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Heat Transfer Modeling in Soil Microwave Heating

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The agricultural neediness of cost-effective, environmental friendly and chemical-free methods for farmlands disinfection led to the development of microwave-based solutions, an efficient way of directly conveying energy to the target. Harmful agents such as weeds pests, fungi and bacteria can be suppressed heating the contaminated soil up to pasteurization or sterilization temperatures by irradiating electromagnetic energy by an antenna. The treatment can be carefully devised and designed optimizing the temperature distribution and calibrating the exposure time depending on the soil characteristics, and on the environmental and boundary conditions. In this work a computational model to solve the non-linear multi-physic dielectric heating phenomenon is presented, so taking into account the temperature dependence of the dielectric and thermal soil properties, in order to demonstrate the possibility of properly tuning the microwave application depending on the external heat transfer conditions. It was found that, in the specific conditions here analyzed, an increase of the external convection heat transfer coefficient up to 50 $W \cdot m^{-2} \cdot K^{-1}$, despite being a possible critic condition for the surface, brings to the possibility of treating a soil layer of higher thickness, up to 20 cm. On the other hand, doubling the microwave power from 12 to 24 $kW \cdot m^{-2}$ generally reduces the treatment time to less than half, with overall energy savings.

1. Introduction

The need, in the agricultural practice, of cost-effective, eco-friendly and chemical-free non-polluting methods of soil disinfection is a relevant contemporary issue (Hansen et al., 2011). The infected agricultural productions demand for techniques capable of achieve the almost complete elimination of insects, soilborne pathogens and weeds without employing noxious agents such as pesticides (Oliver and Gregory, 2015), or avoiding invasive procedures like fumigation (Grey and Webster, 2015).

This is why the so-called thermal quarantine methods, pasteurization techniques or, more in general, heat treatments (HT) have been investigated as an alternative and more suitable non-chemical methods to reduce the populations of undesired agents in the soil (Hansens et al., 2011). HT for agricultural lands share with them the aim of rising the soil temperature over a lethal threshold value for a sufficiently long time to cause the denaturation of the cellular proteins, irreversible damages and metabolic disturbance, thus causing the thermal death, as well as long-term lethal effect and chronic mortality of the targeted biological enemies (Nelson, 1996).

A very popular, well known, cost-efficient and eco-friendly thermal quarantine method is solarization (Vitale et al., 2011). Anyway, to be effective, i.e. to reach lethal conditions, considering the low reachable temperatures of about 311-321 K, it requires days or weeks of treatment, e.g. about 9-25 d (Vitale et al., 2011).

A more controllable and faster way to perform the soil disinfection is to use electromagnetic (EM) energy in the microwave (MW) frequency range (1-8 GHz) to irradiate and heat the soil (Nelson, 1996). In fact, as previously stated by Komarova et al. (2008), even higher temperatures can be reached in the soil, e.g. 353 K or 363 K, but in about 5-10 min. Therefore, by carefully designing the irradiation system and procedure, these temperature values can be kept for 20 min or more, also after irradiation stopping, and hence killing the target pathogens.

The physical phenomena can be easily described considering that MW energy increases the rotational energy of water molecules, whose electric dipolar moment has an angular frequency equal to that of MW (Desogus et al., 2016a). This selective energy transfer leads the water molecules to dissipate heat as a consequence of the induced rotation. Hence, since agricultural soils are humid, the temperature of the irradiated layer increases and

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heat is also conducted to the layers below, so involving microorganisms or other biological agents inside (Brodie et al., 2016). The soil is a dielectric heterogeneous medium (Behari 2005), and its properties and hence the energy absorption and the heating rate depend on the water amount and on its distribution, but in turn the water dielectric properties are a function of the temperature and of the frequency of the applied EM field (Fanti et al., 2017). Thus, in order to devise a proper thermal treatment strategy, since the temperature distribution varies in the space and with time, the EM set of equations must be solved coupled to the heat and transfer equations (Zhang et al., 2001). Furthermore, also the thermal properties of soil, which is a mixture of air, sand, clay and pit, depend on the local temperature (JAHM, 2018), and this aspect of the problem is included and analyzed in this work too. Hence, in this paper a finite difference time domain (FDTD) approach to simulate the microwave heating treatment is presented, like proposed by Fanti and Mazzarella (2010a). Non-linear soil dielectric and thermal properties were explicitly taken into account, and close attention was paid to the heat transfer modeling in the wet soil for different external convection conditions, in order to show how the MW application can be properly adapted depending on the real and time changing boundary conditions.

