Microwaves in Soil Remediation from VOCs. 2. Buildup of a Dedicated Device

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This work presents the design of a microwave opened applicator useful to perform the Microwave Induced Steam Distillation (MISD) process for soil remediation treatments. The prototype has been also realized and used to irradiate a 40 x 30 cm area with a given electromagnetic field distribution. Experiments carried out by in situ operations on a soil contaminated with VOC's are reported. Finally, the experimental data collected are described by a mathematical model previously proposed. *AIChE J,* 50: 722–732, 2004
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Introduction

It has been recently shown that microwaves can be successfully adopted to remedy, in short times, a soil contaminated by VOC in a nonintrusive way, with a low environmental impact. The process, so-called microwave induced steam distillation (MISD) endogenously generates the water vapor necessary to strip the contaminant out of the soil matrix at a relatively low temperature, below the boiling point of water. Under these mild conditions, the soil does not suffer from thermal stresses. The process, when performed in a closed applicator, also shows a very high efficiency of remediation (Acierno et al., 2003).

Based on the advantages above, it is obvious that the process would become greatly enticing only once an apparatus for performing *in situ* the operation would be realized. The apparatus should be transportable; have a good trade-power off between the extension of the irradiated surface and the incident microwave power density; be able to minimize the power radiated in undesired directions; and have good power handling and fault tolerance.

In this work a dedicated microwave device is presented. In particular an opened microwave applicator was realized to meet the requirements above listed. The design, which is based on fundamentals of electromagnetism, had to face with coupled phenomena of heat and mass transfer in a complex system with continuously changing chemical and physical properties, complex permittivity in particular. The goal was to realize an efficient tool, well controlled, to use in campaigns of remediation without any intrusion or excavation and transport of the soil.

In the following the keynotes of microwave heating and their application to soil remediation are briefly presented.

In situ steam distillation process

Radio frequency (RF) heating, as an auxiliary process to be added to soil vapor extraction, (SVE), has been proposed to clean, by *in situ* operations, soil polluted by volatile organic compounds (Regan et al., 1995; Price et al., 1997; Kawala and

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Atamanczuk, 1998; Jones et al., 2002). RF energy was delivered by an antenna applicator located in an underground tube between the extraction wells of the SVE equipment. RF heating improves the SVE treatment but does not solve the environmental impact problems with the need of adding supplementary equipments within the site. The idea of an endogenous generation of the cleaning phase inside the soil matrix by applying an external electromagnetic field appears to be interesting when performed by a superficial irradiation inducing a deep heating (Windgasse and Dauerman, 1992; Abramovitch et al., 1998).

Soil decontamination from VOCs performed via microwaves is reported in a previous work (Acierno et al., 2003). In particular, that work deals with the propagation of the electromagnetic waves in a naphthalene polluted soil undergoing remediation, and related heat and mass transfer. Moreover, the critical parameters of the process were identified. Actually, the experiments were performed in a microwave closed applicator, using a special sample-holder in which soil carrots were representative of a semi-infinite portion of the real contaminated area. Indeed, the phenomenology of the microwaves treatment was identified as occurring in four steps: (a) superficial irradiation to induce the heating; (b) progress of the heating front, allowed by the simultaneous progressive drying of soil; (c) generation of a vapor flux, and (d) starting of the stripping process.

Everything is then reproduced layer by layer.

Brief on microwave heating

Electromagnetic phenomena are described by the well-known Maxwell's treatise formulated in coupled sets of differential equations that provide the relations between the electric and magnetic field quantities (field strength vectors) (Metaxas and Meredith, 1988). To solve the differential equations sets, appropriate boundary conditions and constitutive relations are needed. In particular, the constitutive relations have the information concerning the properties of the matter to be treated by electromagnetic fields.

In the microwave applications, electromagnetic radiations with frequencies in the range 300 MHz to 300 GHz are used, and the heating process involves the conversion of electromagnetic energy into heat by migration of ionic species and/or rotation of dipolar structures.

The fundamental macroscopic parameters in microwave processing are: the power absorbed and the microwave penetration depth. The power absorbed is described by the common form of the average power loss density obtained from the Poyting's theorem

$$\dot{Q} = \frac{1}{2} \cdot \omega \cdot \varepsilon_0 \cdot \varepsilon' \cdot \tan \delta \cdot |E|^2 = \frac{1}{2} \cdot \omega \cdot \varepsilon_0 \cdot \varepsilon'' \cdot |E|^2 \quad (1)$$

where E is the magnitude of the internal electric field, ω the angular frequency, ε_0 is the permittivity of free space, ε' and ε'' are the real part (dielectric constant) and the imaginary part (loss factor) of the complex permittivity, respectively. The real and the imaginary parts of its complex structures are often expressed through the loss tangent parameter, tan δ, that is the ratio between the loss factor and the dielectric constant. As can be seen from the absorbed power equation (Eq. 1), the dielectric properties assume a significant role in the microwave heating treatments. The dielectric properties also are a significant parameter in determining the penetration depth, that is, the depth to which microwaves will penetrate into the material (Saltiel and Datta, 1999; Haque, 1999; Clark et al., 2000). In particular, the penetration depth is the distance from the surface of the material at which the power drops to e^{-1} from its value at the surface, and is often reported in the specialized literature, as its inverse form, called attenuation factor. For low loss dielectric materials ($\varepsilon''/\varepsilon' \ll 1$), the penetration depth is given by the simplified relation

$$D_p = \frac{\lambda_0}{2\pi} \cdot \frac{\sqrt{\varepsilon'}}{\varepsilon''} \quad (2)$$

where λ_0 is the wavelength of the radiation in the free space. It has to be noted that the dielectric properties can change during the microwave heating, depending on the changes of chemical and physical characteristics of the materials (temperature increases, drying effects, structural modifications, and so on). This means that studies on heat and mass transfer occurring are a complex problem because dielectric properties and their evolutions are often not available.

Basic components of a microwave heating system

A microwave heating system is made up of three basic components: the power supply, the applicator, and the transmission-lines or waveguides for transporting microwaves from the generator to the applicator (Chow Ting Chan and Reader 2000; Haque, 1999; Thostenson and Chou, 1999).

The commonly used source of microwave energy is the magnetron and the supplied energy is driven to the applicator by waveguides.

Waveguides are hollow metallic tubes either of rectangular or circular cross-section. They are usually jointed by flange connections. The largest variety of this kind of devices is made of copper, aluminium, or brass. Cross dimensions are crucial for the propagation modes from the electromagnetic source to the applicator. Waveguides are officially identified by codes.

