at a field site as presented in SI Figure S1b. The application of a single antenna (coaxial dipole) or several antennae in an array has been described in the literature and applied in field experiments (*18, 23*).

Combination of Low- and High-Frequency Heating. The subsequent application of low-frequency (PLF) and high-frequency dielectric (RW) heating has already been described in the literature (*19*). The usual procedure includes PLF heating up to about 100 °C and switching to RW heating when the soil has been desiccated.

In the present study, a combined application has been found to be very suitable for heating the capillary fringe at the boundary between saturated and unsaturated zones. For this purpose, the separate utilization of the heating methods would lead to preferential heating of either saturated zones by PLF or unsaturated zones by RW (due to the voltage attenuation along the rod electrodes). However, the large temperature differences would cause risks of recondensation or readsorption as well as undesired mobilization of pollutants. To solve this problem, the simultaneous application of PLF and RW energy into the soil via a single electrode system has been developed. It is exemplarily demonstrated for a field site (cf. SI Figure S2). The remediation of the former storage facility for solvents (compare (*28*)) was constrained by the condition that the solvent tanks should remain in the soil during the process. Therefore, the metallic tanks were

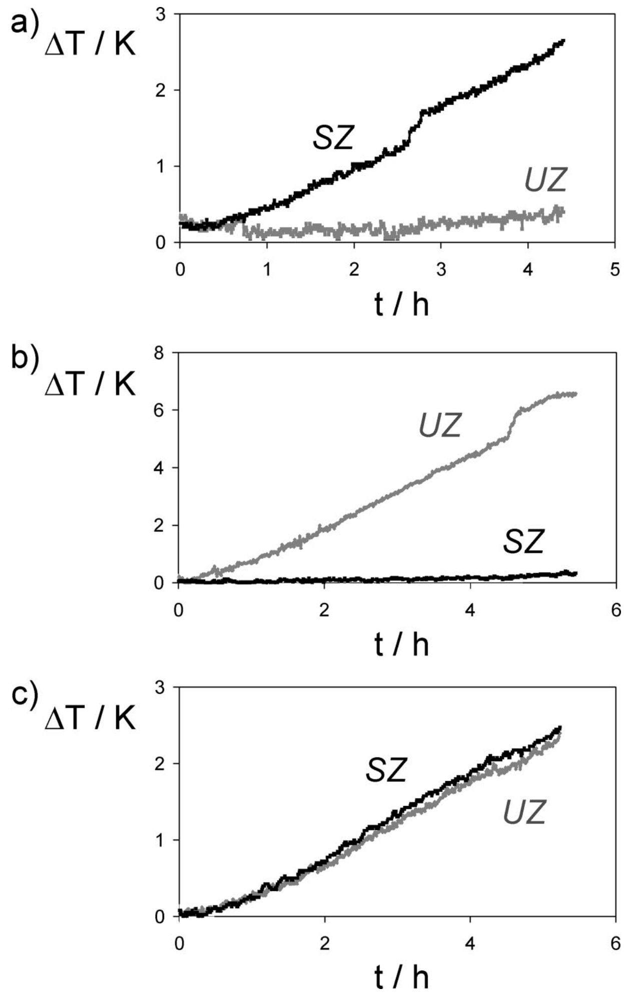

FIGURE 2. Heating process in the saturated and the unsaturated zones (SZ and UZ, respectively) during electrical heating using various power sources (diagrams represent the mean values obtained by seven fibre optical temperature sensors for each level, arrangement according to SI Figure S2): (a) PLF heating (frequency 50 Hz, power 1 kW), (b) RW heating (13.56 MHz, 2 kW), and (c) simultaneous application of PLF (50 Hz, 1 kW) and RW energy (13.56 MHz, 0.9 kW) via a single electrode system.

included into the electrode system by using them as so-called cold (grounded) electrodes. A set of rod electrodes simultaneously also acting as extraction wells were introduced into boreholes in the volume between the tanks. Due to special hydrogeological conditions, the water table was at a relatively high level within the soil volume to be cleaned.