2. Electromagnetic model: heat dissipation in the soil

2.1 Microwave propagation

To model the EM exposure system and the MW heating phenomenon, the MW field is supposed to be an impinging plane wave with a power superficial density S_0 and with a frequency (*f*), of 2.45 GHz. Assuming an infinite treated surface, both the EM and the thermal problems can be considered as mono-dimensional. In the case of a MW field propagating into a dielectric medium, the transmission line method can be uses to find the electric and magnetic field as a function of the depth (Fanti et al. 2017). In this way, the EM equations reduce to the so-called “telegrapher’s equations” in the frequency domain, which can be written as (Desogus and Carta, 2019):

$$\begin{cases} \frac{d}{dz}E(z)=-j\omega\mu_0 H(z) \\ \frac{d}{dz}H(z)=-j\omega\varepsilon_s E(z) \end{cases} \tag{1}$$

where z is the vertical axis in m, E indicates the electric field in $V\cdot m^{-1}$, H the magnetic field in $A\cdot m^{-1}$, ω the angular frequency in s^{-1}, i.e. $2\pi f$, μ_0 is the vacuum magnetic permeability, i.e. $4\pi\times10^{-7}$ $H\cdot m^{-1}$, and ε_s is the soil relative complex dielectric permittivity in $F\cdot m^{-1}$.

In this work, to solve Eq(1), the FDTD resolution scheme by Fanti and Mazzarella (2010b) was employed, with a step Δz equal to 0.1 mm and a time interval Δt equal to 1 s. In Eq(1), ε_s is a function of both position and temperature T (in K) which is in turn a function of position, i.e. $\varepsilon_s=\varepsilon_s[z,T(z)]$. The use of the total derivative, instead of the partial one, is justified by the assumption that the dielectric soil properties variations during the heating need a time interval which is much longer than the MW oscillation period by orders of magnitude.

The propagation of an EM plane wave in the medium (here the soil) progressively develops up to a depth value indicated with z_∞, beyond which the system is not affected by the irradiation above. Therefore, to solve Eq(1), z_∞ was set to 0.6 m, in fact the thermal treatment is addressed to the top layer of soil (5-10 to 20 cm from the surface), and the chosen z_∞ value allows to properly take into account the downward heat transfer.

2.2 Soil dielectric properties

As previously discussed, the soil can be considered as a porous material and a mixture of mainly air, water, fragmented or eroded minerals, decomposing organic matter (Desogus et al., 2016b). The soil properties are generally affected by its texture, which allows to evaluate the hydrogeological field capacity, from which the volumetric amount of water and moisture can be derived (Behari, 2005). Water is entrapped in the soil pores in different states (free or bound liquid, or vapor), depending on the soil composition. In fact, for example, a sandy soil (0-15 % of humidity) would typically retain less water than a clayey one (25-40 % of humidity). Therefore, the field capacity linearly increases with the clay fractional content (C) in the soil texture, whereas it decreases as a function of the sand fractional amount (Sd) (Desogus et al., 2016b). Relying on these considerations, the complex dielectric permittivity of the soil solid components (ε_{sol}) can be estimated, in its real and imaginary components, by using the empirical model developed by Hallikainen et al. (1985) and applied by Spanu et al. (2016), as a function of sand and clay fractions, as well as of the frequency of the applied field. To take into account the air and water contribution, a volume weighted mixing formula (Sihvola, 1999) can be used, so obtaining that:

$$\varepsilon_s[z,T(z),\omega,C,Sd,St]=x_{sol}\cdot\varepsilon_{sol}(\omega,C,Sd,St)+x_a\cdot\varepsilon_a+x_w\cdot\varepsilon_w[T(z),\omega] \tag{2}$$

in which x_{sol}, x_a and x_w are, respectively, the volume fractions of solids, air and water in the soil (being the sum of x_a and x_w equal to the total porosity), *St* is the fractional content of silt, ε_a and ε_w are the dielectric permittivity of air and water in F·m^{-1}. The value of the air dielectric permittivity can be well approximated by the vacuum one, which is ε_0=8.85·10^{-12} F m^{-1}; instead, for the water permittivity, which is temperature and frequency dependent, the model proposed by Ray (1972) was used.

