Concerning the computation program of the magnetron geometry to operate in dynamic oscillation regime

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Abstract— This paper deals with an automatic program to design the anode-cathode geometry of a coaxial high power magnetron, which is a part an experimental setup to thermal processing of medical solid waste. The program design developed in Matlab has the purpose to give information concerning the allowable variation of the power supply parameters so that to maintained the oscillation regime of magnetron. The design program is based on the analytical algorithm which was applied in references in the field. In the introduction, a bibliographic synthesis of the main theoretical aspects of magnetron operation is made. It is highlighted the influence of the geometric sizes and the correlation of this with the values of the supply voltage and magnetic induction on the magnetron oscillation regime. The results obtained with the design algorithm are compared with the measured sizes on the sectioned magnetron from the our electrotechnologies laboratory. The magnetron oscillation conditions, which are specified in the references, are also verified. Analyzing the numerical and graphical results, the conclusions concerning the variation range of power supply can be drown and consequently, the voltage supply of the experimental setup can be controlled

Keywords— magnetron, oscillation regime, computation program.

I. Introduction

THE magnetron is the key component of the microwave oven. The magnetron is an electronic tube in vacuum used to produce the microwave electromagnetic field; the magnetron functioning is based on the electrons movement under simultaneously actions of the static and orthogonal electric and magnetic fields.

Microwave oven uses the cylindrical magnetron with identical resonant cavities in the copper anode, working in the dynamic oscillation regime. The magnetron provides 2.45 GHz microwaves field which are propagated by means of a waveguide to the inside of the applicator (oven cavity) where it interacts with the material to be thermal processed, resulting its heating. The magnetron construction comprises the copper anode having the resonant cavities and slots whose sizes determine the value of the output electromagnetic field frequency; the cathode made of molybdenum or wolfram – thorium, is heated by a filament to provide thermo electronic emission of the electrons [1],.[2],[3], [4], [5]..

Between anode and cathode a high voltage U_a is applied and consequently, an intense radial electric field E_o is created. The axial magnetic field is created by means of two permanent magnets which are transversely mounted on the magnetron axis. The main electrical parameters of magnetron are the frequency of oscillations f, anode voltage U_a, anode current I_a, filament voltage U_f, filament current I_f, number of resonant cavities N, magnetic induction B_o.

The number of resonant cavities N can be 6, 8, 10,... . The operation mode of the magnetron is the progressive waveform with π oscillations type, meaning the phase difference of the electromagnetic field from two neighboring cavities is π. Under the simultaneous action of the electric and magnetic fields, electrons move after cycloidal curves. For a given value of the anodic voltage, if $B_o > B_{ocr}$, the electrons does not reach the anode, but they move on a cardioids trajectory. The critical value of the magnetic induction B_{ocr} depends on by the anodic voltage value U_a and by the values of the anodic radius r_a and cathodic radius value r_c, according to relation [3]–[4]:

$$B_{ocr} = \frac{\sqrt{\dfrac{8m \cdot U_a}{e}}}{r_a\left(1-\dfrac{r_c^2}{r_a^2}\right)}, \tag{1}$$

where m and e are the values mass respectively the charge of the electron.

The dynamic regime of magnetron operation requires that electrons to move long time in the anode - cathode interaction area, having the size $d=r_a-r_c$; this requirement means the fulfillment of the relation [6], [7]

$$U_a < U_{acr}, \text{ where } U_{acr} = \frac{e}{8m}\cdot r_a^2\left(1-\frac{r_c^2}{r_a^2}\right)^2\cdot B_o^2 \tag{2}$$

U_{acr} is the critical value of the anodic voltage. This equation represents the Hull's parabola of the critical regime $U_{acr} = f\left(B_o\right)$. In case of the magnetron with N resonant cavities, N oscillation modes appear, with the phase shift

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$\varphi_n = \frac{2\pi \cdot n}{N}$, $n = 0,1,...,N-1$; for $n = N/2$, $\varphi = \pi$. For a certain type of oscillations, for a given value of *n*, there also may be spatial harmonics.

$$v_{pn} = \frac{l_o}{\Delta t} \tag{3}$$

where $l_o = 2\pi \cdot r_a / N$ is the distance between two neighboring cavities and Δt is the time it takes for l_o distance. Depending on the angular frequency ω_n the phase velocity can be expressed:

$$v_{pn} = \frac{\omega_n \cdot r_a}{n} \tag{4}$$

Taking in to account the spatial harmonics, results:

$$(v_{pn})_p = \frac{\omega_n \cdot r_a}{n + pN}, \quad p = 0, \pm 1, \pm 2,.. \tag{5}$$

where *p* is the order of the spatial harmonic; for *p*=0, the fundamental wave of the considered oscillation mode is obtained.

