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Use of microwaves for in-situ removal of pollutant compounds from solid matrices

A.A. Barba [a,*], D. Acierno [b], M. d'Amore [a]

[a] Dipartimento di Scienze Farmaceutiche e Biomediche, Università degli Studi di Salerno, Via Ponte don Melillo, 84084 Fisciano (SA), Italy
[b] Dipartimento di Ingegneria dei Materiali e della Produzione, Università degli Studi di Napoli "Federico II", P.le Tecchio, 80, 80125 Napoli, Italy

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This work is dedicated to the memory of Dr. Pino Marucci.

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ABSTRACT

Thermal treatments are the most used methods to remediate contaminated solids. However, they may seriously damage the otherwise recoverable matrices, especially when mild operating conditions cannot be used. Microwaves recently raised as a powerful tool in industrial engineering for their ability, among other advantages, to offer a selected heating, thus allowing to treat and remove only the undesired components of a matrix. This work approaches the microwave assisted thermal treatments of waste from a physical–chemical point of view. Two recovering operations have been performed, respectively, on a soil contaminated by volatile organic compounds and on a ceramic filter spoiled by soot, using two specially designed prototypes, both realized on pre-pilot scale. The heat and mass transfer balances have then been analyzed in their more general form, and terms related to the use of microwaves outlined. Solutions of the differential equations have been applied to interpret the effects of microwaves on rate and efficiency of the remediation processes.

1. Introduction

The current way to treat wastes is their thermal disposal in special plants [1,2]. Expired drugs in pharmacy as well as hospital waste and contaminated food are destroyed by high temperature treatments in dedicated apparatuses, with afterburning of the exhaust to oxidize possible secondary compounds generated in the first step of the incineration process. Municipal wastes are incinerated, once the humid and the re-usable fractions are separated to increase their calorific value. Once again, an afterburner is required to clean up the exhaust. Thermal treatments are also frequently applied to remediate contaminated soils and groundwater.

Since several decades the potential use of microwave technology as an energy-efficient alternative to current heating technologies in waste-streams was investigated [3–5]. Microwave energy is an innovative tool for heating processes, although microwaves have been firstly adopted for communication purposes [6,7]. Reasons for the growing interest in their applications shown by both Academies and Industries can be found in the occurrence of benefits such as improved products uniformity and yields, reduction in manufacturing costs due to energy saving and shorter processing times (process intensification), unique microstructures and properties of the treated materials and synthesis of new materials that otherwise would be difficult to be produced. These advantages focused the attention on the use of electromagnetic energy in many applications, ranging from materials processing (foods, polymers (curing), wood, ceramics and composites), to mineral treatments and, finally, as reported above, to environmental remediation processes (soil remediation, toxic wastes inertization, and so on) [8–10]. Whether microwaves act in a thermal or a chemical way is still under discussion. As a matter of fact, very interesting results have been obtained, so as to extend their field of application even to drug production in pharmaceutics. Key of all processes above is the energy transfer. In conventional heating processes energy is transferred to materials by convection, conduction and radiation phenomena through the external body surfaces in presence of temperature gradients [11]. In contrast, microwave energy is delivered directly to the materials through interactions between the molecules and the electromagnetic field applied.

Examples of researches on microwave applications in environmental remediation are reported in [4,12–16]. In particular, in Remya and Lin [4] a review of current status of microwave application in wastewater treatment is presented; in Robinson et al. [12], Yuan et al. [13], Huang et al. [14], studies on remediation processes assisted by microwaves of soils contaminated with heavy- and light-hydrocarbons and with poly-halogenated-phenyl compounds, respectively, are discussed to emphasize feasibility and importance of in-situ microwave heating. In Abramovitch

* Corresponding author. Tel.: +39 089969240; fax: +39 089969206.
E-mail address: aabarba@unisa.it (A.A. Barba).

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et al. [15], preliminary studies on decontamination process of soils contaminated by toxic metal ions have shown the possibility to immobilize the latter by microwave irradiation, making them virtually unleachable. Finally, in Kulkarni and co-workers [16] a review on current remediation technologies, which included microwave heating, of dioxin polluted soil and sediment is discussed.

All applications above are linked together through the heating step performed by microwave irradiation. Physical and mathematical descriptions of the thermal processes of remediation can be trivial as the tools used are partial differential equations of heat and mass balances, whose terms are consolidated by prolonged and successful applications in engineering, chemistry and physics. Difficulties may arise when new terms have to be introduced into the equations due to other phenomena driving or triggering the processes. Chemical reactions with related heat release, or heat generation caused by electromagnetic fields may thus deeply modify the equations, dramatically changing the results. Therefore, the coupled balance equations of heat and mass transfer, and the electromagnetic field propagation equation have to be simultaneously solved to interpret phenomena occurring during microwave irradiation, in order to attain the final goal of designing and realizing microwaves apparatuses (applicators) able to perform the desired operations.

This work intends to show how microwaves can greatly modify the thermal remediation processes, helping in reducing times and improving efficiencies. The two “case studies” reported refer to both a purely physical process, i.e. the microwave remediation of a soil contaminated by VOCs (volatile organic compounds), and a process with chemical reaction, i.e. the microwave regeneration of a soot trap ceramic filter used to clean up the exhausts of industrial diesel engines. Both applications are currently at the pre-pilot phase of the scale-up process. Energy transfer by microwave irradiation is the actor of the processes, so as the complex permittivity of the irradiated materials is the key parameter governing the processes in their entirety.

