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EXPERIMENTAL STUDY OF MICROWAVE SLOW WAVE COMB AND CERAMIC APPLICATORS FOR SOIL TREATMENTAT AT FREQUENCY 2.45 GHZ

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Abstract

In many cases in industry it is required to heat or treat surface layers of different material (soil, timber, concrete, plastics and so on) with microwaves (MW). Traditional MW irradiators (antennas) cannot provide heating only to the surface areas and energy penetrates deep into the material, where it decays exponentially due to normal attenuation. To reduce energy losses it was required to develop special MW applicators for surface treatment to increase process efficiency. To address this problem, a slow wave ("surface wave") comb and ceramic applicators were designed, built and studied. The main property of slow waves is that the energy concentration is very near impedance electrode – comb or ceramic plate surface. Comb and ceramic slab applicators for frequency 2.45 GHz operation were designed for the soil treatment and studied using soil with moisture content range 32-174% and density range 590-1070 kg/m^3. 30 kW MW plant was used for experiments.

Results of the experiments showed that a ceramic applicator provides better uniformity of energy distribution across the width of the applicator. It reduces overheating of the soil surface and energy losses. The depth of energy penetration provided by ceramic applicator is lower compared with the comb applicator. It means that the ceramic applicator provides better energy localization and more energy absorption in the soil surface layers compared with the comb applicator. The ceramic applicator is more effective for MW treatment of the soil surface areas and is recommended for practical use in machines for thermal treatment and sterilization of surface layers of the soil and other materials.

Introduction

Traditional MW irradiators (antennas) cannot provide heating only to the surface areas and energy penetrates deep into the material, where it decays exponentially due to normal attenuation. Therefore, energy losses are very significant when heating depth of 20 - 40 mm (for example to heat soil for killing weed seeds) is all that is required. Therefore, it is required to develop special MW applicators for surface treatment to increase process efficiency.
To address this problem, a slow wave (which is sometimes called a "surface wave" applicator) comb and ceramic structures, were studied. The main property of slow waves is that the energy concentration is very near impedance electrode – comb or ceramic plate surface. Previously, slow wave structures (SWS) were used mostly as delay lines [4] and as interaction circuits in MW vacuum devices, and their properties were explored only for these specific applications [3]. Extending MW technologies to industry, medicine, and army initiated a study of slow wave structures, properties and peculiarities which can be used for developing novel technologies for industrial, medical, domestic and military applications [1], [5]. It was shown by the full-wave analysis, as well as by experiments, and practical

realization that the SWSs have many previously unknown peculiarities, which can be used for creating novel technologies for domestic and industrial heating, plasma generating, etc. The work objectives of this study were:

1. design slow wave, ceramic and comb structure applicators for soil treatment at frequency 2.45 GHz;
2. experimentally study the energy distribution from slow wave applicators in the soil;
3. examine opportunities to use slow wave structures for surface soil layer heating; and
4. recommendations for practical use of new slow wave applicators.

Applicators design

On the base of the theoretical study [2] and computer modelling slow wave comb and ceramic slab applicators for frequency 2.45 GHz were designed. Comb applicator made from aluminium and ceramic applicator made from alumina are shown in Fig 1. Main dimensions of comb and ceramic applicators are displayed in Table 1.

Table 1. Applicator parameters.

Parameters	Comb, mm	Ceramic, mm
Working length	356	356
Applicator body thickness	23	23
Applicator body width	150	150
Comb electrode width	100	
Ceramic slab width		100
Comb electrode thickness	16	
Ceramic slab thickness		13
Comb electrode conic part length	185	
Grove depth/ width	13/3	
Comb tooth thickness	3	
Material	Aluminium	Alumina slab (DC=9.8, loss tangent 0.0002)
Ceramic plates covering comb and ceramic slab	Alumina (99%) ceramic plate size 3x84x146 mm (4 pieces), (DC=9.8, loss tangent 0.0002)	

In experiments the comb and ceramic slab (Fig.1) surfaces were covered by 3 mm thickness alumina plates.

