RF RADIATORS FOR HOMOGENEOUS HEATING

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ABSTRACT

A novel method of electromagnetic heating of high-permittivity materials and radiators for heating realization are described in this paper. Based on slowing an electromagnetic wave up to the light velocity in a treated material, this method makes it possible to control distribution of electric field energy in the cross section of a heated object. It is shown that a homogeneous distribution of electric field in a high-permittivity material can be achieved in radiators based on a circular waveguide. The required deceleration is provided by a thin tube manufactured from a magnetic material. Diaphragms installed in a circular waveguide (diaphragm waveguide slow-wave structure) or a tape helix in a metal cylinder (helical slow-wave structure) can also provide the required deceleration and a homogeneous distribution of electric energy in a heated object.

INTRODUCTION

A successful realization of new heating technologies based on slow-wave structures (SWSs) application, including microwave radiators for physiotherapy [1-7] confirmed high effectiveness of a novel method of electromagnetic energy radiation into materials with high permittivity [8]. This method is based on the difference between electromagnetic wave velocities in a dielectric object, e.g. human tissue, and in a section of a SWS taking place of a radiator. In a free space, slow electromagnetic wave propagates along SWS without radiation, its field concentrating near the surface of the SWS. In the presence of an electro-dynamically dense material, adjacent to the SWS with a small gap, the field distribution changes (Fig. 1), and a part of electromagnetic energy propagates in this media in the same direction. As soon as the phase velocity of the slow wave in the SWS exceeds the light velocity in the adjacent media, the energy, propagating in the adjacent material, splits from the wave in the SWS and is radiating. Intensity of the radiation and its direction depend on velocities relation and a gap between the SWS (radiator) and a treated material. This technology can be very effective for heating relatively large objects, when a homogeneity of heating is not important.

As it will be shown below, to obtain a homogeneous distribution of the heating energy in a treated material, e.g. a pasteurized milk or a biomass, one can control an electric field distribution choosing an appropriate configuration of the radiator, adjusting an electromagnetic wave velocity as well as an operating frequency.

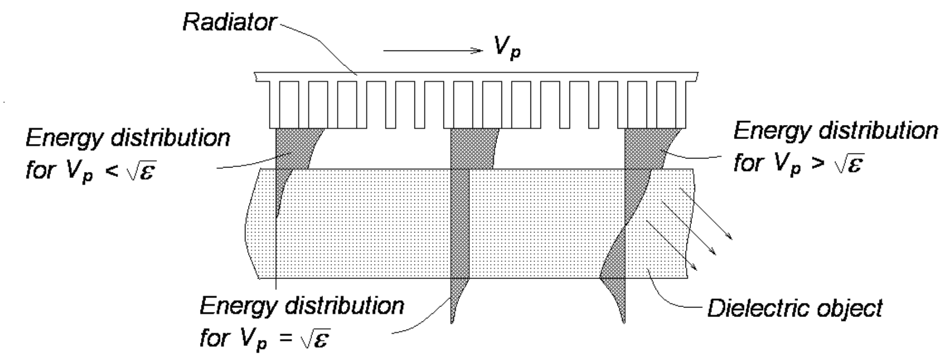

Figure 1. Energy distribution in a treated object.

1. E_{01} WAVE IN A CYLINDRICAL WAVEGUIDE

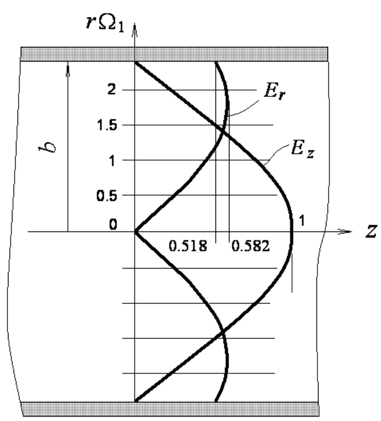

Figure 2. Components E_z and E_r distribution along radius r in the field of E_{01} wave for $\Omega_1 = \beta$.

