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IMPROVED CYLINDRICAL STRAYFIELD APPLICATOR FOR UNIFORM HEATING OF LOSSY DIELECTRIC TUBES WITH THERMAL MEMORY

BY

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Abstract. The paper presents a new technique for improving the power density uniformity and the total absorbed power in a cylindrical strayfield applicator for heating lossy dielectric tubes. The technique consists in using a supplementary grounded electrode and lossless dielectric bands of adequate permittivity that cover the load. Simulations show that in this way uniform heating occurs in over 85% of the total load volume.

Key words: dielectric heating; strayfield applicators; numerical analysis of electric fields; optimization.

1. Introduction

The possibility to use high frequency electric fields in order to heat lossy dielectrics has been established and studied in the past five or six decades (Metaxas, 1996). The industrial applications fall into the class of radio-frequency (RF) or in that of microwave (MW) heating, depending on the generator frequency. The main applications of dielectric heating are in the plastic, wood and textile industries, as well as in food processing (defrosting, tempering, cooking).

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Currently, there are standard allocated frequencies for dielectric heating in the RF range (13.56 MHz, 27.12 MHz, 40.68 MHz, 81.36 MHz) and in the MW range (2.45 GHz, 0.915 GHz, 5.8 GHz, 22.125 GHz), the first two in both lists being the most common. The existing applicators for dielectric heating are capable of generating an active power ranging from 1 kW to 100 kW.

Generally, the dielectric heating equipment consists of four parts: the high voltage supply, the high frequency oscillator, the transmission line and the heating system (the applicator). The applicator is a capacitive type load in RF heating, whose geometry depends on the intended heating application, or a resonant cavity, in the case of MW heating.

There are applications that require a concentrated heating in a small region, and others (the majority) that require a uniform heating throughout the volume of the dielectric load. A variable, but imposed heating pattern can be also imagined.

Efforts in designing applicators that produce a uniform or quasi−uniform heating in loads with different geometries have been made, the design being based on analytical or numerical solutions for the electric field and implying an optimization stage (Ţugulea *et al*., 1993; Tortajada *et al*., 2007).

The present paper considers the case when the load is a lossy dielectric tube with thermal memory. The tube is heated in a RF applicator and inflated using air. After the tube is stabilized to a larger radius, a further heating shrinks it to its original dimensions. The process is largely used in coating metal pipes with an insulating layer. In Ţugulea *et al*. (1993), a technique for creating an electric field in a dielectric tube, that depends only on the radial coordinate and is independent of the tangential coordinate, was proposed. It is to be noted that in a classical strayfield applicator the electric field depends to a larger extent on the coordinate along which the active electrodes are distributed (tangential or axial). The technical solution, although perfect from a theoretical point of view, is however difficult to put in practice, implying the use of multiple phase−shift circuits.

In Tortajada *et al*. (2007) the solution, previously suggested by other authors, that consists in packaging the load with dielectric layers of adequate permittivity in order to increase the uniformity of MW heating, is tested and subjected to an optimization process using genetic algorithms.

The present paper considers the technique used by Tortajada *et al*. (2007) and adapts it for the case of a lossy dielectric tube with thermal memory heated in a strayfield RF applicator. The effects of some geometrical and electrical parameters on the uniformity of heating are investigated.

2. Physical Model of the Cylindrical Strayfield Applicator

The two−dimensional model of the applicator is presented in Fig. 1. The lossy dielectric tube having the complex permittivity $\underline{\varepsilon}$, has the inner radius a and the outer radius b. The active electrodes, having the potentials V_0, $-V_0$, the radius c > b and extending a center angle α, are arranged symmetrically in n pairs around the lossy dielectric tube.

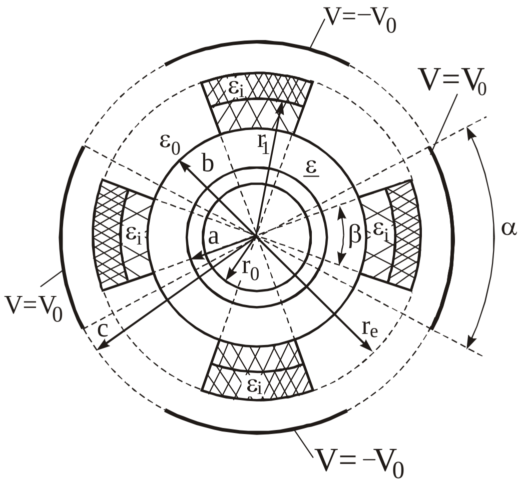


Fig.1 – 2-D physical model of the applicator.

