THERMAL BALANCE IN PLANE THERMOIONIC CATHODES OF RADIO-FREQUENCY TUBES WITHOUT ANODES

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Abstract. Cathode units of high power radio-frequency tubes are conventionally used in electron injectors with high repetition rate. This cathode utilization results in disturbance of the temperature regime of the cathode surface because of cutting the anode, which is “thermal mirror” in the tube. Estimations made in this work show an essential lowering of the emitter temperature for both porous metal and oxide cathodes without anodes. It shows that the oxide cathode utilization results in a significant thermal gradient in the oxide layer.

The test stand was designed for the testing of the emission capability of cathode units with different type of emitters. The temperature measurements of the emitter surface and compensation of the thermal losses are available on that stand.

The results of the testing and recommendation for the use of cathodes of a high power radio-frequency tube without the anode are discussed.

Keywords: filament, thermal mirror, gradient, oxide layer, emitter surface, thermal losses,

I. Introduction

Heat emission in the grid(s) not taken into account, the heat distribution in the heater-core-oxide layer gap in a radio-frequency tube with a plane oxide thermoionic cathode seems to be practically uniform since a polished copper anode is a “thermal mirror”. According to the “Winn” law, one can estimate for the operation temperatures of the thermoionic cathode the wavelength corresponding to the maximal value of the core emitting ability. The copper reflectance for the wavelength obtained ($\lambda \approx 3 \mu m$) is not worse than 97%. In this case, though the oxide layer of the cathode is of low thermal conductivity, but in the environment of the “reactive heat” between the heater and anode it gets under “hothouse conditions” without temperature gradient and, subsequently, without thermal stresses. The picture changes significantly when there is no anode. An uncompensated thermal flow from the core and oxide layer appears, which leads surely to a significant lowering of the temperature and emitting ability of the cathode oxide layer. The temperature distribution across the oxide layer will become non-uniform because of the low thermal conductivity of the layer and can result in large mechanical stresses of the oxide layer and separation of it from the core.

II. Heat balance equation

In order to estimate the temperature of the tube cathode, we will divide schematically the radio-frequency tube into the left part, comprising the heater, cathode and grid (grids), and the right one with the copper anode only (see Fig.1). We will re-write the Fourier thermal conductivity differential equation $dQ=\lambda\cdot dS\cdot dt\cdot dT/dx$ in a microscopy form for the power: $P=\lambda_0\cdot S\cdot(T_c-T_0)/d$, where T_c – the core (and oxide layer) temperature, T_0 – the temperature of the structural elements around the tube (in the computations we will take its value equal to 293^0K), λ_0 and d – some average values of the thermal conductivity and thickness, which represent the metal-ceramics composition of the tube. By the S value is meant all the left radiating surface of the tube, since losses in the right part are small due to the low anode temperature as compared to the core temperature. We will consider the value $\lambda_0\cdot S/d = \bar{a}$ to be

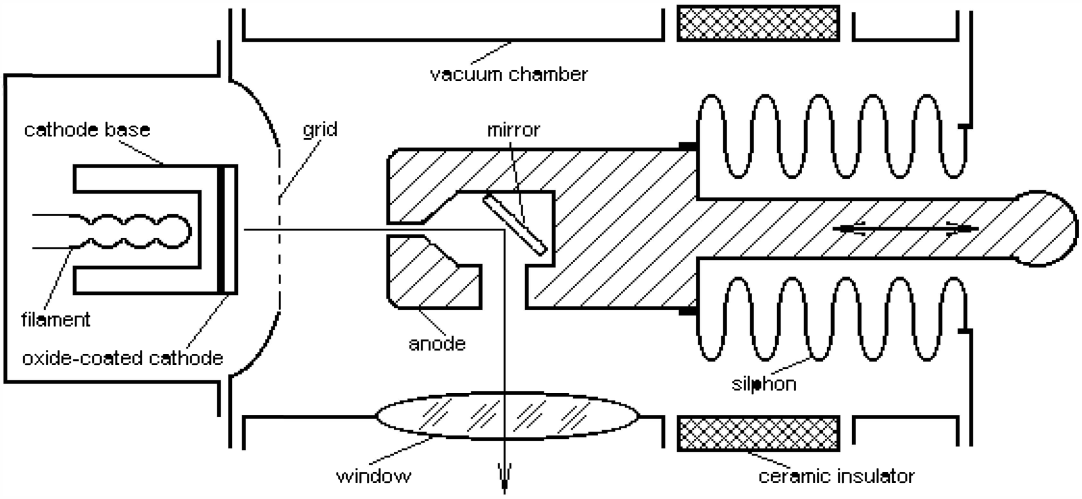

Fig.1. Scheme of the experiment.

independent on T_c in the temperature range which is interesting for us. Then the power balance equation from the heater to the tube surface will take the form $P = \bar{a}\cdot(T_c - T_0)$.