Separate heating using only one frequency led to strong temperature gradients in the soil, whereas simultaneous PLF and RW application established near-homogeneous temperature profiles. The mean values for the temperature measured at 7 points in each level as a function of time are shown in Figure 2a–c. Thus, the combination of two different frequencies of the electric field and, consequently, the parallel exploitation of resistive and dielectric heating allowed a controlled heating of the whole capillary fringe. This new method holds great potential for the treatment of hydrocarbon phases, especially of LNAPLs.

The technical condition of electrically separating the two power sources (PLF transformer and RW generator) from each other was fulfilled by a low-pass filter in combination with a $\lambda/4$ cable and the capacitors of the matchbox, respectively (*30*).

Combination of Radio-Wave Heating with Established Remediation Techniques. *Thermally Enhanced Biodegrada-*

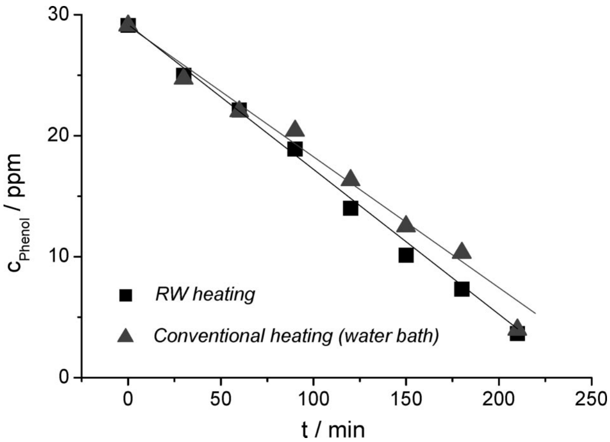

FIGURE 3. Phenol degradation by *Pseudomonas fluorescens* SV 35 at 31 °C with the temperature stabilized either by RW application (200 W pulses of 15 s duration every 15 min) or by a water bath.

tion. It is known that mesophilic microorganisms (MO) exhibit a maximum for microbial activity in general and biodegradation rates in particular in the temperature range between 30 and 40 °C. For thermophilic MO, it may be significantly shifted to higher temperatures. This fact leads to the requirement for relatively homogeneous temperature profiles in the soil when biological processes are to be supported. For RW heating this demand can be fulfilled by adequate electrode geometry (preferentially parallel plates) and the utilization of spontaneous heat transport processes within the soil.

However, even when the temperature can be held within the desired range, a possible negative effect of the application of electromagnetic radiation on the MO cannot be a priori excluded. A significant impeding impact would call into question the application of the RW method for supporting biological remediation processes.

Therefore, a number of different studies have been carried out to compare the influence of conventional and RW heating on biological processes. Specifically, the soil respiration, the reduction of dimethyl sulfoxide (DMSO) as a measure for total microbial activity (*31*) and the degradation of several model pollutants were studied.

The effect of RW radiation was exemplarily studied with the phenol-degrading bacterium *Pseudomonas fluorescens* SV35. The strain was isolated from a flocculated carbonization wastewater (Lake Schwelvollert, Saxony-Anhalt, Germany). It was cultivated in a mineral salt solution (*32*) with 100 ppm phenol as sole carbon source at 30 °C. To determine the degradation rate, a number of 1 mL aliquots of the precultivated batch culture were distributed into 2 mL tubes. These tubes were placed either in a water bath for conventional heating or in a bed of dry sand for RW heating (13.56 MHz). In both cases, the temperature was kept constant at 31 °C with an accuracy of ±0.3 K. The phenol concentration as a function of degradation time was measured by HPLC analysis for two parallel samples (*32*). As shown in Figure 3, the pulsed application of an RW power of 200 W (pulses of 30 s duration at 15 min intervals, maximum field strength about 20 kV m^{-1}) to maintain the temperature at 31 °C did not affect the microbial degradation when compared with conventional heating. The pulse regime was applied deliberately to intensify the electromagnetic stress for the MO compared with a steady RW radiation.