The basic equations holding have been analyzed and solved. The heat and mass transfer equations are modified due to the presence of electromagnetic field induced energy dissipation. The modified equations are used to improve design and performance of microwave assisted remediation processes.

2. In-situ remediation thermal processes: Heat and mass transfer aspects

Logistics is one of the crucial points in remediation operations. Often, contaminated sites have large extensions, remarkable amounts of materials to be processed, significant operation costs. Sometimes, the way of working ex-situ can be adopted, transferring solids to chemical plants equipped for decontaminations. However, this implies a number of issues, including operational strategies, safety risks, personnel expertise and money. In some cases the in-situ option is strongly desired: in industrial remediation operations, the possibility of recovering a material without any plant stopping or dismounting gives a tremendous added value to a process.

Whenever a contaminant may be separated from a solid matrix, remediation may be performed, and the easier the separation, the larger the number of usable methods. Among them, thermal treatments have always been of great interest for the number of ways they can be applied and for the easiness of the applications. Possibility of local heat generation induced by an electromagnetic field definitely opened new perspectives. In particular, in-situ treatments are possible using electrical energy, radio frequencies, microwaves. As long as the irradiated material is susceptible of dissipating the ingoing energy flux, the heat may be generated inside and the decontamination may be really performed in-situ.

Starting from this premise, two processes (named case study 1 and case study 2) have been examined from the same point of view: to carry out in-situ remediation by microwaves thermal treatments using pilot-scale applicators, based on both results obtained on lab scale as well as the solutions coming from the mathematical models formulated.

Basically, three equations have been considered to describe mathematically a microwave induced thermal process: the equation of energy, the conservation of mass equation and the Maxwell equations accompanied by the materials' constitutive equations. For all of them, simplified forms have been used.

For each case under consideration, the more general equation of energy can be simplified to the one of temperature (T) variation, provided that the viscous term is negligible, the pressure derivative is zero and Fourier's equation holds. The equation then becomes:

$$\rho C_p \frac{D}{Dt} T = -K\nabla^2 T + \sum_i \Delta H_i r_i + \sum_j \dot{Q}_j \qquad (1)$$

where t is the time, ρ is the density, C_p is the specific heat, K is the thermal conductivity; $\sum_i \Delta H_i r_i$ and $\sum_j \dot{Q}_j$ are, respectively, the sums of the terms of heat generations due to phase change/chemical reaction (ΔH_i latent heat, r_i rate of state change/reaction) and heat supplied/removed due to external causes ($\dot{Q}_j$). The latter term can represent the energy dissipation induced by microwave radiation. In particular, starting from the Poynting complex vector, introducing the constitutive equations for isotropic temporally non-dispersive materials and the Maxwell equations, through the use of the Gauss/Green theorem of divergence, the energy dissipation can be calculated by [3,5]:

$$\dot{Q} = \frac{1}{2}\omega\varepsilon_0\varepsilon'' \left|\underline{E}\right|^2 \qquad (2)$$

where ω is the angular frequency ($\omega = 2\pi f$, f frequency), ε_0 is the vacuum permittivity, ε'' is imaginary part of the material permittivity (loss factor) and E is the electric strength. It is important to note that Eq. (2) quantifies the heat flux dissipated during the microwave irradiation, for given electric field and permittivity of the material.

Finally, for a binary system with constant density (ρ), if Fick's equation holds, the mass variation of the generic A component is:

$$\frac{\partial}{\partial t}\rho_A + \underline{v} \cdot \underline{\nabla}\rho_A = D_{AB}\nabla^2 \rho_A + r_A \qquad (3)$$

where D_{AB} is the diffusivity of the component A in a B phase, $\underline{v}$ is the velocity field and r_A the consumption rate of A.

3. Experimental

3.1. Materials and instruments

3.1.1. Case study 1

A commercial gardening soil is used as a porous soil model and naphthalene is selected as a model soil contaminant. Methanol is used both as a solvent for contaminant solution (naphthalene is insoluble in water) and as the liquid-phase extractor.

Dielectric properties of soil–water mixtures are measured by an HP 851907B vector network analyzer with dielectric probe meter HP 85070B.

A Soxhlet extractor system and an HP 5890 gas chromatograph are used to extract and to assay the contaminant, respectively.

3.1.2. Case study 2

Soot powder deposition on a trap filter is carried out at the exhaust of a gas-oil burner. A commercially available gas-oil is used; the soot generator apparatus is described in details elsewhere [17]. A ceramic foam with 92% in porosity is used as an inert trap filter for diesel soot (*DS*). The trap filter has a cylindrical shape (76 mm in diameter and 15 mm in thickness). So is the shape of the microwave applicator realized. Wool quartz, with a maximum allowable temperature of 2000 °C, is used to isolate the ceramic foam disk.

The IR thermography system (INFRAMETRICS SC 1000) with a temperature sensitivity of 0.07 °C and a scan rate of 50 Hz, is used to acquire the filter superficial temperature evolutions during the remediation process.