Previous studies (Petrescu, 1994; Petrescu *et al.*, 2008) showed that the power density nonuniformity in tangential direction can vary , for this applicator between 7% and 50%, depending on the values of c, α and n.

In order to improve the power density uniformity, a supplementary cylindrical electrode of radius $r_0 < a$ and potential $V = 0$ is introduced. Moreover, supplementary loss free dielectric bands of inner radius b or r_1 and outer radius r_e covering the dielectric load to be heated, and extending a center angle β, were also considered in this model.

According to the fundamental energetic identity for electromagnetic fields, the active power dissipated in sinusoidal steady state in a spatial domain v_Σ has the expression:

$$P = \iiint_{v_\Sigma} \sigma E^2 \mathrm{d}v + \omega \iiint_{v_\Sigma} \varepsilon'' E^2 \mathrm{d}v + \omega \iiint_{v_\Sigma} \mu'' H^2 \mathrm{d}v = P_J + P_{\mathrm{diel}} + P_{mg}, \quad (1)$$

where: σ is the conductivity, $\underline{\varepsilon} = \varepsilon' - \mathrm{j}\varepsilon''$ the complex permittivity, $\underline{\mu} = \mu' - \mathrm{j}\mu''$ is the complex magnetic permeability.

It is commonly accepted that a dielectric can be considered eligible for high frequency heating if $\varepsilon_r'' = \varepsilon_r \sin\delta \geq 0.02$. Since dielectric conductivities are in the range $\sigma = 10^{-17},\ldots,10^{-8}$ S/m and the frequency f is greater than 10^7 Hz, it follows that $P_j/P_{\mathrm{diel}} < 10^{-3}$ in all dielectric heating applications. For a dielectric having the loss angle tgδ and taking into account that $\varepsilon'' = \varepsilon \sin\delta \cong \varepsilon \,\mathrm{tg}\,\delta$ (due to the small values of δ), the power density in the lossy dielectric is:

$$p_{\mathrm{v}} = \omega \varepsilon_0 \varepsilon_{\mathrm{r}} \mathrm{tg}\delta\, E^2 . \quad (2)$$

The power density uniformity can be appreciated with one of the following factors:

$$K_1 = \frac{\max(p_v)}{\min(p_v)}; \tag{3}$$

$$K_2 = \frac{\max(p_v) - \min(p_v)}{P_{\text{mean}}} \tag{4}$$

where P_{mean} is the mean power in the dielectric load calculated as

$$P_{\text{mean}} = \frac{\iiint\limits_{v_{\text{diel}}} p_v \,\mathrm{d}v}{V_{\text{diel}}}; \tag{5}$$

$$K_3 = \frac{\sqrt{\dfrac{\iiint\limits_{v_{\text{diel}}} \left(E - E_{\text{mean}}\right)^2}{V_{\text{diel}}}}}{E_{\text{mean}}} \tag{6}$$

where

$$E_{\text{mean}} = \frac{\iiint\limits_{v_{\text{diel}}} E \,\mathrm{d}v}{V_{\text{diel}}}. \tag{7}$$

In eqs. (4),…,(7) V_{diel} is the volume of the dielectric load and E is the electric field norm.

3. Determination of the Power Density Uniformity

Due to the symmetry conditions, the analyzed domain can be reduced to $(r, \theta) \in [0, c] \times [0, \pi/n]$.

In order to determine the analytical solution for the electric field, and thus for the power density, the equation

$$\mathrm{div}\left(\underline{\varepsilon}\,\mathrm{grad}V\right) = 0 \tag{8}$$

with the boundary conditions

$$\begin{aligned} & V(r_0,\theta) = 0, \quad \theta \in [0, \pi/n], \\ & V(c,\theta) = V_0, \quad \theta \in [0, \alpha/2], \\ & V(c,\theta) = -V_0, \quad \theta \in [\pi/n - \alpha/2], \\ & \frac{\partial V}{\partial r} = 0, \quad r = c, \theta \in (\alpha/2, \pi/n - \alpha/2), \\ & \frac{\partial V}{\partial \theta} = 0, \theta = 0 \text{ and } \theta = \pi/n, r \in [0, c], \end{aligned} \tag{9}$$

must be solved. As may be seen, for $r = c$ the boundary conditions are hybrid, Dirichlet on part of the boundary and Neumann on the rest. In this case an analytical solution using the separation of variables method cannot be found (Ioan, 1988). The hybrid boundary condition may be transformed into a Dirichlet one if a known variation of $V(c, \theta)$,

$$V(c,\theta) = g(\theta), \theta \in \left(\alpha/2, \pi/n - \alpha/2\right) \tag{10}$$

can be assumed. In this case the potential has the expression:

$$V^{(i)}(r,\theta) = \sum_{k=1}^{\infty} \left(A_k^{(i)} r^k + B_k^{(i)} r^{-k}\right) \cos k\theta , \tag{11}$$

where the subdomain (i) has a constant permittivity $\varepsilon^{(i)}$. In the simplest case $g(\theta)$ is a first grade polynomial function and the coefficients $A_k^{(i)}, B_k^{(i)}$ represent the solution of a linear system of algebraic equations obtained by imposing the boundary conditions (9), (10) and the continuity conditions for V and for the electric flux density normal component on the surfaces of discontinuity in ε.