Consider an E_{01} wave in a cylindrical waveguide with inner radius b (Fig. 2). The electrical field distribution along radius r for such a wave is characterized by a zero radial component E_r on the waveguide axis ($r = 0$) and a maximum value of its longitudinal component E_z. A wave equation solution for E_r and E_z components can be written as

$$E_r(r,z,t) = E_0 J_1(r\Omega_1) \cdot e^{j\omega t - j\beta z}, \tag{1}$$

$$E_z(r,z,t) = -\frac{j\Omega_1}{\beta} E_0 J_0(r\Omega_1) \cdot e^{j\omega t - j\beta z}. \tag{2}$$

Here and further, E_0 is an amplitude constant, exp. $(j\omega t - j\beta z)$ is the wave factor, which we will always take into account emitting its writing in further of formulas, ω- is an angular frequency, J_0 and J_1 are Bessel functions of the first kind and zero and first order, Ω_1 and β are, accordingly, transverse and phase constants related one to the other and wave number k by relations

$$\Omega_1^2 = k^2 - \beta^2, \tag{3}$$

$$k = \omega\sqrt{\varepsilon_0\mu_0} = \frac{2\pi}{\lambda}, \tag{4}$$

where λ - is a wavelength in a free space, ε_0 and μ_0 are permittivity and permeability of vacuum. We'll remind that, as it follows from an equality of E_z to zero on the wall of the waveguide (at $r = b$), the product $b\Omega_1 = 2.41$ (first root of function J_1). It allows us to write instead of (3)

$$(b\beta)^2 = (bk)^2 - 5.808. \tag{5}$$

The total density of electric field energy $W^e(r)$ distribution in the considered wave can be calculated using the well known expression

$$W^e(r) = \frac{\varepsilon_0|E_z|^2}{2} + \frac{\varepsilon_0|E_r|^2}{2}. \tag{6}$$

Formulas (1) - (5) allow writing instead of (6)

$$W^e(r) = \frac{\varepsilon_0 E_0^2}{2}[J_1^2(r\Omega_1) + \frac{J_0^2(r\Omega_1)}{\frac{\lambda_c^2}{\lambda^2} - 1}], \tag{7}$$

where $\lambda_c = 2.62\ b$ is the cutoff wavelength.

Curves in Fig. 3 demonstrate the distribution of a total electric energy density inside the waveguide for three different wavelengths λ equal to $0.707\lambda_c$, $0.578\lambda_c$, $0.5\lambda_c$. The values at ordinate axe are normalized (divided by $\varepsilon E_0/2$). It is seen that at $\lambda = 0.578\ \lambda_c$, the total density of electrical energy is constant in the range $r\Omega_1 = 0\text{-}0.5$ and is slightly decreasing from $r\Omega_1 = 0.5$ to $r\Omega_1 = 1.0$ that corresponds to $r/b \approx 0\text{-}0.2$ and $0.2\text{-}0.4$. Thus, there is a practical possibility to achieve a homogeneous distribution of electrical energy in the inner part of a circular waveguide.

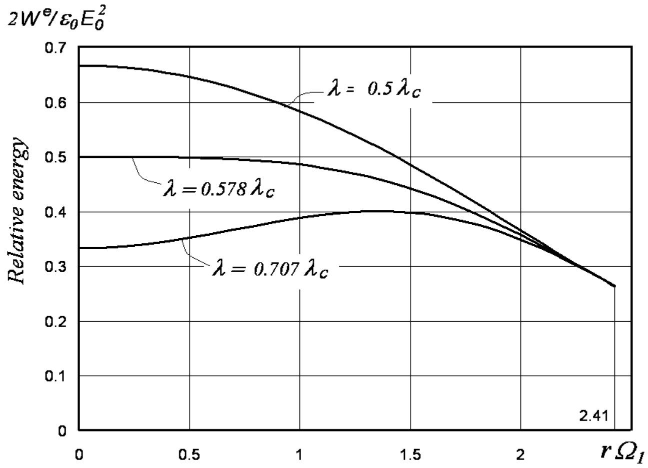

Figure 3. Density of electric field energy distribution along radius *r* for different values of wavelength λ.