3. Microwave heating and heat transfer modelling

The temperature distribution in the soil can be computed by solving the heat balance equation (Zhang et al., 2001) written in the following form (Acierno et al., 2003):

$$\rho_s Cp_s \frac{\partial T(z,T)}{\partial t} = k_s \frac{\partial^2 T(z,T)}{\partial z^2} + P_{EM} \tag{3}$$

where ρ_s, Cp_s and k_s are, respectively, the soil density in kg·m^{-3}, specific heat at constant pressure in J·kg^{-1}·K^{-1} and thermal conductivity in J·m^{-1}·K^{-1}, t is time in s, and P_{EM} is the dissipated power per volume unit in W·m^{-3} (i.e. the generated thermal power per volume unit in the soil). Of course, all the cited thermophysical quantities depend on the water amount, and so on the specific kind and conditions of the considered soil (Fanti et al., 2017), and on the temperature, therefore, change with the soil depth. In the literature, a temperature dependence for Cp_s and k_s is reported (JAHM, 2018) for the soil here considered (*Sd*=0.30, *St*=0.50, *C*=0.20, porosity of 70 %, x_w=0.10), consisting in the following relationships:

$$Cp_s = 2.320 + 0.019 \cdot T \tag{4}$$

$$k_s = 0.0747 + 1.451 \cdot 10^{-4} \cdot T \tag{5}$$

The dissipated power P_{EM} is dependant on the electric field intensity and it can be calculated by the following expression (Brodie et al., 2016):

$$P_{EM} = \frac{1}{2} \sigma_s |E(z)|^2 \tag{6}$$

where σ_s is the soil electric conductivity in S·m^{-1}, which can be calculated as follows (Franceschetti, 1983):

$$\sigma_s = 2\pi f \varepsilon_0 \varepsilon_s'' \tag{7}$$

Eq(3), to be solved, needs proper boundary conditions. For z=0, the soil surface is in contact with the atmosphere and so cooled due to the air convection, that is:

$$k_s(0,t) \frac{\partial T(0,t)}{\partial z} = h_c [T(0,t) - T_e] \tag{8}$$

where h_c is the convection heat transfer coefficient in J·m^{-2}·K^{-1} and T_e (here equal to 20 °C) indicates the external air temperature. On the other hand, for z_∞, it can be assumed that no heat transfer occurs, that is:

$$\frac{\partial T(z_\infty,t)}{\partial z} = 0 \tag{9}$$

As the starting solution, for t=0, it can be assumed that the temperature distribution in the soil is uniform and equal to the external one:

$$T(z,0) = T_e \tag{10}$$

4. Results and discussion

On the basis of the model above, a proper script was built and solved by Matlab software. The computation algorithm consisted in an iterative procedure, at each step of which the frequency domain solution of the EM problem and the time domain solution of the heat transfer problem were performed in sequence, until the maximum local temperature (here 85 °C) had been reached in at least one point of the space domain. The maximum temperature had its reason in the need of prevent overheating in the soil, and the time of reaching should be thought as the time at which the MW application device is stopped and heat is generated no more, but only transferred.

Different simulations were performed, varying the power superficial density (S_0) and the external convection heat transfer coefficient (h_c) values, to obtain the time evolution of the thermal distribution in the soil in the different cases and compare them. For the sake of brevity, in this paper, six solutions are shown in Figure 1, which were obtained at two levels of S_0 (12 and 24 kW·m^{-2}) and for three values of h_c (2, 10 and 50 W·m^{-2}·K^{-1}), and can be considered representative of the entire set of solutions, in order to give an idea on how the model is able to take into account for different conditions that could arise in a real application.