Although the assumption that V has a linear variation in tangential direction between the active electrodes for $r = c$ is not true to reality, using higher order interpolation polynomials for $g(\theta)$ leads to cumbersome calculations. The numerical analysis of this electric field problem is however easy to implement using a suitable software. In this paper COMSOL Multiphysics was used.

4. Study of the Influence of Geometric Parameters and Permittivity of the Auxiliary Dielectric

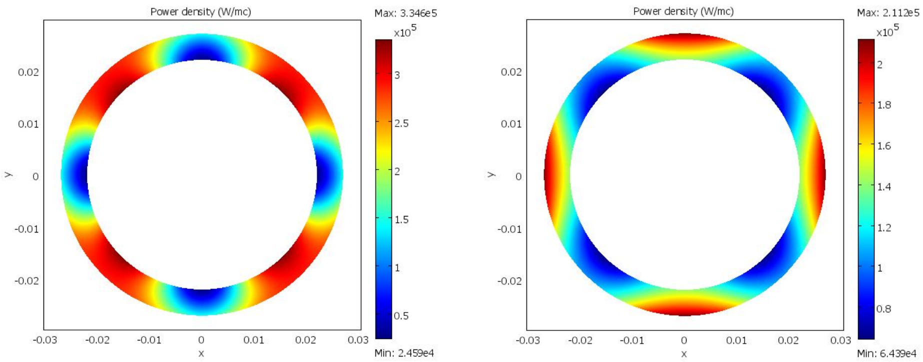
In this study the load is considered invariable (a = 2.2 cm, b = 2.7 cm, c = 4 cm, ε_r=0.4(1 – j tgδ), tgδ = 0.07, corresponding to high density PVC), while the angles α, β and the permittivity of the auxiliary dielectric assume discrete or continuous values. The first preliminary studies aimed to determine the optimal values for r_0 and c and the optimal position of the auxiliary dielectric layers with respect to the dielectric load and the active electrodes. Two objectives were taken into account: maximization of the total absorbed power P and minimization of the nonuniformity factor. The factor K_1 defined by (3) was used, considering that it reflects in the highest degree the existing power density nonuniformities. Idealy the factor K_1 is 1. Simulations showed that, for increased power absorbtion, tha radius of the grounded electrode, r_0, must be as large as possible and the radius of the active electrodes must be as small as possible, considering that there are also restrictions imposed by the technological process. Fig. 2 *a* plots the power density profile inside the lossy dielectric tube for the original configuration of the strayfield applicator, without grounded electrode and auxiliary dielectric layers; Fig. 2 *b* plots $p_v(r, \theta)$ in the case when the supplementary electrode of radius r_0 is introduced. The heating pattern is clearly modified and the factor K_1 decreases.

Next the effect of the position of the auxiliary dielectric layers was investigated. Results showed that in order to decrease the nonuniformity factor K_1 these layers must be centered with respect to the active electrodes (as in Fig. 1). The effect of using two layers of auxiliary dielectric, extending a center angle β and having different permittivities, was also studied. Table 1 summarizes the results obtained in 6 cases: a) using only the outer dielectric layer; b) using only the inner dielectric layer; c) using both layers; d) using a full coating (a coaxial losless dielectric tube); e) without auxiliary dielectrics; f) without grounded electrode and auxiliary dielectrics. The results correspond to the angles $\alpha = \pi/6$, $\beta = \pi/3$, to a permittivity of the auxiliary dielectric ε_i = epsi = 6 and to V_0 = 2 kV. The data in Table 1 show that if the most important of the two optimization criteria is the heating uniformity, then clearly only outer dielectric bands must be used (case a); this, however, leads to a smaller power absorbtion in the lossy dielectric. If the emphasis falls on the amount of absorbed power, then both dielectric layers must be used (case c) this leading to a substantial increase in P, but also to enhanced power density nonuniformity.