4. Case study 1: Soil decontamination from VOCs

4.1. Premise

A number of in-situ and ex-situ decontamination methodologies have been developed to remediate polluted soils, ranging from physical–chemical to thermal and biological processes. As outlined above, in-situ treatments are preferred since the remediation is applied in loco without auxiliary operations (soil excavation and conveyance).

In-situ physical–chemical treatments applied to separate a contaminant from a soil matrix initially mobilize the pollutants by means of a medium (water, air, steam, and so on) and then extract medium and contaminant out of the soil. For this technique, the soil matrix has to be permeable, and pollutants must have interactions with the used media. Even biological cleaning treatments are applicable to soils contaminated with degradable compounds, provided that complex pollutants can be transformed into harmless singular compounds by microorganisms' activity.

One of the drawbacks of these techniques is the final condition of the remediated soil after the process. Overheating, chemical solvents or any kind of strong treatments may bring to a clean but useless product, whose living part has been destroyed. This is the reason why mild operations are really welcomed.

Microwaves seem to be a wise solution to the problem, as they allow an in-situ recovery at low temperatures. The in-situ remediation of soils contaminated by volatile organic compounds is based on the use of microwaves as a heating source to induce a steam distillation process (MISD) [18]. The soil–water–VOC system, when irradiated with microwaves, dissipates the energy associated to radiation, giving place to a temperature rise based on the system dielectric properties. The temperature profile follows the exponential decay of the electromagnetic field, whose penetration depth is defined as the distance where the field intensity decreases to $1/e$ of its initial value. The first layers of soil thus show a significant temperature rise, with a consequent loss of water in the form of vapor. Since the dielectric properties of the soil matrix in each layer change with the physical changes of the soil's chemical characteristics, due to the progress of microwaves treatment, the superior soil layers, now dried, become transparent to microwaves so that the electromagnetic field moves deeper inside in a sort of boundary moving process. At this point, the process is reproduced. The endogenously generated vapor has the same efficiency as vapor added to extract the organic compounds. The soil temperature is kept at reasonably low values by the vaporizing water itself that, thus, plays a double role (extraction phase, thermal stabilizer).

4.2. The MISD process

The remediation process has been approached in several steps:

(i) experimental campaign on bench scale to individuate the key parameters;
(ii) design and realization of an opened microwave applicator on pre-pilot size to perform the in-situ operations;
(iii) modeling to define the process mathematically.

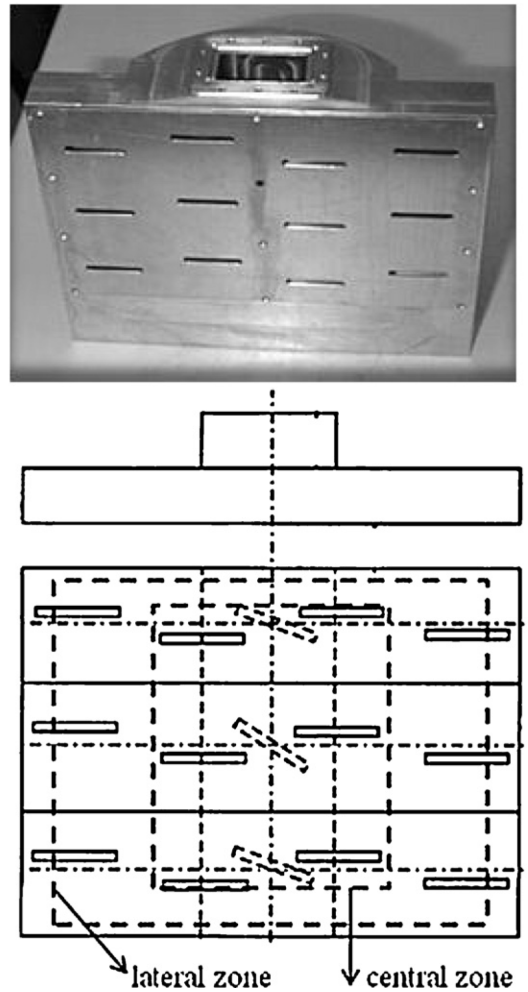

Fig. 1. The opened applicator: slots side particular (on the top); and slots configuration and the different heating zones (central and lateral) indications (on the bottom).

The first step was performed by irradiating small soil cores (12 cm deep cylinders with a diameter of 10 cm) in a multimodal closed applicator. Methods and results in terms of temperature and humidity profiles along the depth coordinate can be found in detail elsewhere [18].

4.2.1. The opened applicator

A microwave opened applicator has been designed and constructed on pre-pilot scale to apply the MISD process, having in mind a number of practical criteria, i.e. the apparatus must:

- be transportable to allow the in-situ operation desired;
- have a good trade-off between the extension of the irradiated surface and the incident microwave power density, to reduce the number of operating cycles;
- be able to minimize the power radiated in undesired directions for safety reasons;
- have good power handling and fault tolerance.