The applicator is the fundamental part of a dielectric heating apparatus. Its proper design is responsible for the efficiency of the heating process. Closed cavities or resonant applicators are classifield as either single or multimode. Rectangular and cylindrical shapes are commonly used for single-mode cavities. Single-mode cavities sustain only one mode, that is, is the field pattern that can hold. The multimode cavity, instead, sustains a lot of number modes. Closed multimode applicators are the most diffuse kind of microwave cavity (in industrial furnace or domestic oven constructions) due to their features of mechanically simple and very versatile equipment, able to process a wide range of heating loads applications. Their structure can be described as a closed metal box with at least two dimensions that should be several wavelengths long. In this way, a large number of modes can resonate. However, construction simplicity is counterbalanced by nonhomogeneous heating that is typically overcome by either movement of the workload, or mode stirrers, or both (Gardiol, 1984; Metaxas and Meredith, 1988).

Opened microwave applicators, characterized by the absence

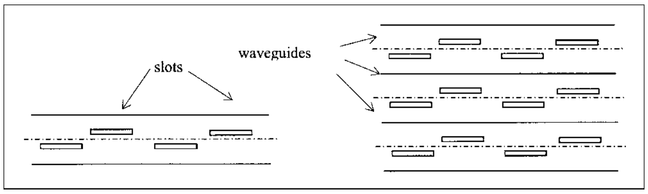


Figure 1. Longitudinal slot resonant array (on the left) and of a planar arrays (on the right).

of the resonant cavity, are noncommon systems due to the not well defined safety technology.

In this work attention is focused on the design, the construction and the characterization of an opened applicator in form of a planar array of resonant slots in longitudinal waveguide for *in situ* low-impact soil remediation process. In the following are reported the design equations, the final working arrangement, the laboratory heating/decontamination test runs, and the comparison between measured data and predictive profiles performed by a mathematical model previously developed for microwave treatments of soil in closed cavities.

Opened Applicator Prototype

Design criteria

The requirements reported in the Introduction are satisfied designing an equipment consisting in a planar array of waveguide longitudinal resonant slots, that is, rectangular opening on lateral waveguide's wall powered by electromagnetic field propagating in the waveguide itself. The planar array design is developed by placing side-by-side three distinct waveguide slot linear arrays (sub-arrays) (Acierno et al, 2000a) as sketched in Figure 1. The better operating exercise (to achieve maximum power in a direction normal to the array plane) of the open prototype has required TE_{10} mode propagation across the waveguides and in phase slots excitation. Cross dimensions of the wavaguide ensure the TE_{10} mode propagation, whereas size and characteristics distribution, that is, the positions along the waveguide axis of both the coupling and radiating slots, guarantee that they are excited in phase.

The rectangular opening can be classified as either resonant or coupling slots, being the former devoted to the waves distribution out of the applicator, the latter charged of transferring the waves from the magnetron to the resonating slots through the launch guide.

The resonant slots are machined so as to have the major dimension parallel to the broadwall. Moreover, each slot is at distance x from the longitudinal axis (Figure 2). Since the design idea was to realize a planar array of half-wavelength antennas, l is consequently imposed as $l = \lambda_g/2$ and $h \ll l$, where h is the slot width (Figure 2). At the operating frequency, 2.45 GHz, the wavelength in the waveguides is $\lambda_g = \lambda_0[1 - (\lambda_0/2a)^2]^{-1/2}$ where λ_0 is the wavelength of the radiation in the free space and a is the larger dimension of the waveguide (Figure 2).

The coupling slots are machined in the waveguide acting as a launching guide. The key parameter is the angular tilt of the slot, that is, the angle between the slot axis and the guide axis (Figure 3).

In the planar array configuration, each sub-array is coupled by the tilted slots to an upper waveguide (dashed in Figure 3) connected to the microwave source. The complete configuration of the waveguide slot linear arrays with the upper longitudinal array and the tilted slots is represented in Figure 3.

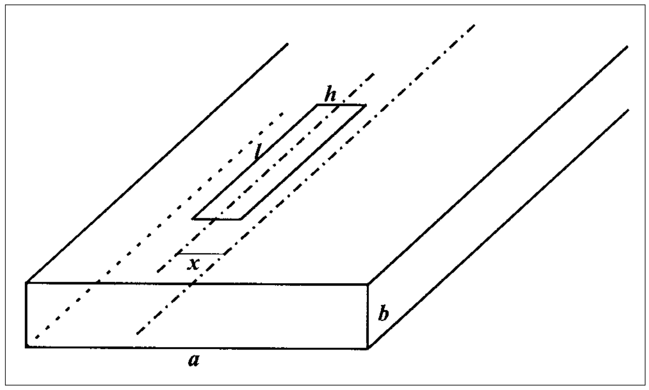


Figure 2. Slot on a waveguide.

To optimize applicator efficiency proper values for both the offset from the waveguide axis of the radiating slots and the angular tilt of the coupling ones were determined by following a classical method (Collin, 1985). Thus, the resonant slots are spaced $\lambda_g/2$ apart and with alternate slots offset (x distance in Figure 2) on opposite sides of the centreline. The study of the array's equivalent circuit gives the offset calculation. In particular, the equivalent circuit of each array consists of the N conductances (equivalent to the slots) g_p connected across a transmission line with spacing $\lambda_g/2$ as shown in Figure 4. A short circuit placed $\lambda_g/4$ beyond the last slot presents an open circuit in shunt with the last slot (Collin, 1985).

The sub-array slots number was determined according to classical wave propagation theory for a broadside array. In our case $N = 4$ (Figure 3). The excitation level of the slots was chosen according to a binomial sequence for which

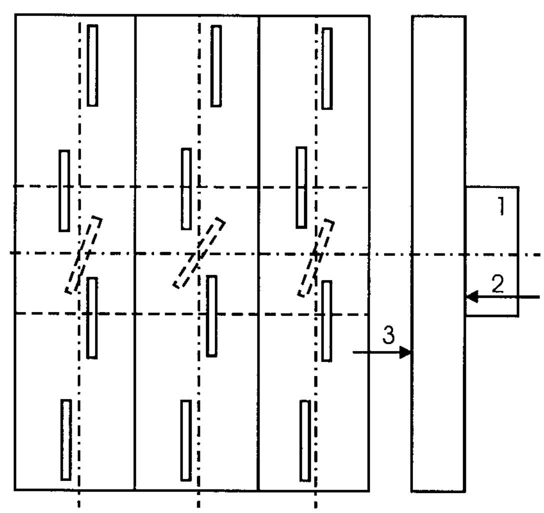


Figure 3. (1) Waveguide connected to the microwave source; (2) upper waveguide with tilted slots; (3) side waveguide longitudinal resonant slots.