Table 1

Total Power and Nonuniformity Factor in Some Cases

Case	epsi	P, [W/m]	K_1	Obs.
a)	6	207.8	2.11	only ext. layer
b)	6	175	6.55	only int. layer
c)	6	518.9	6.85	both layers
d)	6	312.8	3.2	full coating
e)	1	101.1	3.28	no aux. diel
f)	1	160.1	13.65	no grounded electrode

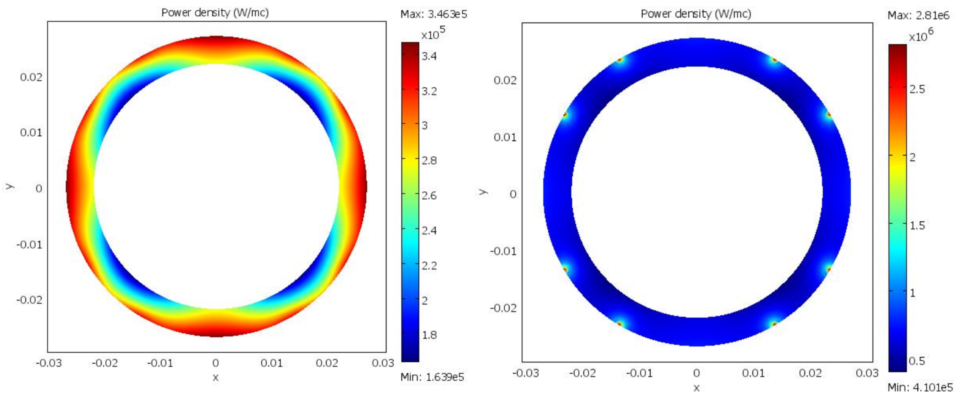


a *b*

Fig. 2 – Power density profile in original applicator (*a*), and in configuration with grounded electrode (*b*).

Fig. 3 *a* and 3 *b* show the power density profile in the lossy dielectric load in case a) and case c) respectively. These plots show that in case c) $p_v(r,\theta)$ is almost uniform, the zones with higher electric field (and thus higher p_v)

occupying very small areas. In fact in case c) a value $K_1 = 2.16$ is obtained for a volume representing 93% of the total lossy dielectric, and, if the excluded zone is increased, a value $K_1 = 1.01$ is obtained for a volume representing 85.6% of the total one.



a *b*

Fig. 3 – Power density in lossy dielectric tube in cases a) and c) – Table 1.

This analysis clearly shows the efficiency of introducing the supplementary grounded electrode (compare cases a), b), c) with case f)), both in terms of absorbed power and temperature uniformity. Moreover, the effect of using two dielectric layers of equal permittivity (practically thicker dielectric bands applied directly on the load) in order to increase P and decrease K_1, is evident (cases a, b, d compared with case c). Case c), which proved optimal so far, was reiterated for $\alpha = \beta = \pi/6$ leading to $P = 507$ W/m, $K_1 = 22.72$; $\alpha = \pi/6$, $\beta = 2\pi/5$, giving $P = 473.7$ W/m, $K_1 = 6.3$; $\alpha = \pi/3$, $\beta = \pi/3$ resulting in $P =$ $= 995.3$ W/m., $K_1 = 7.3$.

These tests, which form a preliminary stage in a cyclic optimization algorithm along the directions of the design variables, showed the efficiency of the technological solution proposed in this paper which consists in using a supplementary cylindrical electrode of potential $V = 0$ and using lossless dielectric bands centered with respect to the active electrodes, that extend center angles $\alpha = \pi/6$, $\beta = \pi/3$, or $\alpha = \beta = \pi/3$. The former of these two cases was considered optimal in this study because it also requires a smaller output power of the high frequency oscillator.

The influence of the auxiliary dielectric permittivity, epsi, over the total absorbed power P is illustrated in Fig. 4. The plots are given for several values of α and β in case c), and for $\alpha = \pi/3$ in cases d) and f). The value epsi = 6, used for all previous simulations was chosen on the grounds that it leads to a maximum value of P in case d) (full coating of the lossy dielectric), both for $\alpha = \pi/6$ and for $\alpha = \pi/3$. These results show that increasing the angle α from $\pi/6$ to $\pi/3$ leads to approximatively a 90% increase in the absorbed power. At the same time if $\alpha = \pi/6$ the value of β ($\pi/3$ or $\pi/6$) bears practically no importance on the value of P, but for $\alpha = \pi/3$ the largest absorbed powers are obtained when $\beta = \pi/3$, with a substantial decrease in P for $\beta = \pi/6$.