The specified requirements are satisfied by designing an equipment consisting in a planar array of waveguide longitudinal resonant slots [19], that are rectangular openings on the lateral waveguide's wall powered by an electromagnetic field propagating in the waveguide itself (Fig. 1). The rectangular openings can be classified as either resonant or coupling slots, being the former devoted to the waves distribution out of the applicator, the lat-

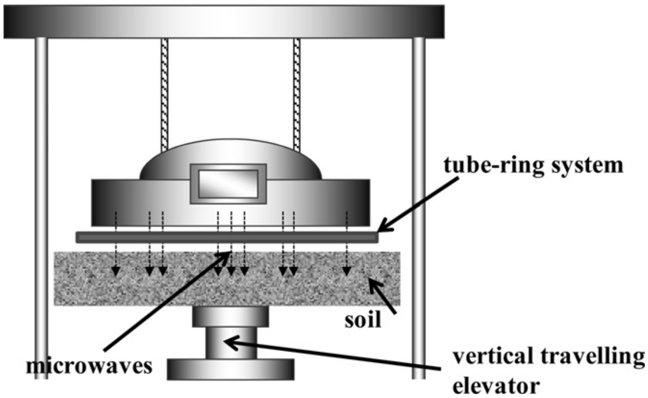

Fig. 2. Sketch of the opened applicator/soil surface configuration.

ter charged of transferring the waves from the magnetron to the resonating slots through the launch guide. To minimize the power radiated in undesired directions, the central radiating slots transmit the highest delivered power density, so that the central area of the soil matrix is more heated. The applicator prototype works at 2.45 GHz and at 1900 W of maximum power, and has been built in aluminum for a number of reasons. Aluminum has a good electrical conductivity, it is chemically inert and its surface machined appears smooth and cleanable. Finally, aluminum has a low specific gravity, that greatly helps in making the applicator a portable equipment. More details of the realized prototype are reported elsewhere [20].

Irradiating runs are performed suspending the applicator with the radiating slots placed close above the soil surface. The soil is placed in a wood container of 1 m^2 area, filled to a maximum depth of 16 cm. The system is sketched in Fig. 2.

Selected parameters of the thermal treatment are time of exposure, applicator/soil configuration, supplied power and initial water content of the soil. An ancillary equipment has also been built to recover the vapor fluxes produced during the soil decontamination treatments. The system is realized by a tube-ring connected to two suction pumps. Generated streams are forced into absorbent traps. In this way, possible phenomena of vapor condensation under the cool radiating plate are discouraged. After each irradiating run, temperature, residual humidity, contaminant concentration data are collected.

Experiments performed with the developed prototype confirm the hypothesized feasibility of recovering polluted soils in open environmental conditions by microwave treatments. Figs. 3 and 4 show temperature and humidity profiles as a function of depth measured in the central and lateral areas of the irradiated soil. Solid and dashed lines represent the model curves, that satisfyingly agree with the collected data. Fig. 5 reports the remediation profiles obtained using the opened applicator in the soil contaminated with naphthalene. The applicator was kept at a 2 cm distance from the soil surface. The soil had an initial humidity of 1.86 (kg_{H_2O})/(kg dry solid) whereas the initial naphthalene concentration was 2000 ppm. The microwaves generator used (magnetron) had a maximum power of 1.90 kW; 30 min of operation were enough to obtain an excellent removal of the contaminant, as shown in Fig. 5. It has to be noted that the performed decontamination using conventional methods (such as stripping by forced water vapor) takes much longer times confirming the efficacy of microwave soil remediation.

Finally, the planar array of resonant slots in longitudinal waveguide appears to be the proper design choice for in-situ interventions in open environment, offering interesting perspectives in the field of remediation operations.

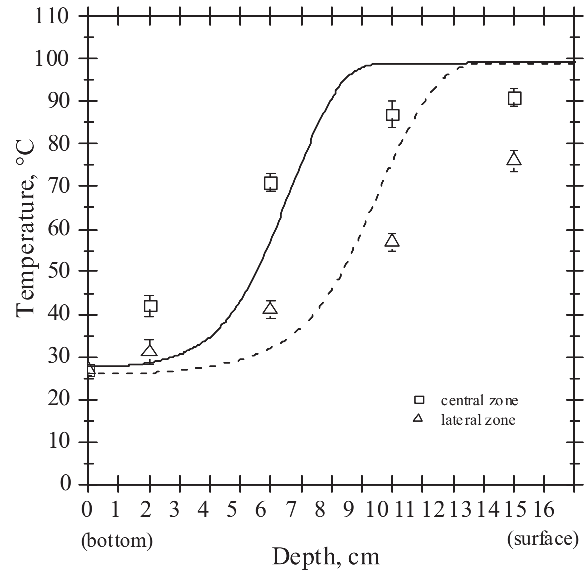

Fig. 3. Temperature profiles as a function of depth: experimental (symbols); and model curves (lines).

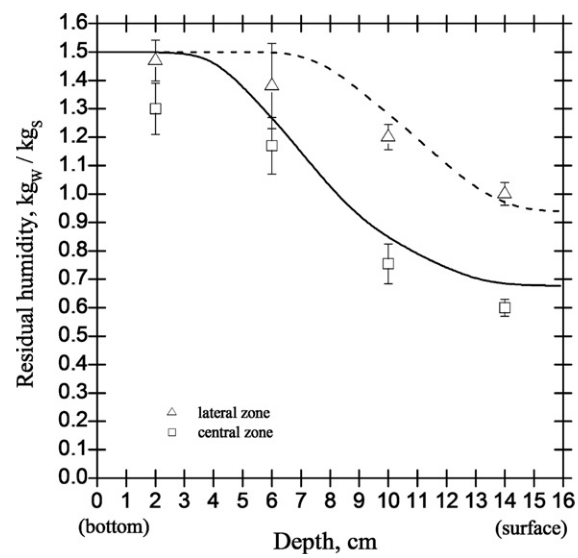

Fig. 4. Residual moisture profiles as a function of depth: experimental (symbols); and model curves (lines).