We will determine the $\bar{a}$ value from the condition of the nominal thermal balance for the tube with the anode. We will consider T_c, the cathode (core) temperature, being equal to 1050^oK from the condition of sufficient emission ($j \approx 5A/cm^2$). We will use the obtained $\bar{a}$ value for the estimation of the core temperature T_c for the case when the anode is removed from the tube and the electron beam is injected into the acceleration system with a sufficient acceleration rate. No virtual cathode can appear in such system and thus there is no additional heating of the grid.

When a tube with no anode is used, the irrevocable thermal radiation of the core with the core material blackness degree $\sigma\cdot s\cdot\varepsilon_c\cdot(T_c^4 - T_0^4)$ appears in the power balance equation. At high core temperatures, according to $^{1)}$, this radiation passes through the oxide layer practically without losses and emanates. Another channel of heat losses is realized through the oxide layer thermal conductivity $\lambda\cdot(T_c-T_{ol})\cdot s/\delta$. The thermal flow through the thermal conductivity turns finally to a radiation with the oxide layer blackness degree. In this approach, the power balance will take the following form:

$$P = \bar{a}\cdot(T_c - T_0) + \sigma\cdot s\cdot\varepsilon_c\cdot(T_c^4 - T_0^4) + \lambda\cdot(T_c - T_{ol})\cdot s/\delta, \qquad (1)$$

simultaneously:

$$\lambda\cdot(T_c-T_{ol})\cdot s/\delta=\sigma\cdot s\cdot\varepsilon_{ol}(T_{ol}^4 - T_0^4) - \qquad (2)$$

where σ - the Stephen-Boltzmann constant, s –the equivalent area of the core radiation towards the anode, ε_c – the core blackness degree, λ and δ - the thermal conductivity and thickness of the oxide layer, T_{ol} – the surface temperature of the oxide layer, ε_{ol} –the oxide layer blackness degree. Since the terms T_0^4 are negligible in comparison with T_c^4 or T_{ol}^4, then equation (2) can be re-written in a simpler form: $\Delta T=(T_c-T_{ol})=\sigma\cdot T_{ol}^4\cdot\delta\cdot\varepsilon_{ol}/\lambda$ (3)

We will seek the joint solution of equations (1) and (3) with above assumptions as $P = f(T_{ol})$

$$P=a\cdot\{[\sigma\cdot\delta\cdot\varepsilon_{ol}\cdot T_{ol}^4+\lambda(T_{ol}-T_0)]/\lambda\}+\sigma\cdot s\cdot\varepsilon_c\cdot[(\sigma\cdot\delta\cdot\varepsilon_{ol}\cdot T_{ol}^4+\lambda\cdot T_{ol})/\lambda]^4+s\cdot\sigma\cdot\varepsilon_{ol}\cdot T_{ol}^4 \quad (4)$$

The expression obtained allows one to trace the temperature of the emitting surface in the tube with the oxide cathode as a function of the applied filament power.

Similar expressions can be obtained for the porous–metal tungsten-barium thermoionic cathode (L-cathode). For this purpose we will use equation (3), the oxide layer temperature T_{ol} being replaced with the emitter temperature T_e, and equation (1) without the core emitting term.

The equation for the numerical computation is

$$P = a\cdot\{[\sigma\cdot\delta'\cdot\varepsilon_e\cdot T_e^4+\lambda'\cdot(T_e-T_0)]/\lambda'\}+s\cdot\sigma\cdot\varepsilon_e\cdot T_e^4 \quad (5)$$

where δ', λ' and ε_e are, correspondingly, the thickness, thermal conductivity and degree of blackness of the tungsten-barium composition of the L-cathode. The rest designations are the same.