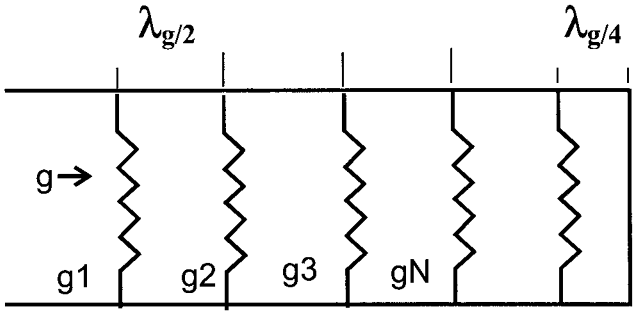


Figure 4. Linear array equivalent circuit.

$$\frac{g_p}{Y_{10}} = K\frac{N!}{p!(N-p)!} \quad p = 1, 2, \ldots, N \tag{3}$$

where Y_{10} is the mode wave admittance (at the input circuit), whose value is given by

$$Y_{10} = \frac{\beta_{10}}{\omega\mu_0} \tag{4}$$

where again β_{10} is the propagating constant of the TE_{10} mode ($\beta_{10} = 2\pi/\lambda_g$). All the N admittances must be transported in input condition by the appropriate admittance transport formula. To optimize the applicator efficiency, the impedance matching condition must be satisfied

$$g = \sum_{p=1}^{N/2} g_p = Y_{10} \tag{5}$$

it then is possible to evaluated the K factor

$$K = \frac{Y_{10}}{\sum_{p=1}^{N/2}\frac{N!}{p!(N-p)!}} \tag{6}$$

and to obtain g_p, $p = 1, 2, \ldots N$, by Eq. 3. Finally, for each slot the offset (x_p) can be drawn from

$$g_p = Y_{10}\frac{480}{73\pi}\left(\frac{a}{b}\right)\left(\frac{\lambda_g}{\lambda_0}\right)\cos^2\left(\frac{\pi\lambda_0}{2\lambda_g}\right)\sin^2\left(\frac{\pi x_p}{a}\right) \tag{7}$$

An analogous procedure has been followed to calculate the angular tilt of the coupling slots (Collin, 1985; Barba, 2001). These latter, in our case, are 3 (Figure 3). To guarantee the best focusing of the microwave on target through the resonant slots, and to simultaneously reduce losses to the environment, the central coupling slots have a major tilt rather then the other slots (Figure 3).

Building the prototype

The applicator is built up in aluminium for its good electrical conductivity, its chemical inertness, the smoothness and cleanability of the machined surface, its low specific gravity (the applicator must be a portable equipment), and its low cost.

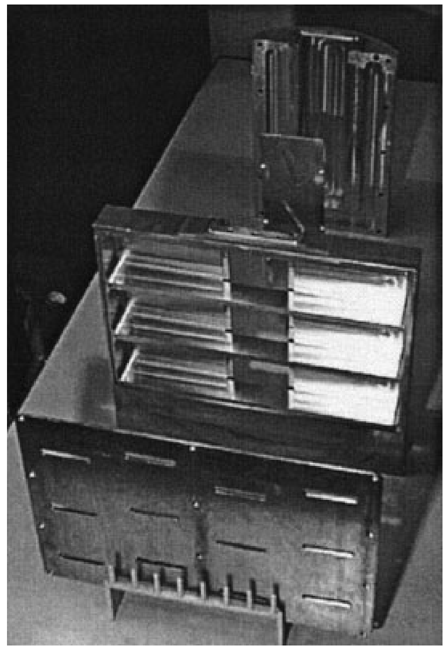


Figure 5. Exploded view of the prototype.

It is made of four different components, as can be seen from the exploded view in Figure 5. The main part, of rectangular front view shape, whose dimensions are 44 ×35 × 5 cm, consists of an aluminium block. Three cavities have been obtained, by milling, corresponding to three standard WR284 rectangular waveguides. Its lower side has been connected with the aluminium plane of radiating slots, while on the upper side another standard WR340 rectangular waveguide has been built by the coupling of a semi-cylindrical aluminium block. Finally, an aluminium plate with the coupling tilted slots has been inserted between the main and the upper semi-cylindrical blocks. The four different aluminium structures, above discussed, were assembled by bolts and screws (Acierno et al., 2000a; Barba, 2001) (Figure 6). At the operative frequency, that is, 2.45 GHz, the transverse sections dimensions of both WR284 and WR340 waveguides allowed the propagation of the fundamental TE_{10} mode only. As a microwave power source, a magnetron supplied by *National Electronics*, mod.

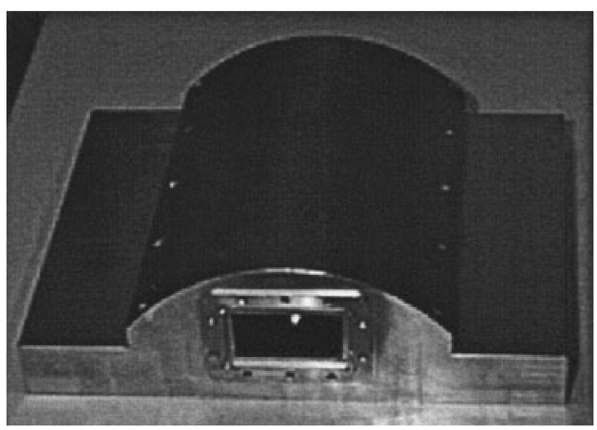


Figure 6. Assembled view of the prototype's components.