2. RADIATORS BASED ON A CIRCULAR WAVEGUIDE

The simplest way of a practical realization of the considered above model is a circular waveguide with a dielectric tube adjacent to its inner surface (Fig. 4). If the permittivity of said dielectric tube and the permittivity of material filling this tube are equal, the energy distribution will be the same as is shown in Fig. 3. To achieve a homogeneous heating of a treated material, one should choose the inner radius of the tube, *a*, at least *0.4* of the waveguide radius *b*. A main disadvantage of such radiator is its large diameter.

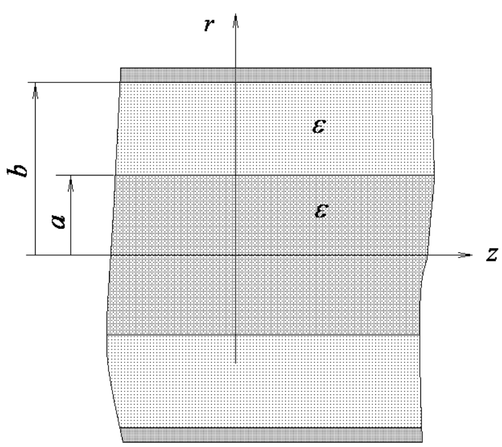

Figure 5. Circular waveguide radiator.

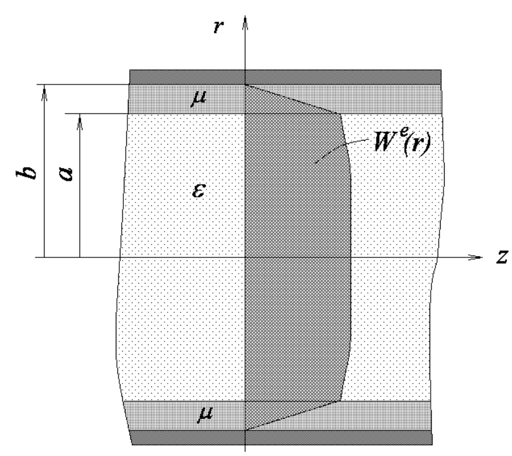

Figure 4. Radiator with a magnetic tube.

The diameter of the considered radiator can be decreased significantly if the tube will be manufactured from a material with a small relative permittivity (we'll assume it to be equal to *1*) and large permeability μ. In this case, the considered waveguide becomes a quasi-waveguide, and its cutoff diameter decreases sufficiently [9].

Consider a cylindrical waveguide with an adjacent to its inner surface relatively thin tube filled by a dielectric material with a relative permittivity ε. Inner radius a of the tube is just slightly less of its external radius, b the last being equal to the inner radius of the waveguide (Fig. 5). Arranging the origin of r, φ, z system of coordinates on the axis of the tube with z coordinate along the axis, we'll consider, as previously, a E_{01} wave propagating along coordinate z with phase constant β.

To widen results of our analysis, we'll include a case when the phase velocity of the considered wave is less than the light velocity in a treated material and transverse constant Ω_1 becomes imaginary. It can be done by converting formulas (1), (2) for components of electric field intensity to the next formulas:

$$E_r(r) = E_0 J_1(r\Omega_1) = -jE_0 I_1(r\tau)\,, \tag{8}$$

$$E_z(r) = -\frac{j\Omega_1}{\beta} E_0 J_0(r\Omega_1) = \frac{\tau}{\beta} E_0 I_0(r\tau)\,. \tag{9}$$