The choice of the constructive parameters of the magnetron, as well as of the U_a and B_o values are conditioned by the delay ratio:

$$\frac{c}{(v_{pn})_p} = \frac{\lambda(n + pN)}{2\pi \cdot r_a} \tag{6}$$

where λ being the wavelength of the high frequency oscillations. It can be seen that the maximum value of the phase velocity is obtained also for $n = N/2$.

The occurrence of oscillations in the magnetron is highlighted by the occurrence of the anodic current as result of the electrons which reach the anode and transfer a part of their energy to the high frequency electromagnetic field.

The auto-oscillation condition is given by the relation $U_a \geq U_{apr}$ where U_{apr} is the anode threshold voltage whose dependence on magnetic induction is given by the Hartree's line:

$$U_{apr} = \frac{\omega_n}{n + pN} \cdot r_a^2 \left(1 - \sigma^2\right) \cdot B_o + \left(\frac{\omega_n}{n + pN}\right)^2 \frac{m \cdot r_a^2}{2e}, \quad \sigma = \frac{r_c}{r_a} \tag{7}$$

The magnetron's allowable oscillation zone is given by the zone between Hull's parabola and Hartree's line of synchronism, curves whose point of intersection is the point of synchronism with the coordinates:

$$U_{as} = \frac{m r_a^2}{2e}\left(\frac{\omega_n}{n + pN}\right)^2, \quad B_{os} = \frac{2m}{e\left(1 - \sigma^2\right)} \cdot \frac{\omega_n}{n + pN} \tag{8}$$

Accordingly, the magnetron operation in the dynamic regime, requires fulfilling the conditions [5]:

$$B_o > B_{ocr}; \; U_{apr} \leq U_a < U_{acr}; \; U_{a\min} = U_{as} \tag{9}$$

The references [6], [7] present electromagnetic design of coaxial cavity for high power X-band coaxial magnetron; the initial dimensions of the cavity have been calculated by solving transcendental equation using graphical method..The obtained results were validated through the experimental methods.

II. Elements Of Magnetron Geometry Design

As can be noticed from the references in the field, the magnetron oscillation regime corresponds to the area between Hartree's line and the Hull parabola. The position of the operating point in the specified area depending on the ratio between the cathode radius and the anode radius as well as the anode voltage and the magnetic induction value. The calculation methodology is based on the design algorithm presented in [2], which it was applied to design the high power industrial installations dedicated to the thermal processing in microwave.

A. The cathode design

The cathode design involves the computation of the cathode radius, cathode and filament sizes, the average value of the emission current density J_e. To calculate the cathode radius r_c it is used a formula which is obtained through the conditions [2] concerning the occurrence of electrons trajectories in the interaction space *d* between anode and cathode:

$$r_c = \frac{m \cdot E_o}{e \cdot B_o^2} \tag{10}$$

The diameter d_f and the active length of the filament l_f are obtained based on the heating specific power value, which corresponding to the used material (eg. wolfram):

$$p = (U_f \cdot I_f)/(\pi \cdot d_f \cdot l_f) \tag{11}$$

If d_f < 1mm, it is recommended [2] that the turn diameter of filament to take a value from the variation range d_{sf}=(4…10)d_f. The number of turns of the filament, will be $n_{sf}=l_f/(\pi d_{sf})$. The active length of the cathode is given by the formula:

$$l_c = n_{sf} \cdot d_f + (n_{sf} - 1) p_i \tag{12}$$

The filament parameters must provide the emission current:

$$I_e = \frac{\pi \cdot d_c \cdot l_c}{J_e}. \tag{13}$$

B. The anode design

The anode geometry must allows the conditions needed to ensure the oscillation regime of the magnetron. The anode radius is computed using formula:

$$r_a = \frac{N \cdot \lambda}{8 \cdot \pi} \cdot k_s \tag{14}$$

This relation is specific to a closed-loop resonant system, having the distance l_o between two neighboring cavities according to $l_o \leq \lambda/4$. Because the surface of the cavity has resonant properties and cavity lamellas have finite dimensions, a shortening coefficient is is taken into account k_s. The length of circle with anode radius is $l=l_o \cdot N$, and the pitch between two neighboring cavities will be $p_a=r_a \cdot 2\pi/N$. From the previous formulas it is noticed that a great influence has the ratio σ, for which references [2], [3], [8], [9]. recommend the relation $\sigma=0,85 \div 3,83/N$. The length of the anode must satisfy the condition $l_a \leq 0,3 \cdot \lambda$. The output circuit, which transfers the high frequency energy to the load circuit, has a length equal to an integer number of quarter-wavelengths $l_{cies}=k \cdot \lambda/4$.

III. The Computation Program

The automatic computation program of the magnetron geometry is developed in an interactive manner. The input data are: The output power P_i, U_a, I_a, U_f, I_f, B_o, N. The flowchart of the program is presented in Fig. 1:

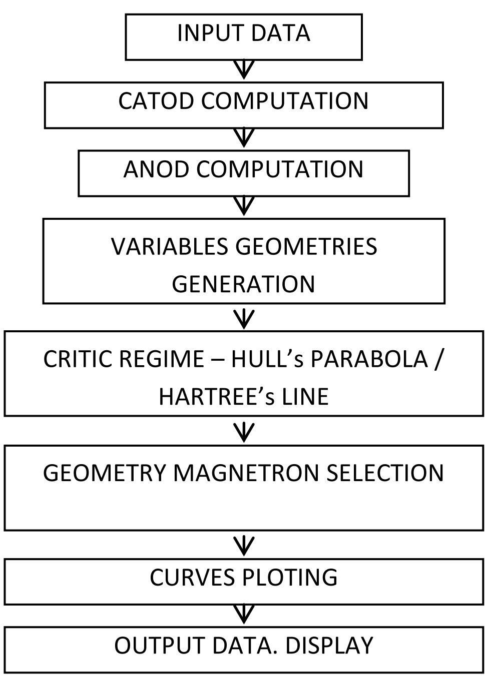


Fig. 1 The main program flowchart

The additional input data are the parameters of cathode material (wolfram-thorium or molybdenum) and the electromagnetic constants. The input data can be entered by means of an *.m file data or from the keyboard. Considering different variation ranges of the magnetic induction admissible values and of the ratio $\sigma=r_c/r_a$ is computed a large number of variable geometries of magnetron. Selection of admissible geometric configurations is done automatically by meeting the requirements: $B_o>B_{ocr}$, $U_{apr} \leq U_a<U_{acr}$. The operating point (U_a,B_o) must be found in the oscillation area between the Hartree's line and Hull's parabola. The final geometry is selected corresponding to the maximum value of the magnetron efficiency. The program allows graphical plotting of the oscillation zone and the operating point. The computed data for the selected constructive variants are automatically saved in text files.

IV. Program Application

The Matlab program was applied for sizing of a magnetron with the rated data:

$$\begin{aligned} &U_a = 4,2kV;\ I_a = 1,2A;\ U_f = 3,15V; \\ &I_f = 10\,A;\ N = 10;\ P_i = 1100W \end{aligned} \tag{15}$$

The constructive variants are obtained corresponding to variation ranges of the magnetic induction $0,03 \leq B_o \leq 0,095$T, respectively of the variation range of the ratio $\sigma=r_c/r_a$, $0,2 \leq \sigma \leq 0,95$. A number of six variants have been selected, from which the final variant corresponds to the maximum value of the magnetron efficiency.

In the figures 2a) and 2b) are shown the graphical variation of the threshold voltage (the Hartree's lines) and the variation of the critical voltage (Hull's parabolas) depending on the magnetic induction value, for three values of the ratio σ.