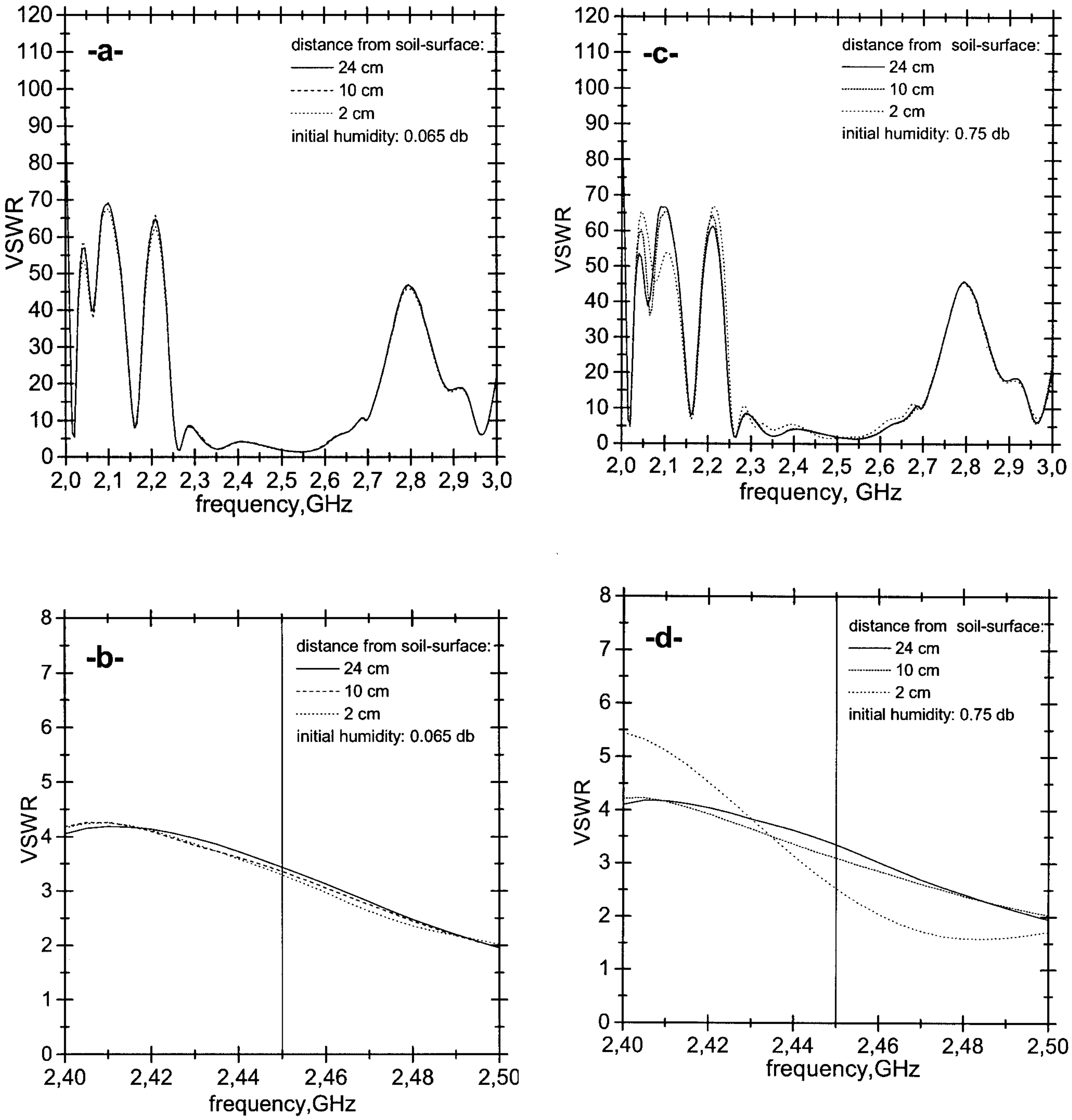


Figure 7. VSWR measurements vs. microwave frequencies at different distance of the applicator from the soil-surface at given soil moistures (-a-, -c-, -e-).

Close up on the operative frequency, 2.45 GHz (-b-, -d-, -f-).

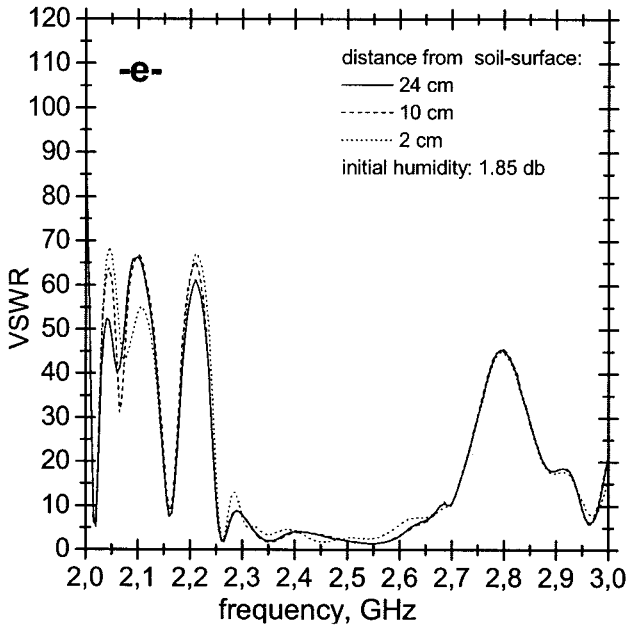
2M130/NL10250, 1900 W maximum power, was used. The connection between magnetron and applicator has been obtained by an external rectangular section waveguide. The electromagnetic power source regulation was performed by voltage manipulation.

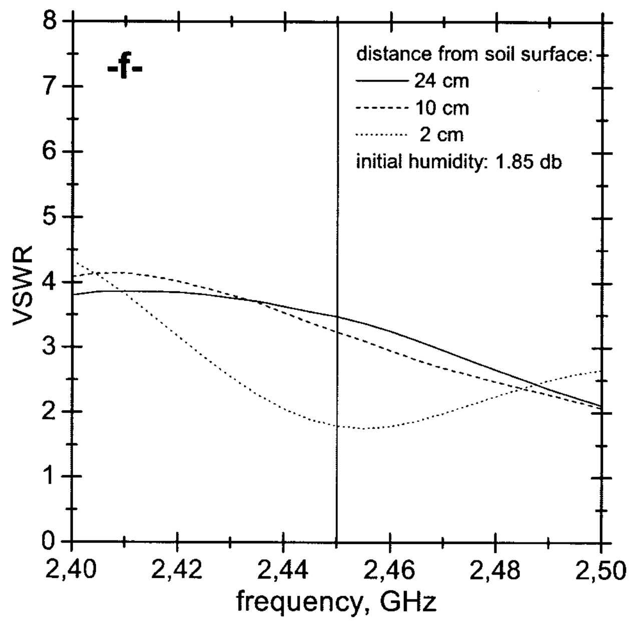
Electromagnetic testing

First of all, the electromagnetic behavior of the applicator has been studied. In particular, the voltage standing wave ratio (VSWR) measurements have been performed. Results are related to the applicator electromagnetic efficiency through the reflection coefficient Γ by Eq. 8

$$\mathrm{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad (8)$$

and than the equation of the radiated prototype efficiency is





$$\frac{P_{irr}}{P_{in}} = 1 - |\Gamma|^2 \tag{9}$$

where P_{irr} and P_{in} are the radiated power (from the applicator) and the supplied power (from the microwave source), respectively. By way of Eqs. 8 and 9, high efficiency corresponds to low values of both $|\Gamma|$ and VSWR.

VSWR measurements are performed using a vector network-analyzer HP 851907B, at frequencies ranging from 2 to 3 GHz, by placing the applicator just above the soil surface. VSWR measurements are purposely performed on noncontaminated soil, since attention is focused on water, which is the strongest microwave adsorbed of the soil/water/naphthalene mixture. Actually, soil and contaminant have a very low loss factor (Acierno et al., 2003, 2000b).

Figure 7 shows VSWR values as a function of the frequency for soil samples with 0.065, 0.75 and 1.85 kg_W/kg_S (db -dry bases- in the following) in the moisture contents respectively. Data collected show that at the operating frequency, for given distances between soil surface and applicator, the VSWR increases as humidity decreases. Best performances are obtained at high humidity and short distance between soil and radiating slots surfaces (Barba, 2001).