Here $\Omega_1 = j\tau$, I_0 and I_1 are modified Bessel functions. Taking into account the relative permittivity ε of the material filling the tube, we should write instead of relation (3)

$$\tau^2 = -\Omega_1^2 = \beta^2 - k^2\varepsilon\,. \tag{10}$$

To derive the dispersion equation of the considered structure, one should find admittances at the boundary between the tube and dielectric filling the tube (at $r = a$) [10]. Equalizing these admittances gives

$$\frac{1}{\Omega_1}\cdot\frac{J_1(a\Omega_1)}{J_0(a\Omega_1)} = \frac{1}{\tau}\cdot\frac{I_1(a\tau)}{I_0(a\tau)} = \frac{1}{\Omega_2}\cot_r(a\Omega_2, b\Omega_2), \tag{11}$$

where Ω_2 is the transverse constant of the tube defined by the relation

$$\Omega_2^2 = k^2\mu - \beta^2\,, \tag{12}$$

$\cot_r(x, y)$ is a radial cotangent defined by formula

$$\cot_r(x,y) = \frac{J_1(x)N_0(y) - J_1(y)N_0(x)}{J_0(x)N_0(y) - J_0(y)N_0(x)}, \tag{13}$$

$N_{0,1}$ are Bessel functions of the second kind.

We'll consider that $b/a \approx 1$. It can be easily shown that in this case [11]

$$\cot_r(a\Omega_2, b\Omega_2) \approx \frac{1}{(b-a)\Omega_2} \quad . \tag{14}$$

It allows writing instead of (11)

$$\frac{1}{\Omega_1} \cdot \frac{J_1(a\Omega_1)}{J_0(a\Omega_1)} = \frac{1}{\tau} \cdot \frac{I_1(a\tau)}{I_0(a\tau)} \approx \frac{1}{\Omega_2^2(b-a)}, \tag{15}$$

At relatively low frequency, when $a\Omega_1$, $a\tau < 0.3$, the left part of (15) can be simplified. Using relation (12), one can obtain

$$n^2 = \frac{\beta^2}{k^2} \approx \mu - \frac{2a}{(ak)^2(b-a)}, \tag{16}$$

where n can be named a deceleration.

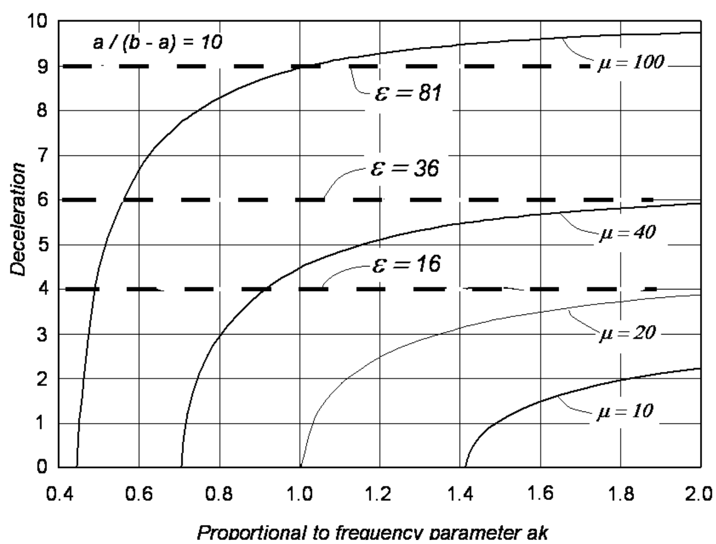

Figure 6. Deceleration dependence upon parameter *ak*, proportional to the operating frequency.

Solutions for n versus ak obtained from equation (16) for $a/(b-a) = 10$ and $\mu = 10, 20, 40, 100$ are shown in Fig. 6. The dotted horizontal lines correspond to three different values of a relative permittivity of a treated material 16, 36, and 81. At points of crossing, when $n = \sqrt{\varepsilon}$, $\tau = \Omega_1 = 0$. Difference between n and $\sqrt{\varepsilon}$ is followed by an increase in τ or Ω_1 and a possible non-homogeneity in the power distribution along the radius r. The larger slope of a curve at the crossing point the less value of transverse constant and the better homogeneity of the power distribution

$$(a\Omega_1)^2 = -(a\tau)^2 = (ak)^2(\varepsilon - n^2). \tag{17}$$

The same effect of a controlled distribution of the microwave electric field in a heated material can be achieved in a diaphragm waveguide [12] (Fig. 7). The areas between the diaphragms can be filled by a dielectric or a ferrite. Dispersion characteristics of such structure have a lager slope and are more sensitive to a change in the operating frequency that makes it difficult to adjust a required regime.