Fig. 1. Comb applicator (left) without covering with ceramic plates. Ceramic applicator (middle) without covering by ceramic plates. Comb and ceramic applicators view (right) covered by ceramic plates (3x84x146 mm - 4pc).

In experiments a ceramic block made from alumina was inserted into the applicator body instead of aluminium comb electrode. The ceramic block (13 mm thickness) with 3 mm thickness ceramic plates formed ceramic part of the applicator with thickness 16 mm.

Experimental study. Material and methods.

Material

The soil "Potting Mix Hortico" was used for tests. The soil had 3 different moisture contents (MC) and densities:
MC = 32% , density =586 kg/m^3,
MC = 89% , density =710 kg/m^3,
MC = 174% , density =1070 kg/m^3.
The soil (mixture of organic and mineral substances) used in experiments had significant percentage of organic particles of different sizes (wood, bark, grass) therefore dielectric parameters of the soil at frequencies 2.45 GHz, temperatures from 15 to 80ºC were in the range: dielectric constant - from 4 to 19 and loss tangent - from 0.2 to 0.3. Only the most significant properties for MW heating of soil: moisture content and density were measured. The soil was placed into polypropylene containers (Fig.2) with sizes 160x250x300 mm.

Experimental installation and procedure

MW plant 30kW (2.45 GHz) was used for experiments (Fig. 2). The applicator was connected to the MW generator by waveguides and placed into the metal box 400x500x1120 mm for leakage protection. Position of the container with soil on the applicator is shown in Fig. 2 (middle). Auto tuners used in MW systems provided good matching for the generator and applicators (with soil) practically without power reflection.

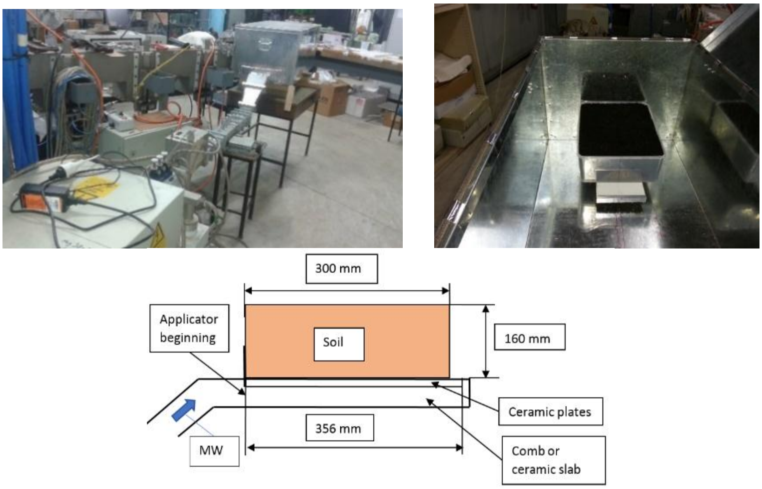

Fig 2. Applicator (in metal box) connection with 30 kW MW generator, 2.45 GHz (left). Container with soil on the applicator inside of the metal box (middle). Scheme of applicator with soil in the container (right).

Temperatures in the soil were measured by thermocouples after MW heating on the depth 10, 30, 50, 80,100 and 140 mm along applicator at distances from applicator beginning 30, 60, 90, 120, 150, 180, 210, 240, 270 and 350 mm, and across the applicator in the central vertical plane and at distances from central vertical plane 37.5 , 75 , and 112.5 mm in both cross directions. Distribution of measuring points covered all volume of the soil along and across the soil samples. Scheme of container with soil position on applicator is shown in Fig.2. Lay-on jig was used for thermocouples positioning during measurements. To get reliable results of MW heating at every soil moisture content four repeats were performed. MW power of 3.5 kW was applied to the soil for 15 sec and after that the temperatures were measured by thermocouples. Energy applied to the soil during experiments was 53 kJ.

Results and discussion

Temperature distribution in the soil by comb applicator

We assume that the temperature distribution in the soil reflects energy release in different spots of the soil volume and allows assessment of the energy distribution by MW applicators. Fig. 3 shows typical temperature distribution in the soil volume at the depth of 10 mm by comb applicator after applying MW power 3.5 kW for 15 sec.