4.2.2. Modeling

Attention was then focused on the mass- and heat-transfer phenomena occurring through the soil undergoing the treatment, as the remediation is associated to both vapor and VOCs leaving the wet soil. The basic statements for modeling the transport phenomena in the soil were formulated [10,11]. The latter are subordinated to the loss properties of the irradiated matter. The MISD process has thus been modeled with coupled mono-dimensional transient equations of energy and mass balances; the generation term takes into account the interaction between electromagnetic field and matter and the electromagnetic relationships are related to plane waves propagation.

Evolutions with time and depth of temperature and humidity of heterogeneous full/empty system (full = liquid water + soil; empty = air + water vapor) were modeled by numerically solving the appropriate balance equations (temperature and moisture in the liquid phase). Focusing on the solid phase (which then occupies

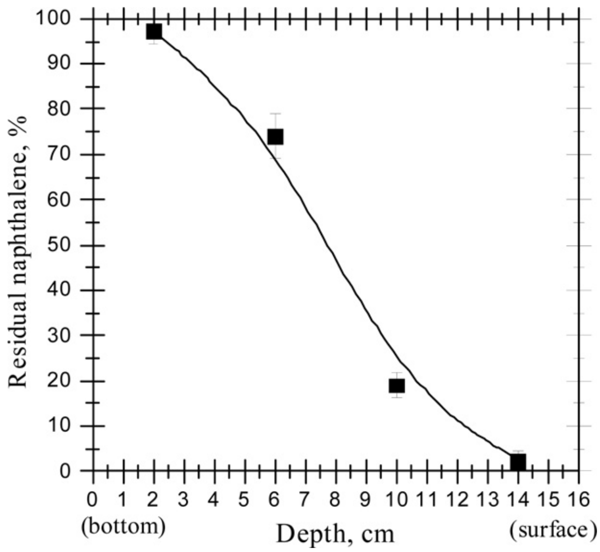

Fig. 5. Residual contaminant profile (mean data assayed in overall zones) as a function of depth (soil initial humidity: 1.86 on dry basis; initial naphthalene concentration 2000 ppm; microwaves power 1.90 kW; and time of exposure 30 min).

only a fraction of the sample volume), the following approximations have been made:

1. no motion in the solid phase, $\underline{v} = \underline{0}$;
2. the functions of interest (residual moisture, X, and temperature, T, profiles) only depend on time (t) and depth (z), i.e. $T = T(t, z)$ and $X = X(t, z)$;
3. liquid water does not diffuse in the solid matrix, $D_{AB} = 0$;
4. the following physical characteristics of the materials are considered constant: density (ρ), specific heat (C_p) and thermal conductivity (K) of the solid, latent heat of evaporation (ΔH_X) of the water.

With the approximations above, the variation equation of temperature becomes:

$$\rho C_p \frac{\partial}{\partial t} T = -K \frac{\partial^2}{\partial z^2} T + \Delta H_X r_X + \dot{Q} \tag{4}$$

whereas the variation equation of mass fraction of water in the solid becomes:

$$\frac{\partial}{\partial t} X = -r_X \tag{5}$$

The partial differential equations (4) and (5) are accompanied by the appropriate initial and boundary conditions:

$$\text{Initial conditions} \quad @t = 0, \forall z \quad T(0, z) = T_0, X(0, z) = X_0 \tag{6}$$

$$\text{Boundary conditions} \quad @z = 0, \forall t - K \frac{\partial T}{\partial z} = h \left(T\big|_{z=0} - T_\infty \right) \tag{7}$$

$$\text{Boundary conditions} \quad @z = L, \forall t \frac{\partial T}{\partial z} = 0 \tag{8}$$

The energy dissipation due to microwaves is taken into account in the term $\dot{Q}$ of Eq. (2). The electric field strength is described, in particular, with the Eq. (9), where it is calculated assuming that microwaves propagate as a plane wave partially absorbed by the material according to the law of Lambert and Beer (being λ the wavelength and E_0 the intensity of the incident field, optimization parameter):

$$E = E_0 \ \exp\left[-\left(\frac{2\pi}{\lambda} \frac{\varepsilon''}{\sqrt{\varepsilon'}} \right) z \right] \tag{9}$$

In this equation, the terms preceding z describe the penetration depth, D_p, (systems having $\varepsilon' \gg \varepsilon''$), that can thus be defined as follows:

$$D_p = \frac{\lambda}{2\pi} \frac{\sqrt{\varepsilon'}}{\varepsilon''} \tag{10}$$

The complex dielectric constant ε was instead evaluated by a constitutive model proposed and validated through a dedicated experimental work, that formulated a dependence of ε on temperature and humidity $\varepsilon = \varepsilon(T, X)$.

Experimental data obtained during the microwave irradiation tests, and comparisons with the model results are reported in Figs. 3 and 4 in terms of soil temperature and humidity profiles along the depth. A satisfying agreement with the model results is shown.