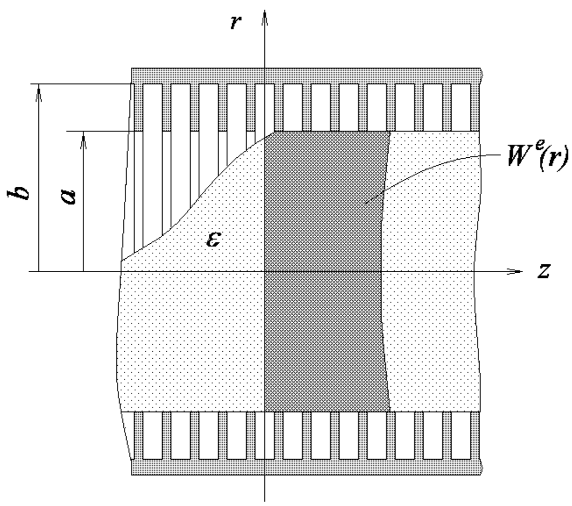

Figure 7. A possible distribution of electrical field energy in a diaphragm waveguide filled by a dielectric material.

3. A HELICAL RADIATOR

The more stable regime can be achieved with help of a radiator formed by a helical conductor wound on a dielectric tube inside a cylindrical screen shown in Fig. 8. A deceleration of an electromagnetic wave caused by a wounded tape, allows achieving approximately the same distribution of the electric power in the treated material as it was in the previous examples. The difference is in an additional energy created by the azimuth component of the electric field, which amplitude is relatively small.

A very important advantage of the helical radiator is the absence of a cut of frequency that allows operating at relatively low frequencies. If the permittivity of the dielectric tube splitting the helix and a treated material equals the permittivity of the material, the dispersion equation of the considered structure can be relatively simple [10].Avoiding a detailed analysis of the helical radiator, we'll replace it by a three-conductor equivalent line shown in Fig. 8 [13]. Here C_1 and C_2 are specific capacitances inside and outside the helix, L_0 is a specific inductance. The equation of such equivalent line can be written as

$$\beta^2 = \omega^2 L_0 (C_1 + C_2) \tag{18}$$

Let's assume that the helix with the average radius *b* is placed in the cylindrical screen with radius *d* and that there is no a tube and material inside the helix. The ratio *d/b*, the winding angle Φ, and the operating frequency are chosen so that $C_2 >> C_1$ and parameter $b\tau \approx 1.0$. It follows from this that the most part of the electric energy is concentrated outside the helix (in capacitance C_2) and the less its part is inside the helix and is distributed non-homogeneously. Installation of the tube with relative permittivity ε exceeding n^2 and filling it by a dielectric with the same permittivity leads to the ε times increase in capacitance C_1 and a relatively small increase in phase constant β

$$\beta^2 = \omega^2 L_0(\varepsilon C_1 + C_2)\,. \tag{19}$$

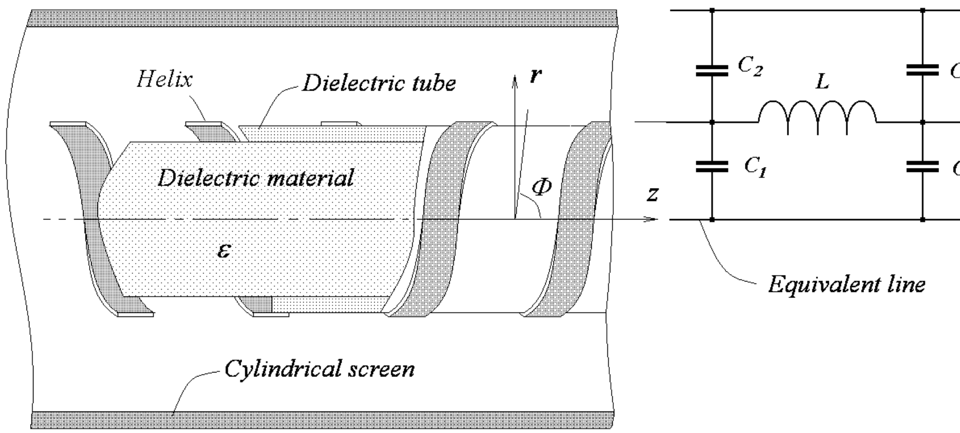

Figure 6. Helical radiator and its equivalent line.