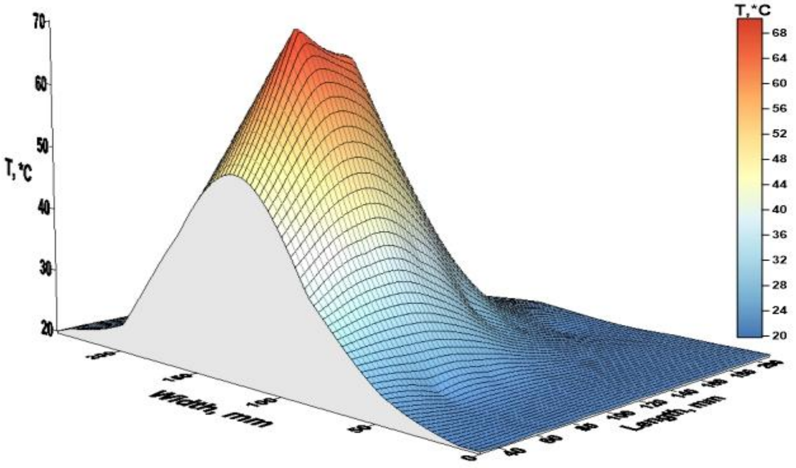

Fig. 3. Temperature distribution in the soil at the depth of 10 mm by comb applicator at F=2.45 GHz, P=3.5 kW, time of MW heating 15 sec, To =20ºC, applied energy 53 kJ. Soil moisture content MC=89%, density 710 kg/m^3.

Temperature distribution in the soil along the comb applicator central vertical plane for soil with MC= 174%, initial temperature To=20ºC, power P=3.5 kW, duration of MW heating 15 sec is shown in Fig. 4.

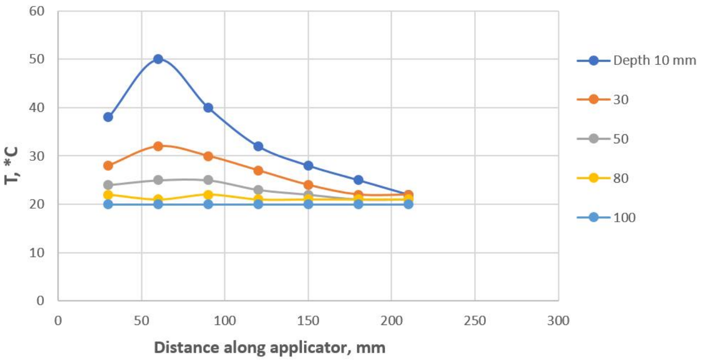

Fig. 4. Temperature distribution in the soil along the comb applicator central plane at F=2.45 GHz, P=3.5 kW, duration of MW heating 15 sec, To=20ºC, applied energy 53 kJ. Moisture content MC=174%, density 1070 kg/m^3.

Maximum energy absorption takes place at a distance of about 60 mm from the beginning of the applicator. Almost all of the energy was absorbed at the distance of 200 mm along the applicator for all of the tested soil moisture contents. Maximum energy release takes place in the zone between 60 to 90 mm from the applicator beginning.

Practically all energy irradiated by applicator was absorbed at the width of about 150 mm across the applicator. This was consistent across different moisture content of the soil samples.

Temperature distribution in the central plane of the comb applicator at soil depth between 10 and 100 mm is illustrated by Fig. 5.

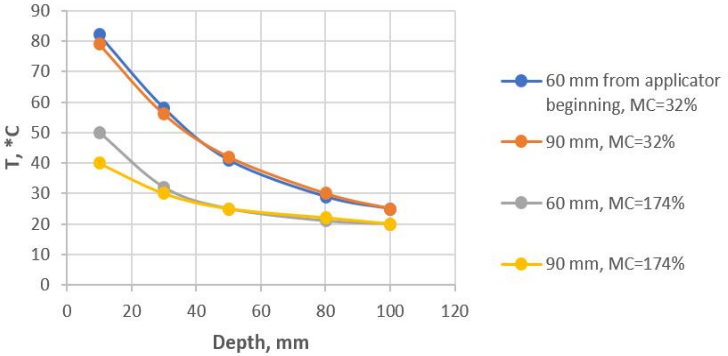

Fig. 5. Temperature distribution in the central vertical plane of the comb applicator at soil depth between 10 and 100 mm after heating. MC=32 and 174%, F=2.45 GHz, P=3.5 kW, time of MW heating15 sec, To=21ºC.

