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MICROWAVE POWER ABSORPTION MEASUREMENT BY MEANS OF CALORIMETRIC METHODS

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Abstract: This paper presents some possibilities for microwave power measuring by means of calorimetric methods. Along with their working principles, the practical devices are also shown. Measurement of microwave power is very important for determining the use of microwave installations and devices according to the required application.

1. INTRODUCTION

Power is defined as energy developed in time unit. In the microwave range, this energy is used for information transmission at long distances (telecommunications, RADAR etc), for molecule excitation in order to obtain thermal effects (industrial electrothermics, medical electrothermics, household utilities etc), for elementary particles acceleration (nuclear physics) etc. Based on the consumed power, the economical efficiency of the installations can be assessed. In the microwave range, the active power cannot be determined from the relation

$$P = U \cdot I \cdot \cos\varphi \qquad (1)$$

by measuring voltage, current intensity and power factor as in audio and radio frequency range, because in most cases voltage, for example, cannot be determined. Voltage can be defined in TEM mode, but it can achieve quite different values in various waveguide zones, which goes also for current intensity distribution. For these reasons, microwave power can be determined only by direct means. Direct power measurement is one of the most useable measuring methods, and can be applied in a wide range of electromagnetic oscillations. An advantage of the direct measurement methods is that the determined quantity – mean power over the measuring time interval – is scalar and can be expresses as a single number.

The power measuring instruments are classified by the effect they are based on, by the power range to be measured and by the way that they are connected to the microwave transmission system. According to the last criterion, there are:

- *transparent instruments*, which absorb only a small known fraction of the transmitted power, without any perturbation of the matching conditions of the main transmission line;
- *terminal instruments*, which are connected conectate ca sarcină a liniei de transmisie şi absorb întreaga putere incidentă; în acest scop ele trebuie să fie bine adaptate la linie (ghid de undă).

2. CALORIMETRIC MEASURING METHODS FOR MICROWAVE POWER

The microwave power measurement by means of calorimetric methods is based on the thermal effects of the microwaves. The calorimetric instruments, which are the most accurate power measuring devices, can be *static* or *flux-based*. The operating medium, which comes under the thermal effects of microwaves, usually consists of a lossy, dielectric, absorbing fluid.

2.1. Direct method of measuring microwave power in the applicator

Water is used as an absorbing load, within which the high-frequency power is transformed into heat. Taking into account the load mass, the initial and final temperatures and the exposure time, the microwave power can be calculated. This method is one of the most accurate microwave power measuring methods.

The water used as dielectric load is a dielectric material with relative permittivity $\varepsilon_r = 81$. This quantity varies greatly with temperature; the value $\varepsilon_r = 81$ was measured at 15°C, but at 60°C the value $\varepsilon_r = 65$ is obtained.

Within the calorimetric methods, specialized devices (named as *calorimetric wattmeters*) can be used, along with several devices recommended by international standards, such as glass recipients of certain dimensions and quality, thermometers and chronometers.

This method is recommended by CEI705 (committee 59H), and uses as load a quantity of 1000 g ± 5 g of potable water in a borosilicate glass container, with 3 mm maximum thickness and 190 mm outer diameter. After pouring in this amount of water and measuring the initial water temperature, the recipient is placed in the geometrical center of the applicator. The generator is then started at maximal power, the exposure time is counted and, after stopping the generator, the water final temperature is measured. The microwave power, in watts, is then calculated by means of the formula:

$$P = 4187 \cdot \frac{\Delta T}{t} \quad [\mathrm{W}] \tag{2}$$

where $\Delta T = T_f - T_i \; [^\circ\mathrm{C}]$ is the variation between the initial and final temperatures of the water sample, and *t* (in seconds) is the exposure time. If the 1000 g of water is exposed to microwaves for one minute, the microwave power is:

$$P = 70 \cdot \Delta T \quad [\mathrm{W}] \tag{3}$$

2.2. Static calorimetric devices

Static calorimeters are used for measuring low and medium microwave power ranges (10^{-8}W – 1 W). The adiabatic static calorimeter consists of a thermally insulated load, which absorbs the incident microwave power and is fitted with a temperature measuring instrument. The heat balance is expressed as follows:

$$P = C \cdot \frac{d(\Delta T)}{dt} + \frac{\Delta T}{R} \tag{4}$$

where ΔT is the temperature increase, *P* is the incident microwave power, *C* is the caloric capacity and *R* is the thermal resistance versus the surrounding medium. The solution of this equation is:

$$\Delta T = P \cdot R \cdot \left[1 - \exp\left(\frac{1}{R \cdot C} \right) \right] \tag{5}$$

the thermal resistance of an ideal calorimeter tends to infinite, so relation (5) becomes:

$$P = C \cdot \frac{d(\Delta T)}{dt} \tag{6}$$

The thermal time constant is an indicator that expresses the capability of a real calorimeter to observe the adiabatic condition:

$$\tau = R \cdot C \tag{7}$$

and it should have a large value.