If $C_2 = \varepsilon C_1$, the increase in the phase constant is less than *1.4*. In the same time, the electric field energy is distributed between both capacitances in equal parts. According to relation (10), in the case when permittivity ε two times exceeds initial deceleration n in power two, transverse constant τ inside the dielectric material is around zero. It means that in this case, two birds are killed by one stone: at least a half of the electric energy is concentrated inside the helix, and its distribution is very homogeneous.

CONCLUSION

It is shown above that radiators based on a cylindrical waveguide as well as on a helical slow-wave structure can be used for a homogeneous heating of different dielectric materials. A solution for simplified dispersion equation of the circular waveguide with a magnetic tube demonstrated possibility to create a real processing technology for high-permittivity materials. Although, this paper did not provide an analysis of the electromagnetic energy absorbing in the treated material, the demonstrated possibility to control its distribution allows adjusting a heating process according to real electromagnetic losses.

REFERENCES

1. RU 2,027,323 C1, Microwave Device for Thermal Processing of Flat Dielectric Material, V. N. Nefedov, Ju. N. Pavlenko, Ju. N. Pchel'nikov, Date of publication: 01.20.1995.
2. RU 2,061,203 C1, Device for Heat Treatment of Flat Dielectric Materials, Pchel'nikov Ju. N., Elizarov A. A., Date of publication: 05.27.1996.
3. RU 2,117,364 C1, Stratified Round Waveguide, Pchel'nikov Ju. N., Annenkov V. V., Dymshits R. M., Elizarov A. A., Date of publication: 02.27.1997.
4. RU 2,061,203 C1, Device for Heat Treatment of Flat Dielectric Materials, Pchel'nikov Ju. N., Elizarov A. A., Date of publication: 08.10.1998.
5. Yu. N. Pchelnikov and V. A. Kholodnyi, Medical Application of Surface Electromagnetic Waves, Bioelectrochemistry and Bioenergetics, 1998, # 47, pp. 283-290.
6. RU 2,077,351 C1, Microwave Radiator for Physiotherapy, Pchel'nikov Ju. N., Nesterov N. I., Kijatkin V. A., Osipov L. S., Date of publication: 04.20.1997.
7. RU 2,117,496 C1, Intracavatory Radiator for SHF Physiotherapy (Versions), Pchel'nikov Ju. N., Nesterov N. I., Kijatkin V. A., Dymshits R. M., Date of publication: 08.20.1998.
8. Yu. N. Pchelnikov, Radiation of Slow Electromagnetic Waves in a Magnetic Insulator, Journal of Communications Technology and Electronics, 1995, Vol. 40, # 6, pp.25-30.
9. Yu. N. Pchel'nikov and A. A. Elizarov, Analysis of a Circular Waveguide with Layered Filling, Journal of Communications Technology and Electronics, 1997, Vol. 42, # 5, pp. 517-520.
10. L. N. Loshakov and Yu. N. Pchelnikov, Traveling Wave Tube Theory and Calculation of Amplification, Moscow: Soviet Radio, 1964, in Russian.
11. Yu. N. Pchelnikov, Slow-Wave Structures for High-Power Electron Devices, "High energy Density and High Power RF," AIP Conference Proceedings # 691, 2003, pp. 386-393.
12. SU 672551, Sensor for Monitoring a Liquid flow, Pchelnikov Yu. N., Uvarov I. A., Lebedev M. A., and Nikitin G. A., Published in B.I. # 25, 1979.
13. Yu. N. Pchel'nikov, On the Replacement of Slow-Wave Systems by a Three-Conductor Equivalent Line, Journal of Communications Technology and Electronics, 1994, Vol. 39, # 9, pp.68-74.