The mathematical model allows to predict the way temperature and humidity content profiles in a microwave irradiate soil evolve. As both temperature and humidity content are crucial in determining the fate of the contaminants present in the soil under treatment, the model simulations make the organization of in-situ remediation campaigns possible for contaminated sites.

5. Case study 2: Soot removal from a ceramic filter

5.1. Premise

One of the most important issues in the removal of pollutants from the exhaust of chemical industries is to trap the carbon particulate coming out from diesel engines, whatever the scale of the latter (industrial fixed installations or motor vehicles). Once again, thermal treatments have to be used to burn the carbon particulate that engines emit, provided that the soot is trapped.

Presently, ceramic monolith is generally accepted as the most practicable choice for a trap filter. However, the easiness of operation is counterbalanced by the progressive blocking of the monolith due to the increasing soot load. As a consequence, the total backpressure raises penalising the engine's performance and obliging a periodic cleaning of the filter. Howbeit, self-regeneration is not possible because of the high ignition temperature of diesel soot, typically in the range 500–650 °C, to be compared to the temperature of the exhaust, generally lower than 400 °C.

At a first sight, this would imply to dismount the plant and to submit the filter to an external thermal treatment. One of the possible methods is thermal incineration by fuel burners or electrical heaters to bring the collected soot up to the ignition temperature. However, the high temperatures required for soot combustion and the non-uniform heating of the filter can lead to the filter breakage or melting.

The way hereafter proposed is to use microwave irradiation as an effective mean of particulate trap regeneration inducing a microwave assisted combustion (MAC) of the trapped soot particles. In this way two goals are obtained: (i) instantaneous penetration of microwaves into the filter and their selective absorption makes soot burn whereas the ceramic filter remains undisturbed; and (ii) the regeneration treatment can be performed in situ, without dismounting the filter, as microwaves can be easily supplied by a wave guide.

In the following a single-mode microwave applicator is used to perform MAC on the cylindrical ceramic trap filters currently utilized in the treatments of the exhaust from industrial diesel engines.

5.2. The MAC process

As above outlined, purpose of the microwave in-situ operation is to induce the soot oxidation without thermally stressing the

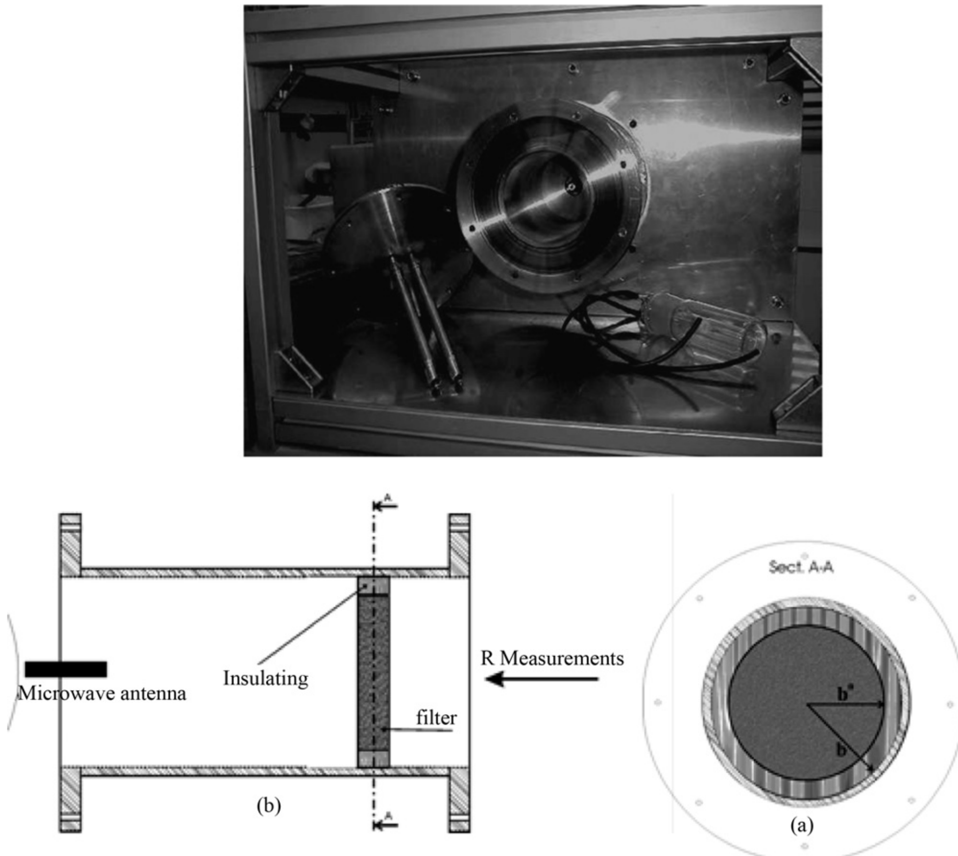

Fig. 6. Single-mode prototype applicator: photo and applicator/ceramic filter configuration.

ceramic matrix. This is obtained taking advantage of the different dielectric properties of carbon and ceramics. As a matter of fact, carbon alone dissipates the energy supplied by microwaves, thus locally reaching the combustion temperature. The relatively fast soot oxidation and the low thermal conductivity of ceramics keep the filter matrix cool and allow the in-situ regeneration.