The double calorimeter (fig.1) is a solution that features great sensitivity. It consists of two identical calorimetric bodies 1 and 2, of which the first one dissipates the incident power to be measured, and the second one stands for temperature reference. The power is assessed by means of the temperature difference between the two bodies in stationary regime, sensed by the thermocouple 3. Calibration is carried out by substitution of the microwave power with a known low-frequency power that is applied by means of resistor R_1. However, a null method is also applicable, according to which the known low-frequency power is applied to the second calorimetric body by means of resistor R_2, without using R_1.

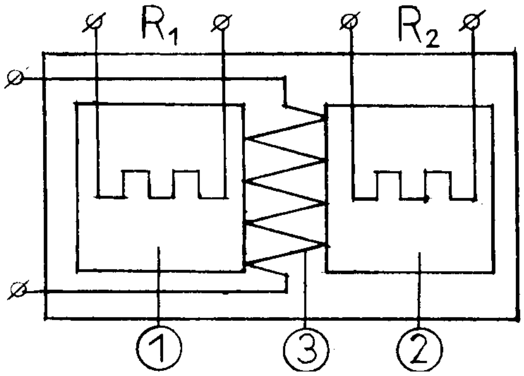

Fig.1. *Principle of the double calorimeter user for microwave power measurement.*

If temperature equilibrium is achieved by the low-frequency power that heats the reference body 2 – which can be measured with classical instruments and is automatically adjusted towards the annulment of the temperature difference by means of the thermocouple – then this power is equal to the incident microwave power to be measured. It is clear that the null method eliminates the errors caused by thermal losses and the influence of the surrounding medium.

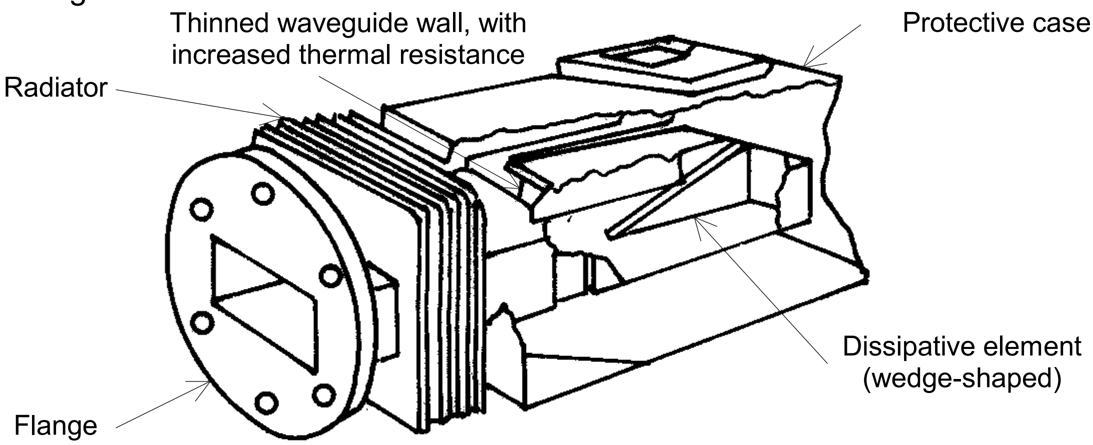

Fig.2. *Dry calorimeter, for microwave power measurement.*

The *dry calorimeter* (fig.2) also belongs to the static calorimeters category. Usually, it consists of a waveguide-shaped terminal load, and it comes mounted at the waveguide end, where it dissipates all the incident microwave power. This device does not require cooling agent and does not have any fragile parts, and its simple and robust construction allows its use as a factory instrument, designed for measuring microwave power levels of tens of watts. The thermal conversion occurs in a wedge-shaped dissipative element, in order to achieve minimal reflections. The wedge has good thermal contact with the terminal portion, which gets heated during measurement. The entrance portion is maintained at the ambient temperature by means of a radiator, and the wall between the hot and cold portions is thinned, in order to increase its thermal resistance. By measuring the temperature difference Δθ (Celsius degrees) between the cold and hot regions in stationary regime, the incident microwave power P (watts) can be calculated with the following relation:

$$\Delta\theta = \frac{P}{G_0} \tag{8}$$

where G_0 is the thermal conductance (W/deg).