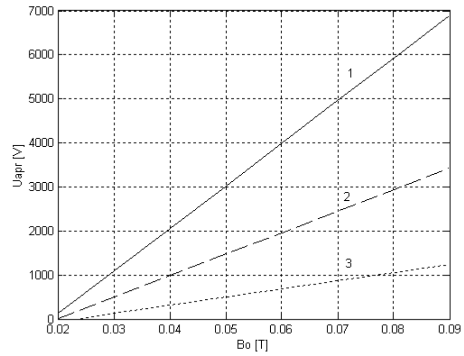
It is found that for the same value of the magnetic induction both threshold voltage and critical voltage increase as the ratio σ increases. For a constant value of the cathode radius these voltages values increase as the value of the anode radius increases or as the value of distance $d = r_a - r_c$ increases. The work [2] recommends for the σ ratio the range of variation $0,21 \leq \sigma \leq 0,85$, suitable for the magnetron having the number of resonant cavities $N \geq 6$.

In the figures 3 a) and 3b) are graphically represented the oscillation zones as well as the operating point for two variants from those six selected variants.

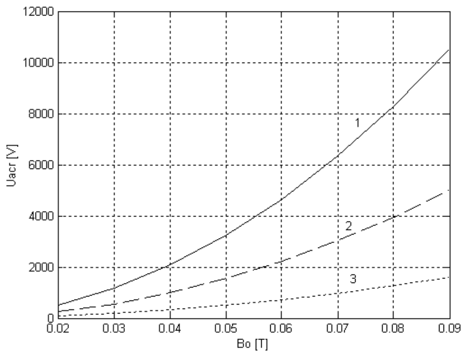
It is noticeable that the anode voltage deviations can lead to the removal of the operating point from the oscillation zone.

The validation of the computation program is made by comparing the calculated data with the measured ones on a magnetron having the same nominal data

The magnetron which was sectioned to measure the sizes is shown in the photo from Fig. 4.

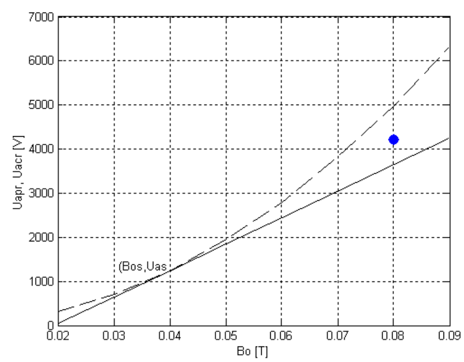


a) Hartree's lines

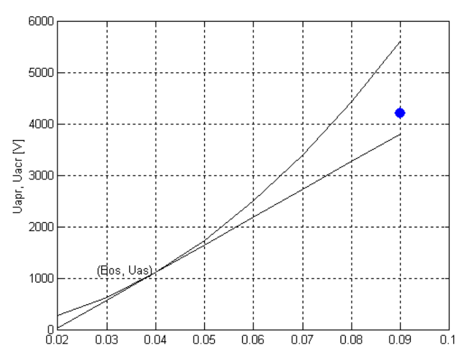


b) Hull's parabolas σ: 1-σ=*0,5*; 2-σ=*0,34*; 3-σ=*0,25*;

Fig. 2 the graphical variation of the voltage



a) variant V_1



b) variant V_2

Fig. 3 the oscillation zones and the operating points for 2 variants

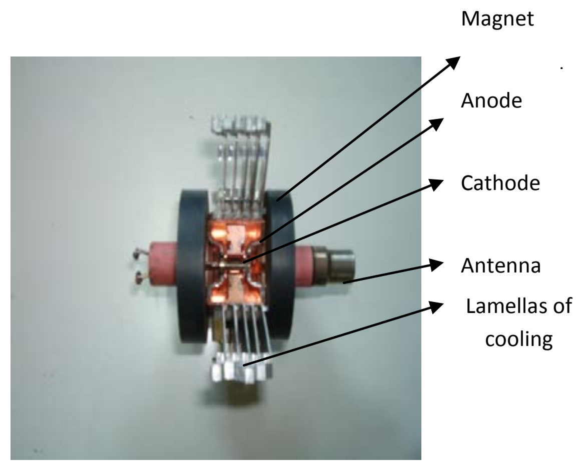


Fig. 4 section through the magnetron

Table 1 presents comparatively the calculated data for three selected variants from those 6 selected, with data measured on the sectioned magnetron. Any errors are due to parameters values for the cathode or filament material, having no knowledge about the right type of materials used by the magnetron producer.