5.2.1. The single-mode applicator

A specially designed monomode (or single mode) microwave cylindrical cavity is used as an applicator for the regeneration process. Monomode cavities are characterized by having only one excited mode, so that the spatial distribution of the electromagnetic field can be fully predicted. The design of the applicator has been developed to obtain a selected propagation mode, namely TM_{010}, in a cavity whose section is circular in shape. Having chosen 200 mm as the applicator length for steric reasons, the internal radius has to be 46.8 mm to obtain the desired propagation mode (Fig. 6). The microwave source is a magnetron operating at 2.45 GHz in frequency and 900 W in power. The applicator is built-up in stainless steel for its good electrical conductivity, chemical inertness and, finally, smoothness and cleanability of the machined surface. Leakage and safety controls have been also checked and accomplished.

In Figs. 7 and 8 the temperature profiles measured by the IR thermo-camera during the filter regeneration process are reported, as well as the photos of the ceramic trap filter at different stages of regeneration, respectively. As experimental results show, the in-situ microwave assisted combustion of soot deposited in the ceramic foam is a feasible process. Filter regeneration can be quickly performed without dismounting the filter from the plant, thus reducing the need of maintenance operations.

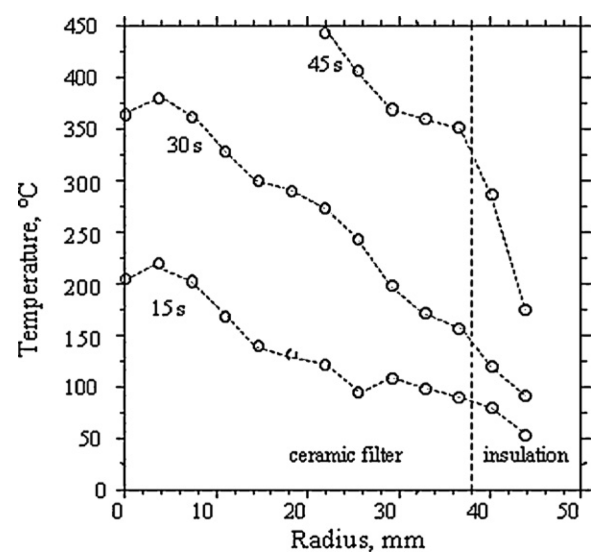

Fig. 7. IR temperature profiles as a function of radius measured during the regeneration filter process.

5.2.2. Modeling

The evolutions with time and along the radius (r) of temperature (T) and residual concentration of carbon black (C_{DS}) have been modeled by numerical integration of the appropriate balance equations (temperature and concentration of carbon black in the solid phase) [21,22]. Focusing on solid phase (which actually occupies only a fraction of the sample volume), the following approximations have been adopted:

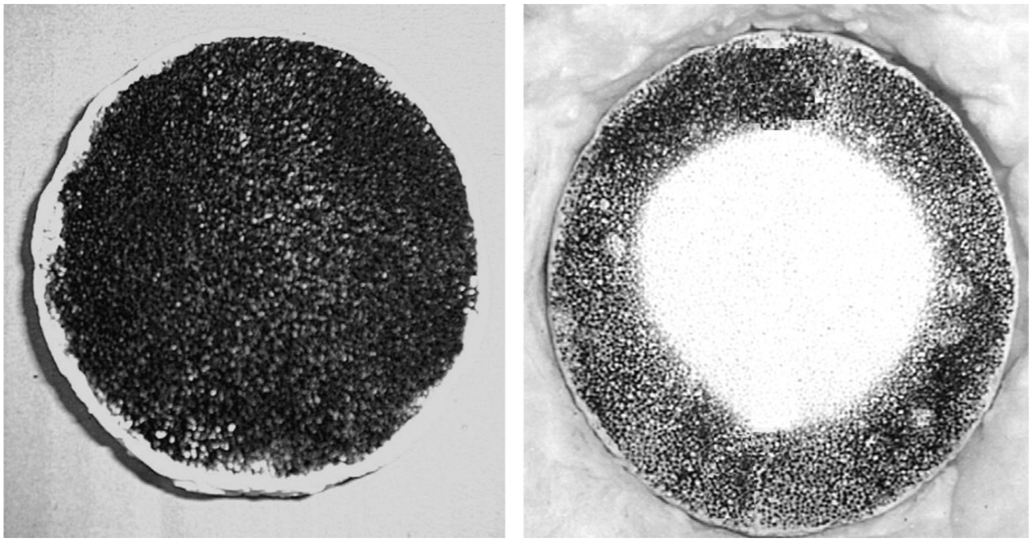

Fig. 8. Photos of ceramic filter before and after a partial regeneration.

1. there is no motion in the solid phase, $\underline{v} = \underline{0}$;
2. the objective functions only depend on time (t) and radius (r), i.e. $T = T(t, r)$ and $C_{DS} = C_{DS}(t, r)$;
3. carbon black does not diffuse in the solid, $D_{AB} = 0$;
4. the electromagnetic waves propagate in the applicator as if it were empty, i.e. that solids inside the applicator do not significantly disturb the electromagnetic field;
5. the material functions are "almost" constant: density (ρ), specific heat (C_p) and thermal conductivity (K) of the solid (with porosity p), heat of oxidation of carbon black (ΔH).