2.2. Flux-based calorimetric devices

The flux calorimeters are used for medium and large power measuring (10^{-2} W ÷ 10^{6} W). They feature a load which dissipates the incident microwave power, and the heat is taken over by a fluid that circulates at constant rate. The power P (watts) is measured by means of fluid temperature difference ΔT (Celsius degrees) between the entrance and exit ports:

$$P = Q_v \cdot c \cdot \rho \cdot \Delta T \tag{9}$$

where Q_v is the volumetric rate (cm^3/s), $c = 4.18\,\mathrm{J/g \cdot deg}$ is the specific heat of water and ρ (g/cm^3) is the fluid density. The fluid circuit can be opened or closed. The devices are simpler in the first case, which use water, and the constant rate is ensured by a raised reservoir where the fluid is kept at a constant level. Other kinds of instruments use other fluids than water and thus are independent of the water network. As shown in fig.3, water features a frequency range below 1 GHz where its dielectric losses are not enough in order to constitute a dissipative medium, so it is recommended to use dielectric add-ons or other fluids.

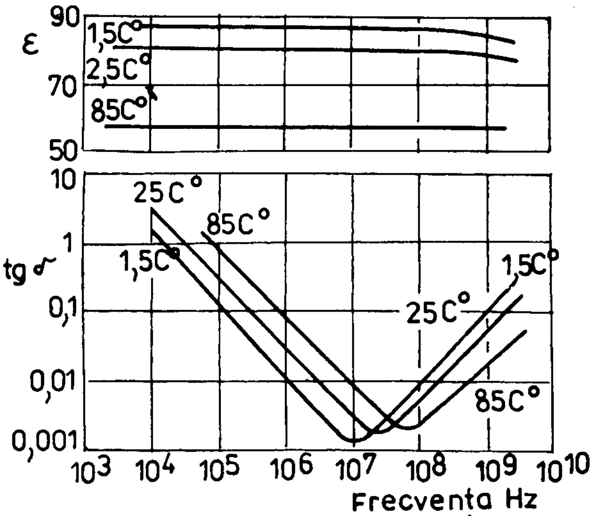

Fig.3. *Variations of the water dielectric properties with frequency and temperature.*

In order to achieve accurate measurements, along with the precise determination of the fluid temperature variations, it is necessary to exactly know the other parameters, of which the rate may be influenced by the viscosity variation caused by temperature.

The problems that arise when using flux calorimeters can be partially eliminated by means of substitution methods. By comparing the microwave power to be measured with a known low-frequency power, it becomes not necessary to accurately know the specific heat, the rate and the temperature increase.

The terminal artificial load devices are built for powers up to 10 kW, in two versions that can be adapted to coaxial and rectangular waveguides. Fig.4 shows a water coaxial artificial load which can be adapted to the 16/39 mm coaxial waveguide, used mostly in Europe.

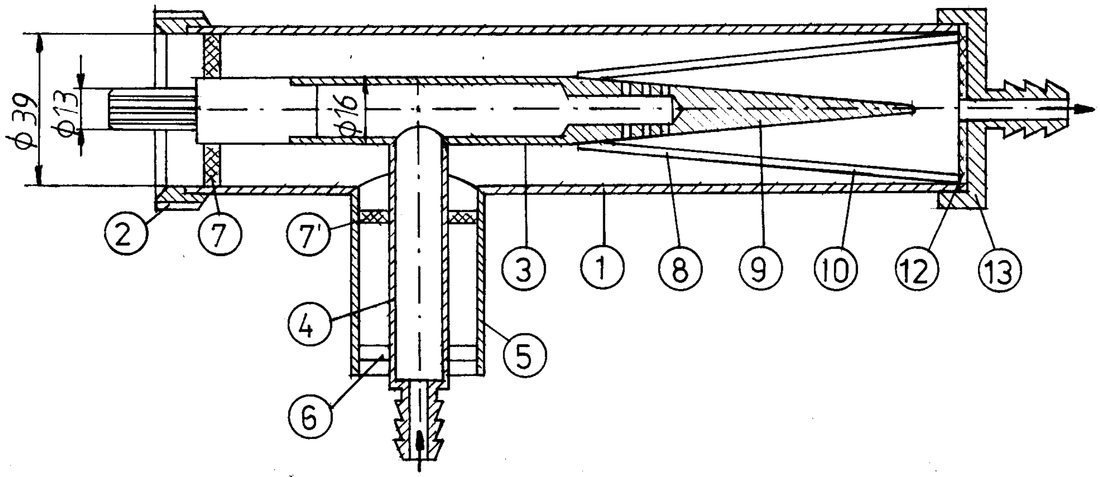

Fig.4. *Water artificial load, used for microwave power up to 10 kW in the 2.45 GHz range.*