III. The digital calculation and experiment results

The results of the numerical computations of T_c and T_{ol} for the oxide cathode are presented in Fig.2. Comparison of the temperature behavior curves for the core and oxide layer surface shows that the core temperature in the tube with no anode is almost by 150° lower than that in the tube with the anode at the nominal regime.

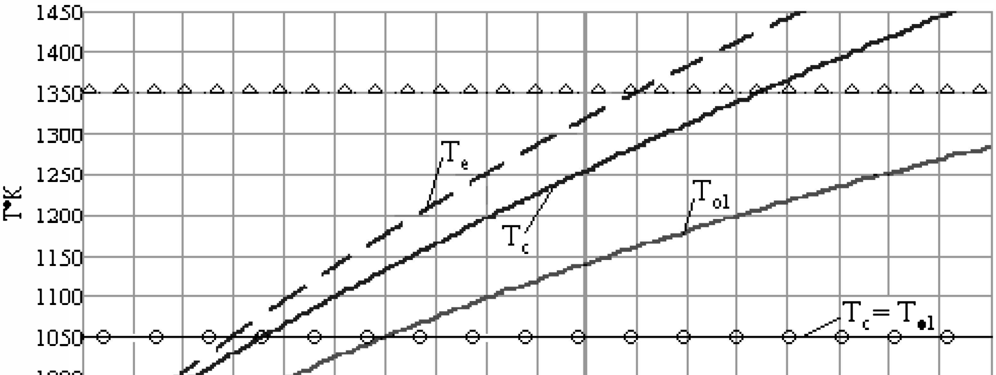

Fig.2. a) behavior of the oxide layer temperature T_{ol} and core temperature T_c (the lower solid curves) as a function of the power applied to the heater; the dots indicate the temperature $T_c = T_{ol}$ for the tube with the anode and nominal regime, b) behavior of the emitter temperature T_e for the tube with the L-cathode and with no anode; the triangles mark the temperature of the L-cathode in the tube with the anode.

Because of the low thermal conductivity of the oxide layer, the temperature difference of the core and oxide layer at the nominal filament is about 30° and is as high as 100° at a recover of the emitting surface temperature through increasing the filament power. General considerations make one think that such temperature gradient on the oxide layer is very large.

Unfortunately, absence of reliable data on the thermal expansion coefficients of the oxide layer as well as on the adhesion to the core does not allow estimating the separation and destruction of the oxide layer.

It should be noted that if the temperatures required for efficient emission of the thermoionic cathode in the tube with no anode are reached via increasing the filament power, its durability lowers significantly. According to the reference data, the durability does not exceed 1000 hours at a temperature of 1100°K and is as small as 30 hours at 1200°K.

Fig.2 presents the results of the numerical computation of the temperature of the emitting surface of the tube with the L-cathode. Comparison of behavior of temperatures of the core and emitting surface shows that the temperatures are practically equal. Thus, due to the high thermal conductivity, in the radio-frequency tube with the porous-metal cathode, is it with or without anode, there is no temperature gradient. The total lowering of the cathode temperature, in principle, can be corrected through increasing the heater power if its design allows this. This increase is estimated as 2.

To verify the estimations obtained, a stand presented in Fig.1 was created. The movable anode is an important element in its design. The anode locating close to the grid, a cathode temperature distribution similar to the one in the tube with the anode can be obtained. The anode being significantly distant from the grid, the thermal balance is destroyed and one can estimate the lowering of the cathode temperature by the emission characteristics of the tube measured in the diode regime. The computed temperature lowering was about 100^{o}K in the first experiments with the oxide cathode. The temperature lowering determined with the help of a pyrometer was not less than 150^{o}K.

IV. Summary

So, one must take into account absence of the anode and correct the thermal regime when using pre-fabricated cathode units. For porous-metal cathodes that can be made by a simple increase of the filament power, which eliminates a part of the problems inherent to the tubes with oxide cathodes, but L-cathodes are inferior to them in the thermal load on the grids and in the slope of the anode-grid characteristic. The second circumstance, combined with the hardly-realized possibilities of the cathode-grid modulator, most likely will not allow one to obtain electron bunches with a sufficient charge of a nanosecond duration and high repetition rate. A serious competition to L-cathodes can be made by the designs of less expensive cathode units with oxide thermoionic cathodes, where the way to compensate the thermal flow from the oxide layer with help of an external source will be found.

References

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