Experimental Studies

As reported in Introduction section, first steps of soil decontamination process via microwave energy are performed in a closed applicator (at 2.45 GHz, 800 W maximum power) at different conditions. In this way the key role of dielectric properties and the influence of other parameters, such as exposure time, have been pointed out.

The scope of this experimental work has been to confirm the feasibility of *in situ*, in opened environmental conditions, heating operations using the realized prototype. The experimental activity has been developed by measurements of temperature, residual humidity and contaminant concentration in deep soil layers, following the same procedures carried out on soil carrots irradiated by the closed applicator. It was expecting the same heat- and mass-transfer phenomena and the same dependence from exposure time and dielectric properties, that is, soil moistures.

Materials and apparatuses

A commercial gardening soil is used and naphthalene is selected as soil contaminant. Methanol is used both as solvent for contaminant solution (naphthalene is insoluble in water) and as liquid-phase extractor in a Soxhlet equipment. Methanol-naphthalene solutions are analyzed by a HP 5890 gas chromatograph. An HP 851907B vector network analyzer with dielectric probe meter HP 85070B is used to VSWR and dielectric measures. Details on materials and apparatuses used are reported elsewhere (Acierno et al., 2003).

Opened applicator bench-scale apparatus

The prototype is suspended under a table by threaded bars screwed in its upper side. In this way the radiating slots are placed close above the soil surface. The soil is putted in a container made in wood of 1 m^2 area and it was filled to a maximum depth of 16 cm. The distance between soil surface and radiating slots has been changed putting the sample holder on a manual lift in order to achieve the better VSWR related to all the other operative parameters.

Due to the binomial tapering of the slot excitation levels, the incident power density (and, consequently, the microwave heating) is very high in the soil immediately under the central slots of the applicator, and decays outward. In particular, for all kinds of measures (temperature, residual humidity and contaminant), a conventional map has been adopted to perform soil sampling. This map has been developed as a three-dimensional (3-D) reference system composed by a plane with two different concentric areas and four different markers to identify four points for soil-deep sampling. The two concentric areas are

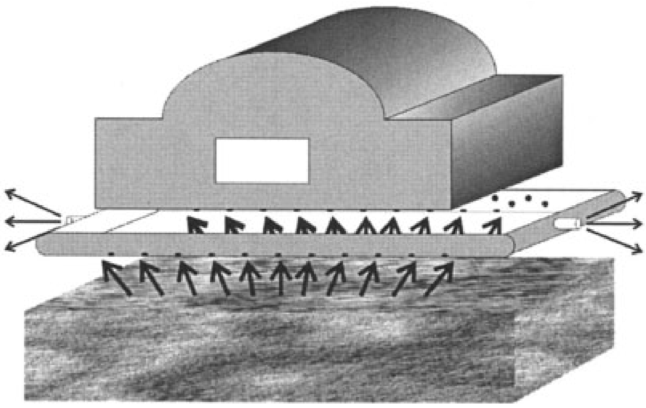


Figure 8. Open applicator/soil surface configuration.

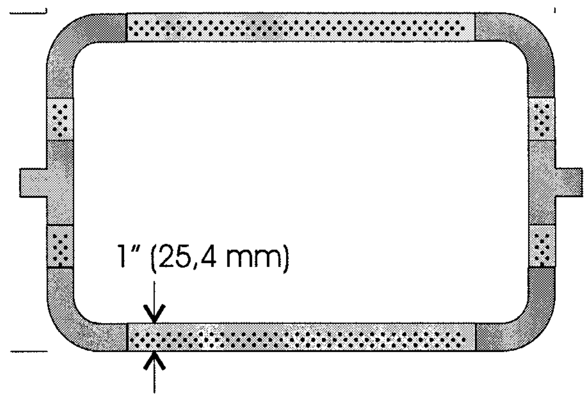


Figure 10. Recover stream tube-ring system.

related to the projections of the two kinds of radiating slots (central - B and C points – and lateral - A and D points -) (see Figure 9).

In order to recover the vapor fluxes produced during the decontamination treatment, a suction equipment is built (see Figure 8 and Figure 10). This system is realized by a tube-ring connected to two suction pumps. The generated streams are then forced into absorbent traps. In this way, possible phenomena of vapor condensation under the cool radiating plate, are also discouraged.

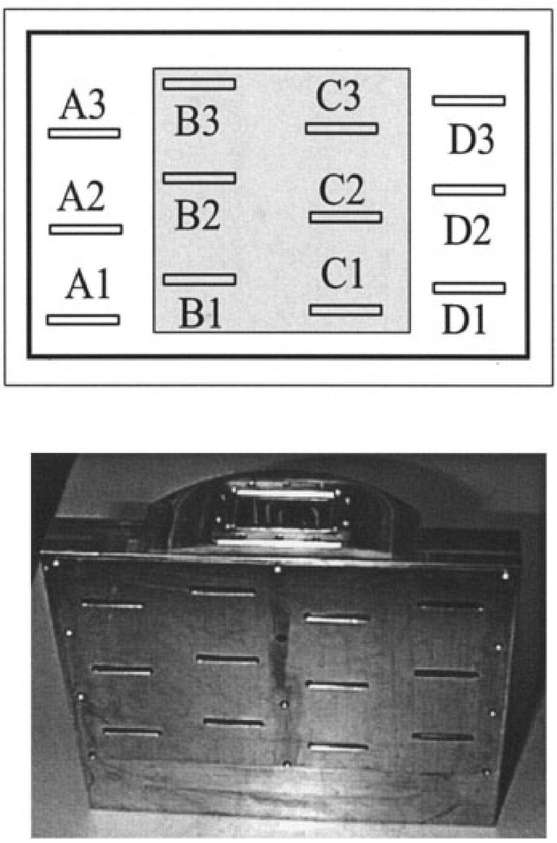


Figure 9. Soil sampling scheme: letters and numbers (in the sketch on the left) represent the trace of each resonant slots (bottom of the open applicator on the right) on the soil matrix.

Finally, hazards, leakage, and safety aspects are considered. A metallic screen (mesh 2 mm) is used to wrap up the bench apparatus to reduce electromagnetic losses, and a remote control is adopted to turn on / turn off the magnetron. Using an environmental electromagnetic field monitor (*TRIFIELD, Velctron Spa*), it is checked that at a distance greater then 2 m from the applicator, the intensity of the electric field is below the current safety standard.

Methodology

Sampling operations are performed in order to collect temperature, residual humidity and contaminant concentrations data. As above reported, a 3-D reference system is adopted and 12 samplings are done for each the four different layers (the four examined layers are spaced 4 cm in depth from each other). Before the microwave treatments, the soil is prepared by sieving and drying, and then water is added to achieve the selected moisture.