The most significant part of the energy is absorbed by the soil, with moisture content in the range 32 to 174%, up to the depth of 50 mm measured in the central vertical plane of the comb applicator. In other volume zones of the soil the share of energy absorbed by surface layers is higher. Almost all of the energy is absorbed at applicator length 200 mm and width 150 mm covering soil surface 300 cm2.

Temperature distribution in the soil by ceramic applicator

Ceramic block with 3 mm ceramic plates on the top forms ceramic applicator with thickness 16 mm from alumina (99%) material with dielectric parameters: DC=9.8, loss tangent 0.0002. When microwaves travel through alumina they reduce in wave length.
The wave length in the material (ceramics):

$$\lambda = \lambda_o / \sqrt{\acute{\varepsilon}} \,,$$

where λ_o-wavelength in vacuum (or in air) and
$\acute{\varepsilon}$ – dielectric constant of material.
In our case at 2.45 GHz wave length is 122 mm and at $\acute{\varepsilon}$ = 9.8 the wave length in alumina is λ= 122: 3.13=40 mm.

This means a wave length in ceramic block is about 40 mm and microwaves in the ceramics will provide two energy maximums (peak volumes) on the applicator width (comb applicators provide one maximum because wave length in it is 122 mm).
Fig. 6 shows typical temperature distribution in the soil at the depth of 10 mm by ceramic applicator after applying MW power 3.5 kW for 15 sec.

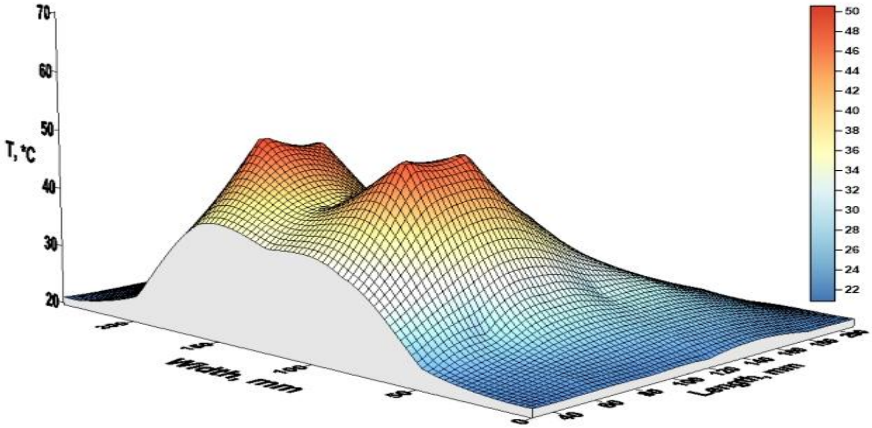

Fig. 6. Temperature distribution in the soil at the depth of 10 mm by ceramic applicator after MW heating at F=2.45 GHz, P=3.5 kW, time of MW heating 15 sec, To =20ºC. Soil moisture content 89%, density 710 kg/m^3.

Temperature distribution along ceramic applicator in the peak vertical plane (38 mm from central vertical plane) is shown in Fig. 7 (left).