By assumptions above, the variation equation of temperature becomes:

$$(1-p)\rho C_p \frac{\partial T(t,r)}{\partial t} = -(1-p)K\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T(t,r)}{\partial r}\right)\right) + \dot{Q}_g + \Delta H \times r_C \quad (11)$$

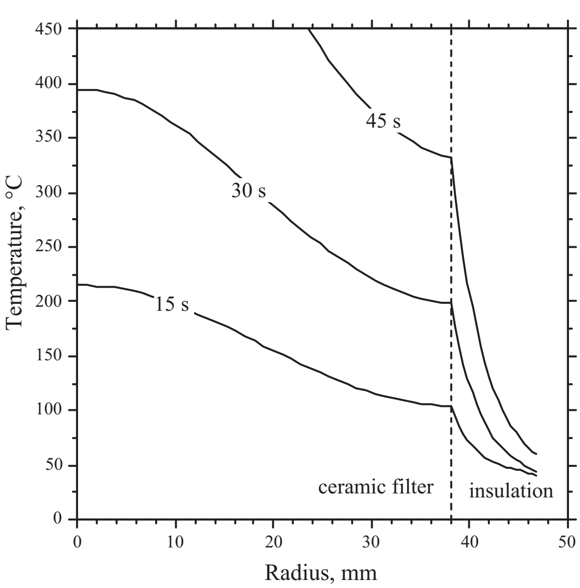

Fig. 9. Simulated temperature profiles as a function of radius during the filter regeneration process.

where the energy dissipation due to microwaves is taken into account in the term $\dot{Q}_g$, while the variation equation of the mass fraction of carbon black in the solid is taken into account in the oxidation rate of the diesel soot (r_c):

$$\frac{\partial}{\partial t}C_{DS} = -r_C = -K_C(T)P_{O_2} = -K_{C0}\exp\left(-\frac{E_{att}}{RT}\right)P_{O_2} \quad (12)$$

where K_C is the kinetic constant (expressed by the Arrhenius' law) and P_{O_2} is the oxygen partial pressure.

The partial differential equations (11) and (12) are accompanied by the appropriate initial and boundary conditions:

$$\text{Initial conditions} \quad @t = 0, \forall r \quad T(0,r) = T_0, C_{DS}(0,r) = C_{DS0} \quad (13)$$

$$\text{Boundary conditions} \quad @r = 0, \forall t \quad \frac{\partial T}{\partial r} = 0 \quad (14)$$

$$\text{Boundary conditions} \quad @r = R_{overall}, \forall t \quad -K\frac{\partial T}{\partial r} = U\left(T\big|_{r=R} - T_\infty\right) \quad (15)$$

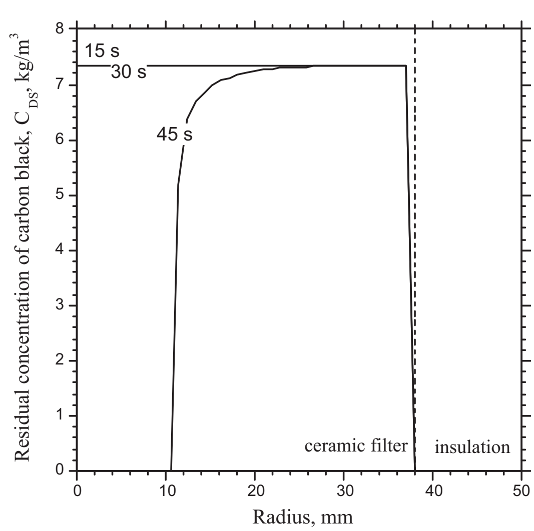

Fig. 10. Simulated residual soot concentration profiles as a function of radius during the filter regeneration process.

where $R_{overall}$ is the radius of the filter including the insulation layer (R_f is the ceramic filter radius); U is the overall thermal coefficient and T_∞ is the bulk temperature referred to the environmental value.

The energy dissipation due to microwaves is taken into account in the term $\dot{Q}$, described in particular with Eq. (2), where the electric field was obtained from the solution of Maxwell's equations assuming a single mode of propagation (TM_{010}) [5]. In the following Figs. 9 and 10, simulated temperature and residual soot concentration profiles are reported. Model results well describe the experimental thermal profile measured (Fig. 7) and the filter regeneration progress worked out by image analysis (Fig. 8).

Using the mathematical model above, it is possible to predict the development of combustion stages and the performance of the remediation process, and consequently to plan the maintenance operations.

6. Conclusions

The mathematical approach presented in the work is able to describe very different microwaves assisted remediation processes, thus becoming a useful potential planning tool.

The methodologies developed to perform remediation processes are non-intrusive and allow to carry out operations at mild conditions.

Soil decontamination obtained exercising the realized prototype for the MISD process confirms the selection of a planar array of resonant slots in longitudinal waveguide as a practical solution for a microwave opened device, whereas MAC operations with the single-mode applicator prove the hypothesized feasibility of an in-situ microwave regeneration of soot trap ceramic filters.

All the above supports the microwaves heating technology as a low-impact emerging methodology.

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