In another case, the soil respiration (standard soil type 0, Gebr. Patzer, Sinntal, Germany; OC content 32%, initial humidity about 68 wt-%) was quantified under conventional, PLF and RW heating, respectively. As shown in Figure 4, the CO_2 emission into a purge gas of pure air was comparable for all three heating methods. The humidity of the soil was kept constant by definitely saturating the gas flow with water at the soil

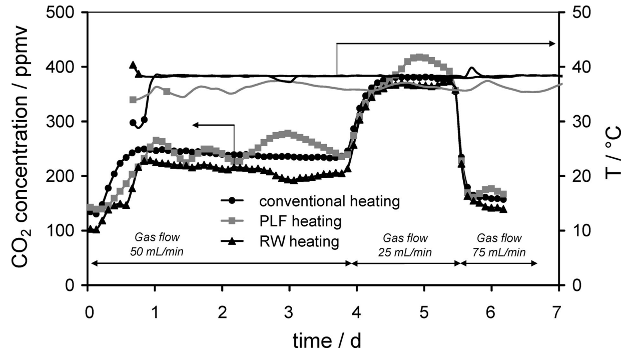

FIGURE 4. Respiration of autochthonous microorganisms in a standard soil type 0 (represented by the CO_2 content of the purge gas) and soil temperature as stabilized by three different heating methods (conventional heating in a water bath, resistive PLF heating and dielectric RW heating).

temperature (*27*). Small differences in respiration can be explained by slight temperature variations between 36 and 38 °C as can also be seen from the temperature axis in Figure 4.

The quantification of O_2 consumption related to soil respiration gave identical results (data not shown, details in ref *27*), thus providing evidence that the CO_2 formation was due to microbiological activity and not due to physical desorption.

The fact that both microbial activity and pollutant degradation are not significantly affected by the applied electromagnetic field (which is valid for RW as well as PLF heating) was proven in a large number of experiments which are described elsewhere (*27*). Under all conditions with field strengths and power densities relevant for soil remediation, the applicability of these electrical heating methods for enhancing biological processes was not limited by harming the microbial population. Even at field strengths up to 20 kV m^{-1} and a specific power input of 2 kW L^{-1} no inhibition of the microbial activity was observed (*27*).

Of course, minor "nonthermal effects" of electromagnetic radiation cannot be excluded. However, they do not limit the applicability of RW and PLF in remediation practice.

Characteristics of Energy Dissipation into Soil by Radio Waves. The importance of thermal effects for the enhancement of remediation processes has been frequently proven and their relevance is unquestionable. However, there is one characteristic phenomenon—self-regulation of heat transfer—which is of particular interest when RW heating is applied for humid soils.

In conventional heating with fixed heat sources, the energy is dissipated by heat conduction. This gives rise to overheating of the near surrounding around the heat sources and finally its desiccation. Dry soil is, however, a poor heat conductor. To transport heat through dry soil layers, steep temperature gradients are necessary. In case of RW application, the undesired overheating can be minimized due to the spatial energy dissipation characteristic of volumetric heating. For RW heating an additional effect aids the homogenization of temperature profiles: the energy absorption is usually higher for humid than for dry materials. Therefore, the distribution of energy input within the soil is changed during the drying process in such a way that the colder, more humid layers absorb more energy, whereas the warmer, more desiccated layers absorb less. During the heating process, the focus of RW energy absorption is shifted away from the electrode due to earlier desiccation of soil in its vicinity. Consequently, the temperature profile is equalized by a self-regulating mechanism. The different heat dissipation mechanisms have significant consequences for the achievable temperature profiles, and thus for the remediation efficiency.

In general, dielectric heating of soil using radio waves is a promising option for thermally supporting several remediation techniques, such as biodegradation of pollutants and soil vapor extraction. Due to the requirements concerning energy transformation, instrumentation, and specific knowledge its application will be focused on source removal, in situ heating of soil near or under buildings, i.e. in urban or industrial areas, and treatment temperatures above 100 °C. If possible, a combination with ERH should be checked for optimization. Results of field tests of various RW application designs are described in ref *33*.

Acknowledgments

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Supporting Information Available

Additional information on the antenna geometry and the related temperature profile as well as on the arrangement for the experiments with the combination of two applied frequencies of electric field. This material is available free of charge via the Internet at http://pubs.acs.org.

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