The brass outer conductor 1, with silvered inner surface and inner diameter of 39 mm, is fitted at the left end with a connecting conical screw cap 2 in order to couple to the measurement waveguide. The hollow inner conductor 6, made of silvered copper, is laterally sustained by a tubular ramification 4, and forms with the metal cylindrical case 5 a short-circuited coaxial waveguide section with $\lambda/4$ electrical length, sustained by the metal washer 6 at the outer end. The length of this section is experimentally set, as it would represent theoretically infinite impedance in order to sustain in an insulate manner the inner conductor 3 of the main waveguide and its water supply. The 3-4 system is also sustained and centered by the Teflon washers 7-7'. The conductor 3, fitted with radial holes 8, allows the passage of water in the space between its conical end 9, the plastic conical case 10 and the thermo-insulating disk 12; the latter acts as tightening garnish between the outer conductor 1 and the metal terminal cap 13 fitted with a water outlet fitting. The microwave energy reflection is negligible due to the smooth decrease of the inner conductor interior diameter and increase of the water-filled section, thus the reflection coefficient Γ and the standing wave coefficient *S* induced by the artificial load are small; the values of *S* are contained in the range 1.02 ÷ 1.05.

This kind of artificial load and the compatible coaxial measuring waveguide were built at the University of Oradea and were used to measure the output parameters of the continuous operating 800 W magnetron.

This artificial load may be used as a simple flux calorimeter, by means of which the power can be calculated with relation (9), but maintaining a steady flow rate and measuring may be affected by errors and temperature variations. It is recommended to better use it as section 1 of the double calorimeter, and section 2 to be constructed in the exact same way with the exception that the water would be heated by means of a resistor, thus allowing the use of the comparison method which features less errors.

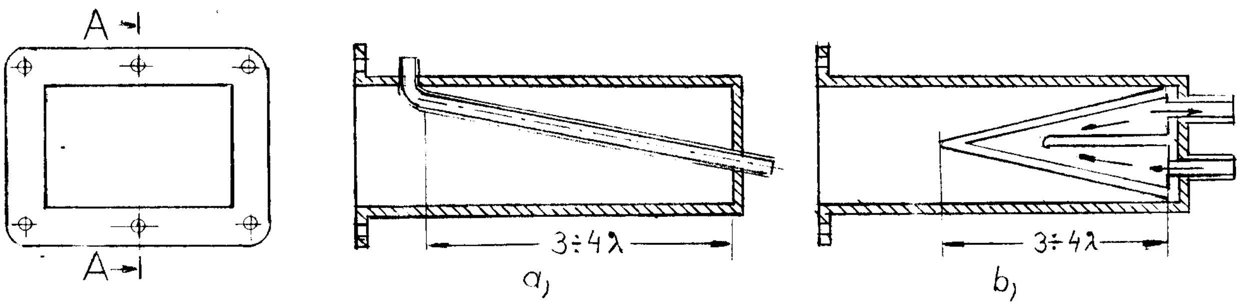

Fig.5. *Terminal artificial loads, adaptable to the 109×54 mm rectangular waveguide.*

The artificial loads that may be adapted to the 109×54 mm rectangular waveguides, used in the 2.45 GHz range, are built as in fig.5, featuring rectangular sections in the median plane parallel to the waveguide smaller sides. When measuring powers of hundreds of watts, absorption of the microwaves is achieved by mounting a water-circulated slanted glass tube of 10 mm internal diameter in the above-mentioned plan.

When measuring microwave power of thousands of watts, the power is absorbed by the water that circulates within a wedge-shaped plastic recipient, with the inlet and outlet fittings mounted at the waveguide terminal end. The wedge width may be equal to the waveguide internal width, thus ensuring the maximal power absorption. The minimal standing wave coefficient has values comparable to the ones for coaxial version.

3. CONCLUSIONS

The calorimetric measuring methods for microwave power feature some advantages versus the other measuring methods, based on mechanical, electrical or magnetic effects of the microwaves. One of them is that the calorimetric measuring devices are more robust and reliable than, for example, the torsion wattmeters (mechanical effect) or the Hall-effect wattmeters (magnetic effect).

The calorimetric measuring devices built at the University of Oradea were useful for the measurement of the power emitted by the magnetrons that were made here for different applications: pre-polymerization of bakelite powder, drying of hemp flakes and of graphite mud, food applications etc.

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