As reported in Acierno et al. (2003), after a given time of treatment, the run was stopped and temperature measured using thermocouples. The soil was then removed, layer by layer, to perform the water/contaminant content analyses. Time of exposure, prototype/soil configuration (distance between radiating slots and soil surfaces) (Figure 8), supplied power and initial soil water content are the variable parameters of the microwave treatments.

Preliminary tests (explorative runs) are performed to find the better time of exposure to show the progress of the microwave treatment (for all the runs, the initial temperature was about 20°C). In a short time of microwave exposure, from 5 to 15 min., the treatments, performed at the same other condition reported in Table 1, induced only a superficial heating according to the penetration depth law (Eq. 2) being the loss factor

Table 1. Applicator Runs: Exercise Conditions

Parameter	Value
Exposure time	60 min
Applicator/soil configuration (distance between surfaces)	8 cm
Power delivered	1,900 W
Initial water content	1.5 kg_W/kg_S (60% on wet basis)

relatively high. Due the low temperature, negligible moistures losses were achieved and, in turn, decontamination phenomenology did not occure. Longer exposure times, from 30 to 90 min., indeed, had shown the progress of the heating front and in turn the simultaneous progressive stripping and drying processes. We choose not to extend microwave exposure times in order to observe different profiles of temperature and humidity. As reported in the following, 60 min. (one hour) of exposure time has been chosen to collect experimental data.

Prototype exercise: results and discussion

The following results are referred to the exercise conditions reported in Table 1.

Data collected show the temperature measurements as a function of the depth and each box is filled with one of four different grey tonalities which correspond to different deep layers (light gray: bottom layer sampling; dark gray: superficial layer).

As reported above, the central slots transmit the highest delivered power density, so that the central area of soil matrix is more heated and more dried (Figures 11 and 12). The temperature reaches the steam distillation point only in a little area and in the superficial layers, but also the whole soil volume (40 × 30 cm in area and 16 cm in depth) is sensitively heated (Figure 11). As an effect of the heating, the soil matrix progressively dries (Figure 12). Being the heat and mass transport correlated, the removed humidity profiles show, as a consequence, strong dried areas and nondehydrated areas.

Obtained results emphasize the evolution in the time of the MISD process. This process is previously described as an interlacing and sub-sequential phenomena which occur layer by layer through the soil matrix (Acierno et al., 2003). In particular, microwave radiation of a soil-water-VOC system induces a temperature increase, which depends in turn of its loss characteristics (fundamentally due to the water, since soil matrix is transparent to microwaves). This substantially occurs in a thickness of soil strictly related to the specific penetration depth of the microwave field. Since the dielectric properties of the soil matrix change layer by layer with the changes of the characteristics of the soil, temperature, and moisture, due to the progress of the microwave treatment, the superior soil layers, now dried, become transparent to microwaves so that the electromagnetic field moves deeper inside.

The decontamination profile for the soil will be given in Figure 14. Polluted soil has an initial contaminant concentration of 4,000 ppm and initial humidity of 1.5 db, and is exposed to microwaves at the same conditions reported above. Decontamination data are obtained by samplings of polluted soil in correspondence of the more heated area (corresponding to B–C points in Figure 13). Results are reported in terms of mean values (expressed in per-cent unit) of residual naphthalene as a function of the distance from the sample holder bottom, and referred to the above identified four different layers.

Figure 13 shows that an appreciable removal performance in about 6–7 cm of soil depth is obtained, while low decontamination efficiencies are performed in deeper layers. All the above agreed with the heat- and mass-transfer phenomena

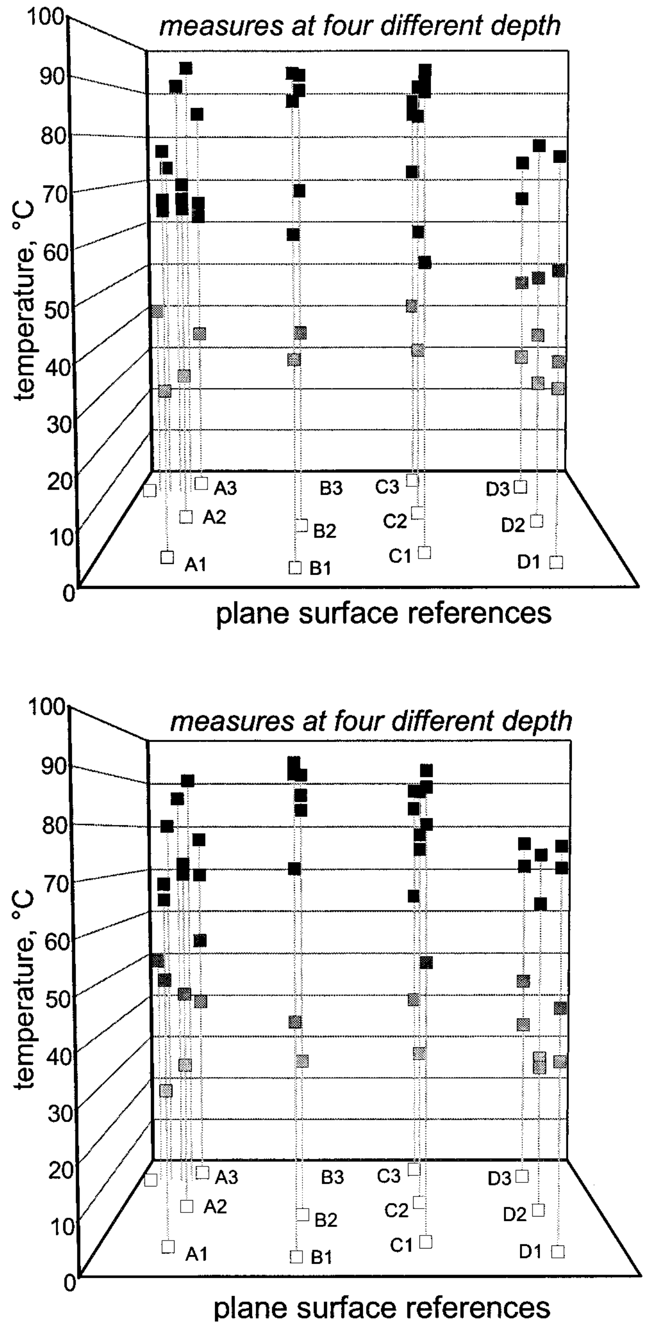


Figure 11. Temperature measures after microwave treatments (two different runs at the same operative conditions).

examined. The low temperatures and, thus, the absence of a vapor streams, cannot allow the contaminant stripping to be achieved. Better performances are certainly obtainable either extending the microwave exposure time, or using a higher incident power density. In Figure 14, the test results performed on the same kind of soil and in the same hot area, but in a thinner layer, are reported (Acierno et al., 2000a). These were obtained at a lower exposure time (30 min.), but at a better VRSW, due to a greater initial humidity (2.0 db) and a lesser distance between soil surface and applicator (2 cm). It can be