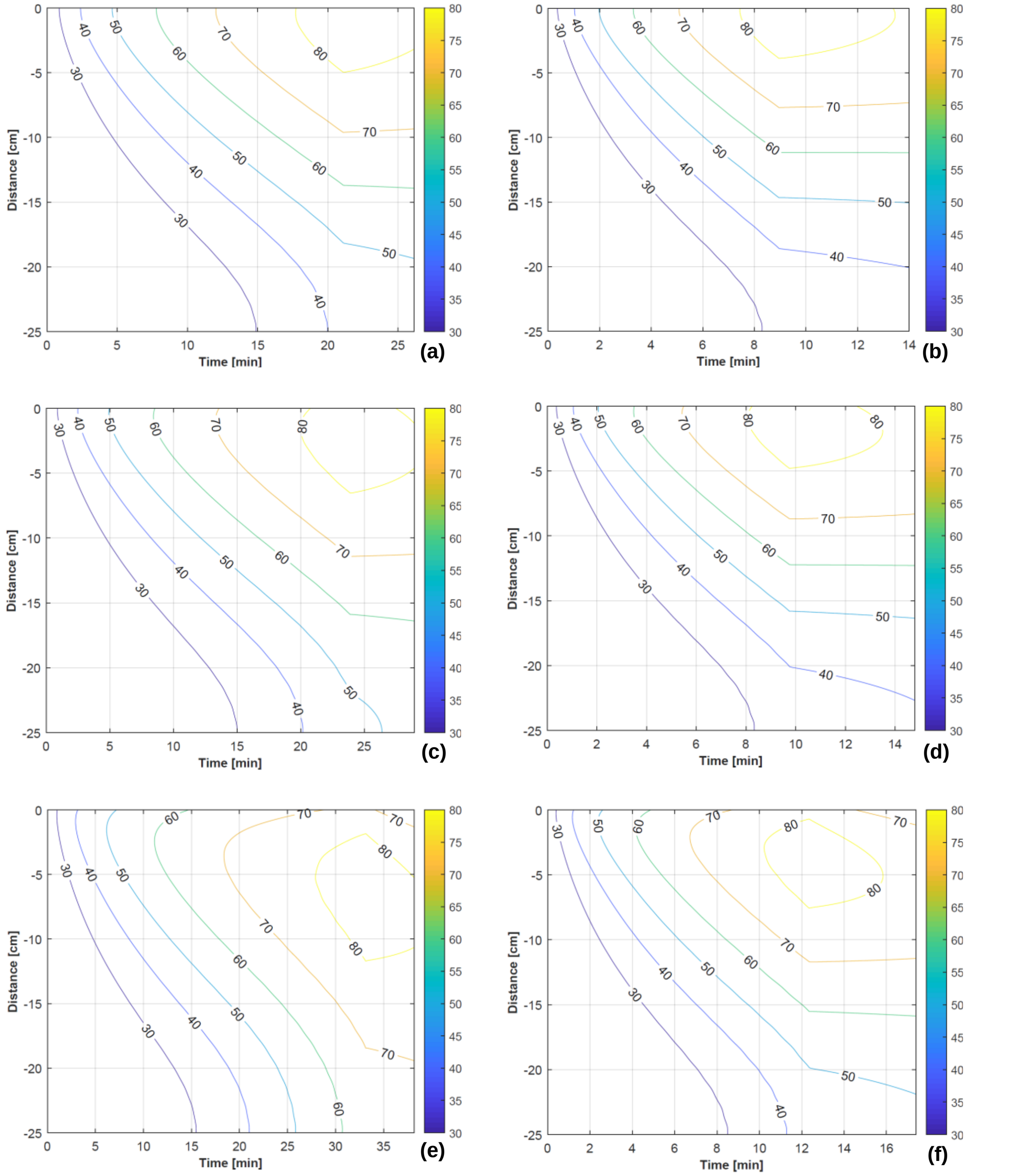

Figure 1: Soil temperature distribution (temperatures in °C) as a function of depth and time of irradiation for different values of S_0 and h_c: S_0=12 kW·m^{-2}, h_c=2 W·m^{-2}·K^{-1} (a); S_0=24 kW·m^{-2}, h_c=2 W·m^{-2}·K^{-1} (b); S_0=12 kW·m^{-2}, h_c=10 W·m^{-2}·K^{-1} (c); S_0=24 kW·m^{-2}, h_c=10 W·m^{-2}·K^{-1} (d); S_0=12 kW·m^{-2}, h_c=50 W·m^{-2}·K^{-1} (e); S_0=24 kW·m^{-2}, h_c=50 W·m^{-2}·K^{-1} (f).

Looking at the results, with reference to the literal notation used in Figure 1, to reach a temperature, at any point, of 60 °C, a time ranging from about 3.2 min (case b) to 11 min (case e) is necessary; to reach 70 °C, a time varying from about 5 min (case b) to about 18 min (case e) is needed; the temperature of 80 °C is reached for the first time after 7.5 min (case b, minimum value) and 27.8 min (case e, maximum value). It should be noted that, in the meanwhile the underlying soil layers are progressively heating, in the surface, even if the electromagnetic power dissipation is maximum, as it is exposed to the atmosphere, the temperature can be lower than that in the layer below, due to the prevalence of the convection heat transfer and to the induced cooling, which propagates downward: this is what happens in the cases c, e and f (and, very slightly, also in the case d).