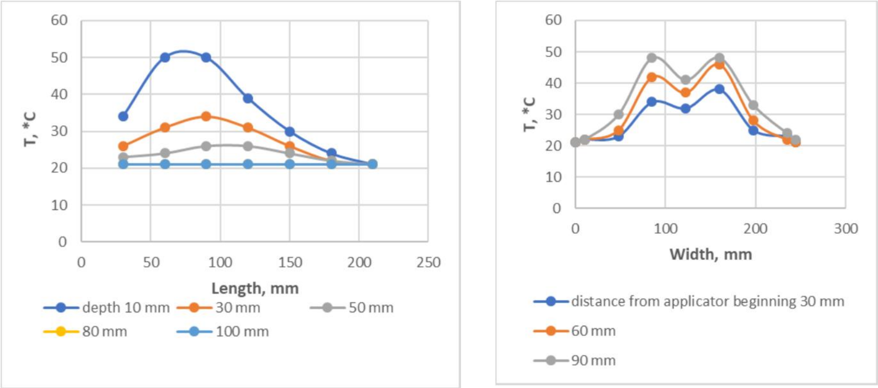

Fig. 7. Left. Temperature distribution along ceramic applicator in the peak vertical plane (38 mm from central plane) at different depths after MW heating of the soil with moisture contents 89%. Right. Temperature distribution across ceramic applicator at the depth of 10 mm after MW heating soil with moisture contents 32%.
F=2.45 GHz, P=3.5 kW, time of MW heating - 15 sec, To=21ºC.

For soil MC = 89 and 174% practically all energy is absorbed at the applicator length of 200 mm. For soil MC=32 % energy spreads along all of the applicator length. The temperature distribution in a soil sample with MC=32% across the_applicator after MW heating is displayed in Fig.7 (right). Temperature curves show two peaks at a distance of 40 mm on each side of the central vertical applicator plane and lowest at the applicator central vertical plane.

Temperature distribution in the peak vertical plane of the ceramic applicator at soil depths and MC= 32, 89 and 174% is shown in Fig. 8.

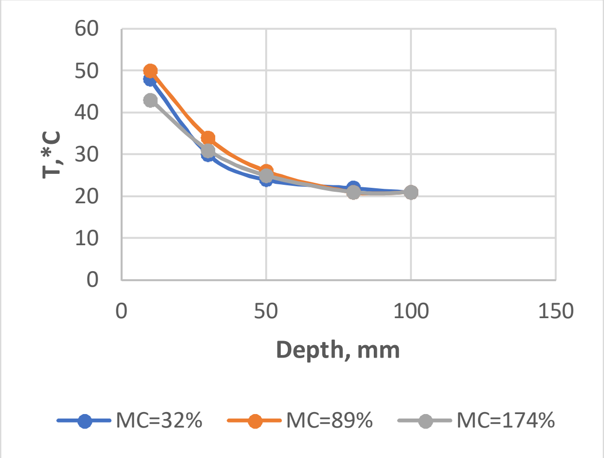

Fig. 8. Temperature distribution by the soil depths at the peak vertical pane of the ceramic applicator at the distance of 90 mm from applicator beginning after heating and MC= 32, 89 and 174%. F=2.45 GHz, P=3.5 kW, time of heating 15 sec, To=21ºC.

The most significant part of the energy is absorbed by the soil at the peak vertical planes on the depth up to 50 mm, and practically all of the energy is absorbed at the depth up to 80 mm. In other volumes of the soil the share of energy absorbed by surface layers is higher.

Comparison of the temperature distribution in the soil by comb and ceramic applicators

Fig. 3 with one temperature peak and Fig. 6 with two temperature peaks illustrate principal difference in energy distribution in the soil by comb and ceramic applicators. Comb applicator provides maximum soil heating in the central vertical applicator plane because the transporting electromagnetic wavelength is 122 mm. Alumina ceramic block transforms electromagnetic wave from 122 mm to the wavelength of 40 mm and provides a different pattern of energy distribution in the soil with two peaks in the vertical cross planes. Fig. 9 illustrates the difference of temperature distribution in a soil sample at the vertical cross section of the two applicators.