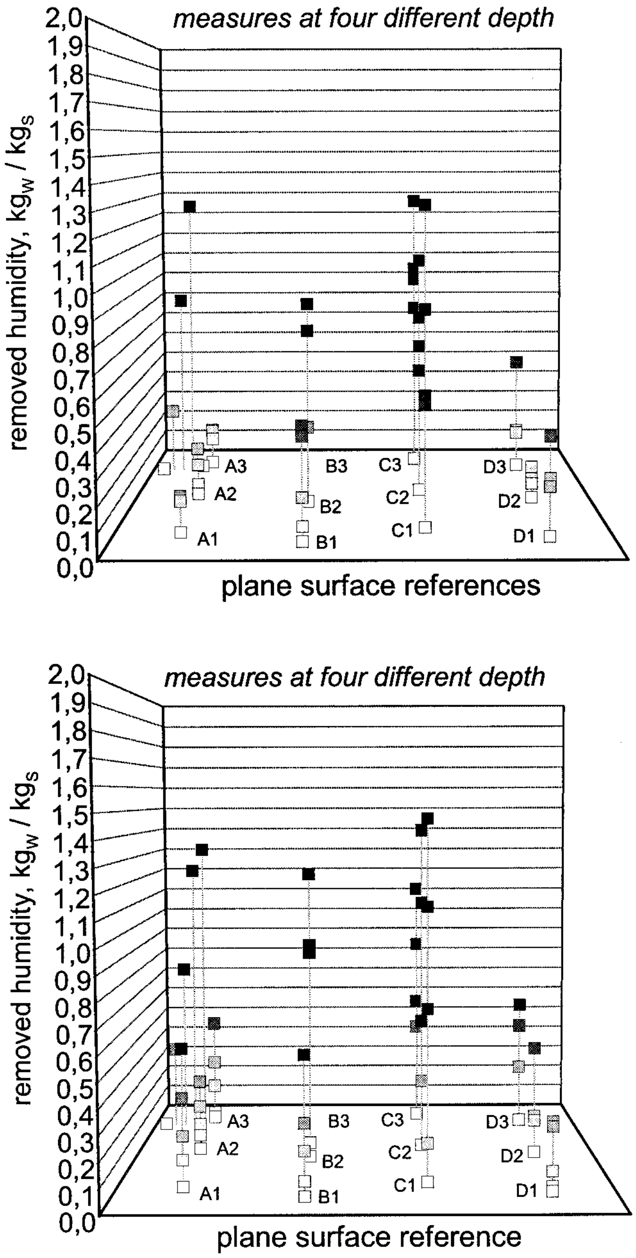


Figure 12. Removed humidity measurements after microwave treatments (two different runs at the same operative conditions).

seen that a very good decontamination is obtained down to the bottom of the soil matrix.

Modeling

The heat and mass transfers occurring during the soil heating via microwave energy have been investigated and modeled (Acierno et al., 2003). In particular, it was proposed a system of 1-D transient equations of energy and mass balance, where the generation term takes into account the interactions between electromagnetic field and matter.

The outlined model equations are:

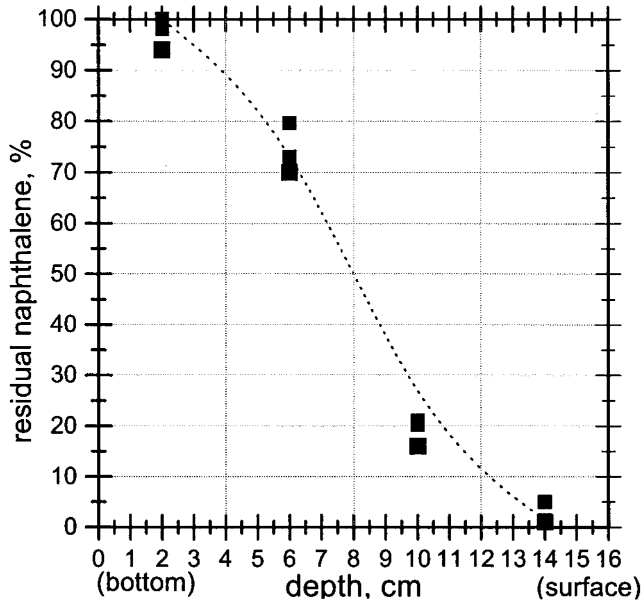


Figure 13. Decontamination measures performed via MISD process.

Energy balance

$$(1-p)\cdot\left[K_{TM}(T,X)\,\frac{\partial^2 T}{\partial z^2}\right]+Q(T,X)-r_v(T)\cdot\lambda_w(T)$$

$$=(1-p)\cdot\rho_M(T,X)c_{pM}(T,X)\,\frac{\partial T}{\partial t}\quad(10)$$

Mass balance

$$(1-p)\cdot\rho_S\,\frac{\partial X}{\partial t}=-r_v(T)\quad(11)$$

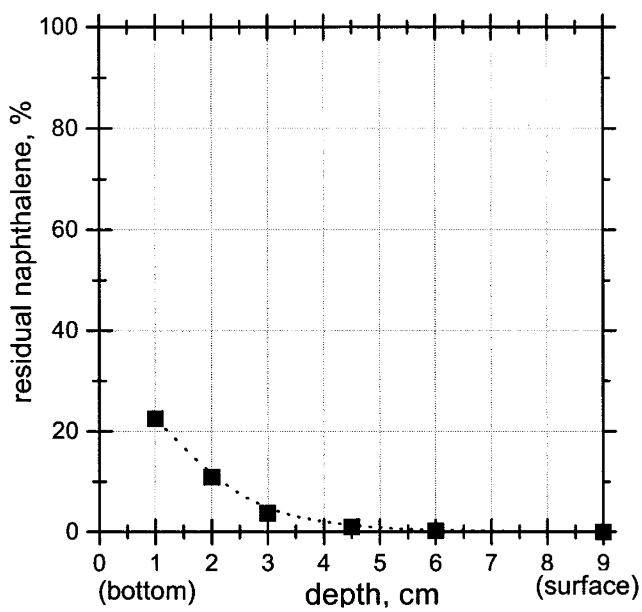


Figure 14. Decontamination measures performed via MISD process (testing results of the open applicator).