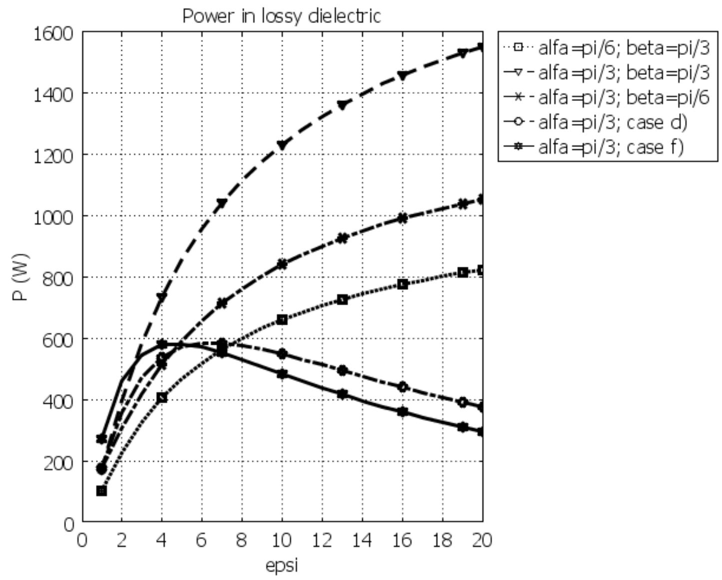


Fig. 4 – Influence of permittivity ε_i on the total absorbed power.

Another interesting observation is that the dependence $P(\varepsilon_i)$ exhibits a maximum value when the dielectric around the load is homogeneous, and it is monotonically increasing if dielectric bands extending an angle β are used instead.

A clear way to increase the absorbed power would be to use auxiliary dielectric bands of higher permittivity, but with a drawback in power density uniformity because the two objectives (maximizing P and minimizing K_1) are in conflict.

5. Conclusions

The technical solution proposed in this paper for increasing the power density uniformity and the total absorbed power in a RF strayfield applicator destined for heating lossy dielectric tubes proved efficient, leading to notable improvements in both objective functions. The technique consists in using a supplementary cylindrical electrode of zero potential, and bands of lossless dielectric, disposed in the same angular positions as the active electrodes. The simulations showed that it is possible to obtain a nonuniformity factor K_1 very close to the minimum value in a substantial volume of the lossy dielectric (over 85%).

The results obtained may be considered as a starting point for applying optimization techniques such as evolutionary algorithms for this particular application.

REFERENCES

Domínguez−Tortajada E., Monzó−Cabrera J., Díaz−Morcillo A., *Uniform Electric Field Distribution in Microwave Heating Applicators by Means of Genetic Algorithms Optimization of Dielectric Multilayer Structures*. IEEE Trans. on Microwave Theory and Techniques, **55**, *1*, 85-91 (2007).

Ioan D., *Methods for the Determination of Electromagnetic Fields* (in Romanian). Instit. Politehnic, Bucureşti, 1988.

Metaxas A.C., *Foundations of Electroheat:A Unified Approach*. Wiley, 1996.

Petrescu C., *Comparative Analysis of Two Radio−Frequency Strayfield Applicators with Axial Symmetry*. Rev. Roum. Sci. Techn.− Électrotechn. et. Énerg., **40**, *3*, 329-339 (1995).

Petrescu C., Ferariu L., *Modeling of Dielectric Heating in Radio Frequency Applicator Optimized for Uniform Temperature by Means of Genetic Algorithms*. World Academy of Sci., Engng. a. Technol., **47**, 129-134 (2008).

Ţugulea A., Petrescu C., *Heating Lossy Dielectric Tubes in a New Type of Radio Frequency Applicator*. Rev. Roum. Sci. Techn.− Électrotechn. et. Énerg., **37**, *3*, 331-344 (1992).

* * * *Dielectric Heating for Industrial Processes*. Union Internationale D'Electrothermie, 1992

INSTALAŢIE ÎMBUNĂTĂŢITĂ PENTRU ÎNCĂLZIREA UNIFORMĂ A UNOR TUBURI DIELECTRICE CU MEMORIE TERMICĂ

(Rezumat)

Este prezentată o tehnică nouă de creştere a uniformităţii temperaturii, precum şi a puterii totale absorbite, într-un aplicator cilindric de tip strayfield destinat încălzirii în câmp electric de înaltă frecvenţă a unor tuburi dielectrice cu pierderi. Tehnica constă în utilizarea unui electrod suplimentar conectat la masă şi a unor straturi dielectrice fără pierderi ce acoperă parţial sarcina supusă încălzirii. Simulările arată că, pentru o alegere adecvată a parametrilor, se poate obţine o încălzire uniformă în 85% din volumul sarcinii dielectrice.