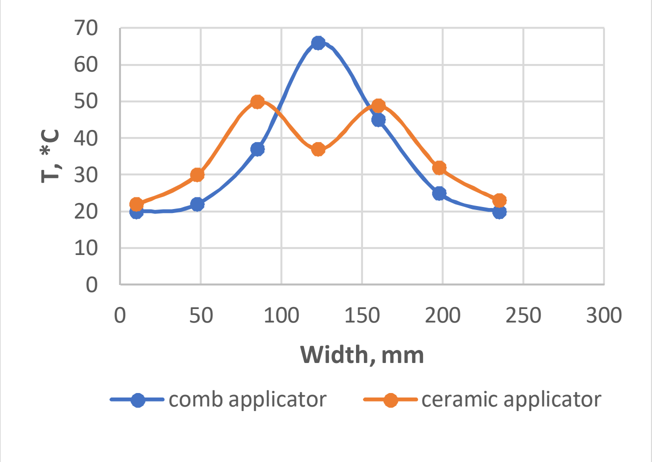

Fig. 9. Temperature distribution across comb and ceramic applicators at the soil depth of 10 mm and distance of 90 mm from applicator beginning after MW heating of the soil with moisture contents 89%. F=2.45 GHz, P=3.5 kW, time of MW heating 15 sec, To=21ºC.

Peak temperature in the soil provided by the ceramic applicator is significantly lower compared to peak temperature provided by the comb applicator. This reduces overheating of the soil surface and energy losses. Test results of comb and ceramic applicators in similar conditions are shown in Table 2.

Table 2. Test results of comb and ceramic applicators for frequency 2.45 GHz.

Items	Units	Comb applicator	Ceramic applicator
Soil moisture content and density		MC = 32 - 174%, density 586 -1070 kg/m^3	
Majority of the applied MW energy was absorbed:			
on the applicator length	mm	200 -210	200 (MC=89-174%) 350 (MC=32%)
on the applicator width up to	mm	150	200-210
on the material depth up to	mm	100-130	80
Length of zone of high intensity heating along applicator (distance from applicator beginning)	mm	30 (from 60 to 90)	70 (from 50 to120)
Average MW specific energy applied to the soil	kJ/cm2	0.18	0.13

Measuring the maximum degree of non-uniformity of the temperature in the soil by ratio of peak temperatures to initial temperatures, the comb applicator provides non-uniformity 3.1, ceramic applicator - 2.3.

The ceramic applicator provides better uniformity of energy distribution on the width of the applicator due to two temperature peaks. In addition, depth of energy penetration is lower. This means the ceramic applicator provides more energy absorption within the soil surface layers compared to comb applicator and therefore is more effective. For practical use, instead of ceramic block (thickness 13 mm) + ceramic plates (thickness 3 mm), it is better to use one alumina ceramic block with thickness of 16 mm.

To improve the uniformity of the energy distribution by ceramic applicators it can be recommended to use ceramics with higher dielectric constant 15-25 (PD- 15, PD-20, PD-25). This creates 3 or 4 MW power peaks along the applicator width keeping the energy closer to the applicator surface. This will increase efficiency of MW energy use.

In terms of effective energy use for thermal treatment and sterilization of soil surface layers, using a ceramic applicator has the following advantage compared to a comb applicator:

- better uniformity of energy distribution on the width of the applicator,
- better energy localization in the soil surface layers,
- the soil moisture content in the range between 32-174% does not have a significant effect on energy localization in the surface layers.

Ceramic applicators can be recommended for practical use in machines for thermal treatment and sterilization of the soil and other materials surface layers.

Conclusion

Comb applicator provides maximum energy release into the soil at the central vertical plane. Ceramic applicator from alumina forms two temperature peaks in the vertical planes at a distance of about 40 mm each side of the central applicator plane and minimum in the applicator central plane. Ceramic applicator provides better uniformity of the energy distribution along the width of the applicator due to two temperature peaks. The depth of energy penetration is lower compared to comb applicator. Thus, the ceramic applicator provides better energy localization and more energy absorption in soil surface layers compared to a comb applicator. To provide better uniformity of energy distribution across ceramic applicator it is recommended to use ceramics with higher dielectric constant. Using ceramics with dielectric constant of 15-25 would provide 3 or 4 temperature peaks on the applicator width, keeping more energy closer to the applicator surface. This will increase efficiency of MW energy use.

The ceramic applicator is more effective for MW treatment of the soil surface areas and is recommended for practical use in machines for thermal treatment and sterilization of surface layers of the soil and other materials.

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