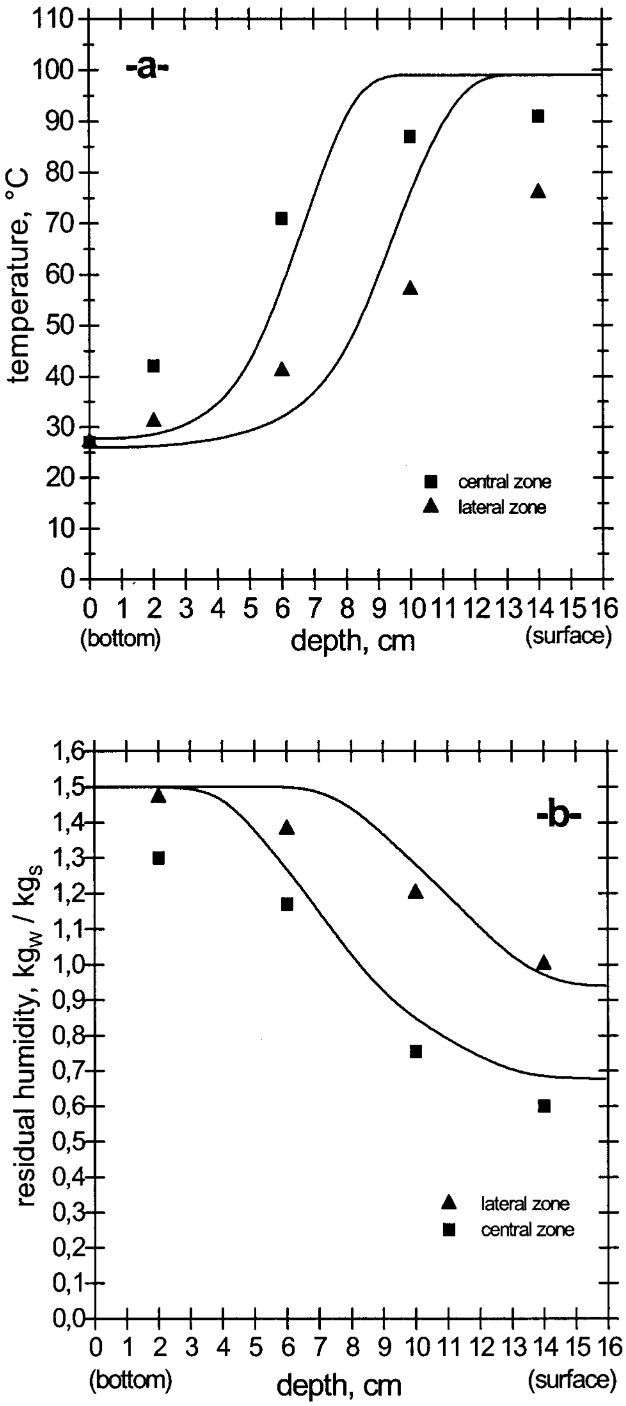


Figure 15. Model predictions of temperature (-a-) and residual humidity profiles (-b-) as a function of the depth of the experimental mean data determined in lateral and central areas (humidity is indicated on dry basis (db)).

Initial and boundary conditions

$$\text{I.C. @ } t = 0, \quad \forall\ z > 0, \quad T(0, z) = T_0 \tag{12}$$

$$\text{I.C. @ } t = 0, \quad \forall\ z > 0, \quad X(0, z) = X_0 \tag{13}$$

$$\text{B.C. 1 @ } z = 0, \quad \forall\ t > 0, \quad K_T \left.\frac{\partial T}{\partial z}\right|_{z=0} = -h_T[T(t, 0) - T_a] \tag{14}$$

$$\text{B.C. 2 @ } z = L, \quad \forall\ t > 0, \quad \left.\frac{\partial T}{\partial z}\right|_{z=L} = 0 \tag{15}$$

The energy generation term Q, given by Eq. 1, deals with the interlacing between dielectric properties, temperature, and water content of the treated systems. This is done in Eq. 10 using an exponential law to describe the electrical field intensity decay (considering microwaves as a plane electromagnetic waves incident on semi-infinite media). Moreover, the soil complex permittivity, which is considered in the Q expression, has been estimated by a relationship where the loss characteristics are a function of the soil water content and its availability to participate to the microwave energy dissipation process on the one hand, and of the temperature on the other hand. Finally, the r_v term in Eqs. 10 and 11 is the rate of vaporization, that is, the vapor flux that leaves the soil particles surface and goes into the steam/air phase. All these sub-models are described in details in the reference work (Acierno et al., 2003)

Predicted and experimental data of temperature and residual humidity, are compared in Figure 15. Modeled temperature profiles are reported as a function of depth and compared to experimental averaged data detected in lateral and central areas. Model curves are obtained using the electrical field intensity as an adjustable parameter. Its different values are used to describe the heating of the two concentric areas.

Conclusions

The design and the realization of an opened applicator useful to perform *in situ* MISD process for VOC's polluted soil remediation are presented. The electromagnetic behavior of the prototype is also described.

The prototype exercise, consisting in irradiation tests of wet and contaminated soil, confirms the heating-decontamination phenomenology already observed in closed cavity experiments. Then, the feasibility of microwave treatments to recover polluted soil in opened environmental conditions is proved. Moreover the MISD *in situ* procedure performed by nonintrusive equipments and at mild temperature can be seen as a low-impact emerging methodology for soil decontamination. Finally, prototype exercise has confirmed the skillfulness of the idea of a planar array of resonant slots in longitudinal waveguide as a practical solution to build up a microwave opened device.

The mathematical model previously developed with reference to the closed applicator exercise shows a good ability to describe the microwave heating phenomenology at opened environmental conditions.

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Notation

a = waveguide width, m
b = waveguide height, m
c_p = specific heat, J kg^{-1} K^{-1}
db = dry basis, see X;
D_p = penetration depth, m
g = slot equivalent conductance, S m^{-1} s^{-1} K^{-1}
h_T = slot width, m
h = convective heat transfer coefficient, J $m^{-2}s^{-1}$
K = binomial tapering factor
K_T = thermal conductivity , J
l = slot length, m
L = maximum depth, m
N = number of slots or equivalent conductances
p = summations index
p = porosity
P_{irr} = irradiated power, J $m\text{-}^3s^{-1}$
P_{in} = power supply, J $m\text{-}^3s^{-1}$
Q = power density, J $m\text{-}^3s^{-1}$
r_v = water evaporation rate, kg_W $m^{-3}s^{-1}$
t = time, s
T = temperature, K
Y_{10} = mode wave admittance, S
x = offset distance, m
X = moisture content, kg $_{H2O}$ $kg_{solid}{}^{-1}$
z = space coordinate, m

Greek letters

α = attenuation coefficient of the electromagnetic field, m^{-1}
β_{10} = mode wave propagating constant, m^{-1}
Γ = reflection coefficient, adim.
ε_0 = vacuum permittivity, F m^{-1}
ε' = dielectric constant
ε'' = loss factor
λ = latent heat of evaporation, J kg^{-1}
λ_0 = free space wavelength, m;
λ_g = wavelength in waveguide, m;
μ_0 = vacuum permeability, H m^{-1}
ρ = soil density, water density, kg m^{-3}
ω = angular frequency, s^{-1}

Subscripts and superscripts

W = water
M = soil-water mixing
S = dry soil

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