Table 1 The comparison between the main measured and computed parameters

Parameters	Measured value	Computed values		
		Variant V_1	Variant V_2	Variant V_3
d_f [mm]	0,5	0,5	0,5	0,5
nspf	8	8	8	8
d_c [mm]	4	4	4	4
r_c [mm]	2	2	2	2
r_a [mm]	5,75	6,3	6,6	6
d_i [mm]	3,75	4,3	4,6	4
σ	0,42	0,32	0,305	0,335
B_o [T]	0,090	0,090	0,090	0,090
B_{os} [T]	-	0,032	0,0386	0,039
B_{ocr} [T]	-	0.078	0.0735	0,082
U_{apr} [V]	-	3806,2	3645,24	3424,5
U_{acr} [V]	-	5610,1	4981,8	5007,5
U_{as} [V]	-	1051,5	1157,5	959,5
η	-	0,45	0,29	0,31

V. CONCLUSION

In this paper are presented the results obtained with a Matlab application of design the anode cathode geometry of a magnetron from the experimental setup dedicated to thermal processing of the medical solid waste. The computed geometries are selected taking into account the constraints concerning the operating point of magnetron which must be found in the area between the Hull's parabola and Hartree's line. The computation algorithm is based on the references in the field. The computed sizes are compared with the measured ones on the sectioned magnetron from the Electrotechnologies

Laboratory. From graphical displayed in Figures 3a) and 3b) it can be noticed that the anode voltage deviations can lead to the removal of the operating point from the oscillation zone. That can be happens at the variation of the supply voltage of the experimental setup beyond the admissible variation range.

It has been determined by measurements that when the supply voltage drops below 180V, it has the effect of removing the operating point out of the permissible area and therefore the magnetron does not generate a microwave field

The criteria of maximum efficiency of the magnetron allows selecting the final anode cathode geometry of the magnetron. In addition to the main program were developed an application to compute the required power to heat in a microwave field a given amount of dielectric material corresponding to the existing applications in the industry.

REFERENCES

[1] Maria Brojboiu, "Electrotehnologies", Publishing House. Orizonturi Universitare, Timişoara, 2003 (in romanian).

[2] M. D. Tucă, V. Cuciurean, "Microwaves in the industrial applications", Publishing House ICPE, Bucuresti, 1985 (in romanian).

[3] D.D. Sandu, "Electronical devices for microwaves", Scientific and Encyclopedic Publishing House., Bucureşti, 1982. (in romanian).

[4] N. Voicu, "Microwave systems", Publishing House MatrixRom, Bucureşti, 2004. (in romanian).

[5] Maria BROJBOIU, Virginia Ivanov, "Concerning the operation regime of the magnetron", *ACTA ELECTROTEHNICA* , vol. 51, No. 5, 2010, ISSN 1841, 3323, MPS 2010, Cluj Napoca, 2010.

[6] Jerry C. Whitaker, "The electronics handbook ",CRC Press, 2005, https://books.google.ro/books?id=9VHMBQAAQBAJ&printsec=frontcover&hl=ro#v=onepage&q&f=false

[7] *** - Microwave magnetron - https://www.jlab.org/ir/MITSeries/V6.PDF

[8] Mohit Kumar Joshi, Sandeep Kumar Vyas, T. Tiwari, Ratnajit Bhattacharjee, "Design of Coaxial Cavity for High Power Magnetron" – available on https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7932354

[9] Kartikeyan Machavaram, D S Venkateswarlu, "Computer Aided Design of the Coaxial Cavity of Circular Electric Mode Magnetron" – available on https://www.researchgate.net/publication/279696139_Computer_Aided_Design_of_the_Coaxial_Cavity_of_Circular_Electric_Mode_Magnetron

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