As reported in the literature, to be effective against some common soil pest agents, alternatively, the temperature of 80 °C should be maintained for 4 min at least, 70 °C for 7 min, or 65 °C for 15 min (Casu et al., 2018). This means that, looking at cases a and b (both with h_c=2 W·m^{-2}·K^{-1}), they represent very favorable conditions: due to the low heat transfer rate to the atmosphere, in the surface it is possible to maintain a temperature of 80 °C and more for more than 10 min in the case a, and for more than 6 min in the case b. In this two cases, positive results are reached not only in the surface, but also up to a depth of, at least,11 cm in the case a, and 8 cm in the case b, were a temperature of at least 65 °C is maintained for more than 15 min. With reference to the cases c and d (both with h_c=10 W·m^{-2}·K^{-1}), proper conditions are still present in the surface, where the temperature of 80 °C at least is maintained for more than 7 min in the case c, and for more than 4 min in the case d. Looking at the deeper layers, temperatures higher than 65 °C for more than 15 min are maintained up to about 13 cm of depth in the case c, and up to about 10.5 cm in the case d. The last two cases, e and f (both with h_c=50 W·m^{-2}·K^{-1}), can become critical: in the surface, the temperature of 80 °C is never reached, and 70 °C (or slightly more) are reached and maintained for about 5 min in both cases. Notwithstanding this criticism, effective conditions are still obtained in the layers below: in the case e, the positively treated zone is that between the depths of about 0.5 cm (70 °C for more than 7 min) and 20 cm at least (70 °C for more than 10 min); in the case f, this zone goes from about 1 cm (70 °C for more than 7 min) to about 13 cm (65 °C for more than 15 min).

It should be noted that, while increasing the h_c coefficient value, the effectively treated soil depth increases: this fact could seem strange, but it is fully justified by the fact that also the irradiation time increases, just because of the faster surface cooling, which delays the reaching of the MW irradiation device preset stop temperature (85 °C in any point of the soil): the irradiation is stopped after about 20.5 min in the case a, 8.8 min in the case b, 24 min in the case c, 9.7 min in the case d, 33 min in the case e, 12.3 min in the case f; of course, the working times are lower in the cases b, d and f than those, respectively, of cases a, c and e, due to the higher (twice) irradiation power.

5. Conclusions

In this work, a modeling approach to soil microwave heating and heat transfer has been presented, together with the solution of a set of possible scenarios with different heating power and surface convection heat transfer coefficient values, in order to point out the best treatment conditions with respect to the depth of the layer to be heated and the optimal time of irradiation.

As discussed in the previous section, the presented MW heating treatment method could be effective against some common pests in the soil, in fact it is able to produce and maintain the desired temperature for the needed time in a layer of depth depending on the soil texture and characteristics but also on the external air conditions and on the irradiated electromagnetic power. With respect to the air convection, which reflects in the convection heat transfer coefficient, the latter can change, as known, depending on the shape and roughness of the soil surface, and also on the air movement (wind) speed. Having said this, on one side it could be possible to simply accept the natural conditions, and accordingly to these, to tune the applied MW power in order to obtain the aimed result; on the other side, it would be possible to artificially change the pre-existent conditions, e.g. by smoothing or rippling the soil surface, by placing a barrier against the wind or ventilating. Working with the lowest value as possible of h_c, aiming at the minimizing the heat dispersion rate to the atmosphere, is not always the best solution: it is cheaper, but allows to effectively treat a layer of lower thickness, even if in this eventuality it is possible to guarantee proper temperature conditions also in the surface, which otherwise might be the part exposed to the greatest risk of failure. Moreover, regarding the electromagnetic power, one can think that the best solution would be that of simply minimizing it, but it should be observed that, for each value of h_c, passing from 12 to 24 kW·m^{-2}, i.e. doubling the power, brings to a reduction in the application time to less than half (about 40 % in all the cases), therefore to overall energy savings.

In summary, careful attention should be paid to the possible real application, which need to be optimized before being implemented depending on the contingent conditions and on the possibility of modifying them, but most of all on the given sanitation goals and on the energy cost and treatment time minimization.

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