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MICROWAVE POWER AND LEAKAGE MEASUREMENT

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Abstract: this paper presents theoretical and experimental research of the authors concerning measuring possibilities for microwaves used in various applications, measuring devices specific for different power levels, factors that influence the measurement accuracy, as well as secure functioning of the microwave equipment.

1. INTRODUCTION

Microwaves are electromagnetic waves with frequencies in the range 300 MHz ÷ 300 GHz. In order to avoid interferences with communication systems, the frequency ranges 2450 MHz (wavelength 12.25 cm) and 915 MHz (wavelength 33.3 cm) – only Canada and USA uses the latter, the first one being allocated for Romania (2325 ÷ 2425 MHz ± 50 MHz) – have been allocated for industrial, scientific and medical (ISM) applications.

Power is defined as the energy developed in time unit. The microwave energy is used to carry information at long distances (telecommunications, RADAR etc), to excite molecules in order to obtain thermal effects (industrial electrothermics, medical diathermy, household uses etc), to accelerate particles (nuclear physics) etc. Due to the particularities of microwaves, their power can be determined only by means of direct methods, and the result is of scalar nature. Besides the known measuring units (μW, mW, W, kW, MW), power is expressed also by referring to a reference power of 1 mW on a logarithmic scale:

$$p_{dBm} = 10 \cdot \lg(1000 \cdot P) \tag{1}$$

where p_{dBm} is the power expressed with dBm units, and *P* is the power expressed in W.

The instantaneous power value oscillates at twice the electromagnetic wave frequency. The average power is:

$$P_m = \frac{\int_0^T p(t)dt}{T} \tag{2}$$

where *p*(*t*) is the instantaneous power value and *T* is the measurement duration; in case of periodical phenomena, *T* equals the period. The usual instruments measure mainly the average power.

The high-frequency power is classified in three categories, according to the value:

- *low-power*: 0 ÷ 10 mW (measurement technique, signal receivers);
- *medium-power*: 10 mW ÷ 10 W (telecommunications);
- *large-power*: over 10 W (TV emitters, RADAR, industrial, scientific, medical and household appliances etc).

2. MEASURING DEVICES

The microwave power measuring devices are based on different principles:

- *thermal effects based devices* – they convert the microwave power into caloric power, producing an easily measurable effect;
- *mechanical effects based devices* – they produce forces or force-couples proportional to the measured microwave power;

- *electrical effects based devices* – they produce continuous or low-frequency currents or voltages proportional to the measured microwave power.

Among the **thermal effects based devices** we mention the *bolometer devices* (for very low, low and medium power) and the *calorimeter devices* (for medium and large power). Fig.1 shows a dry calorimeter consisting of a waveguide-type terminal load mounted on the waveguide end, which dissipates all the microwave power passing through. The thermal conversion occurs in a dissipative wedge-shaped element with good contact to the terminal side, which it heats up. The entrance side is kept at the ambient temperature by means of radiators. The dissipated power is determined by measuring the temperature difference $\Delta\theta$ between these two sides in stationary regime:

$$P = \Delta\theta \cdot G_0 \tag{3}$$

where G_0 is the thermal conductance (W/degree), and P is the power expressed in W. Due to its robust construction, it device can be use as a factory measuring device for microwave power levels of tens of watts.

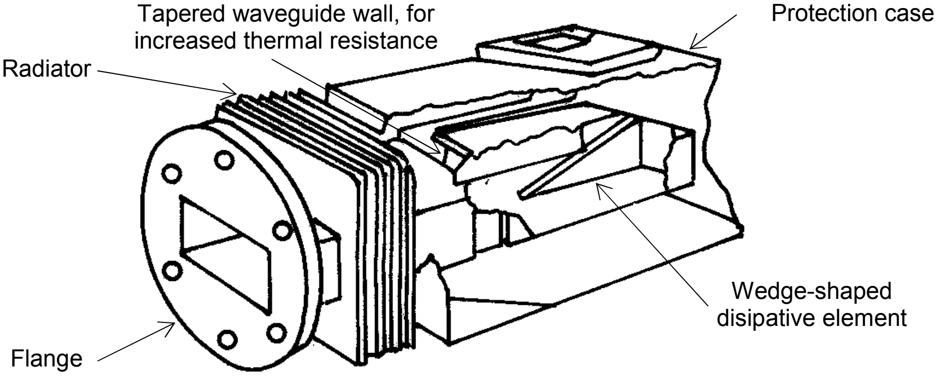

Fig.1. Dry calorimeter, for factory power measurement.

The **mechanical effects based devices** are also known as *torsion wattmeters*. Basically, these devices sense the radiation pressure, which is the force per area unit due to the impulse variation of the incident photons. When electromagnetic waves collide a reflecting surface, the pressure depends on the incident power. If the surface perfect microwave reflecting, the radiation pressure is:

$$p = 2 \cdot \frac{P}{c} \left[\mathrm{N/m^2}\right] \tag{4}$$

where *P* is the absolute value of the Poynting vector perpendicular component, expressed in W/m^2, and *c* is the speed of light expressed in m/s. This measurement is very difficult because the forces are very small; for example, a radiant power of 1 kW produces a $6.65 \cdot 10^{-6}$ N force over a perfect reflecting area unit. If the surface is a terminal short-circuit end of a cylindrical waveguide, the radiation pressure becomes:

$$p = \frac{P}{c} \cdot \frac{f_l}{f} \tag{5}$$

where f_l is the waveguide limit frequency and *f* is the working frequency. Fig.2 shows the basic diagram of the microwave power measuring device based on this principle; the radiation pressure acts on aluminum rings which make the terminal short-circuit of the cylindrical waveguide coupled to the rectangular one. The pressure effect is evaluated by the rings rotation angle, measured by means of a small mirror which reflects a luminous spot. The antagonist coupled is ensured by a torsion wire.

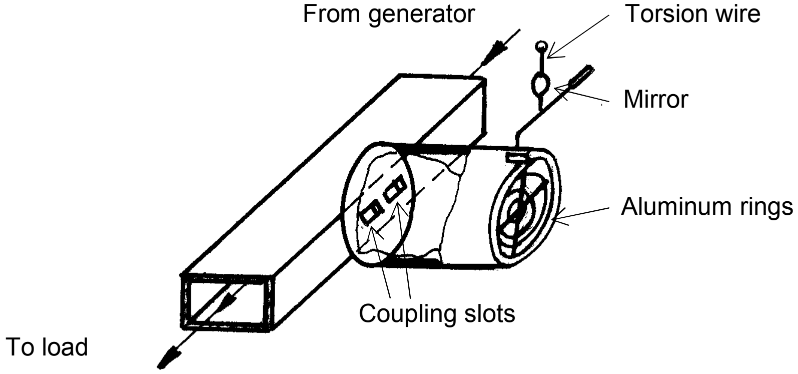

Fig.2. Basic diagram of the torsion wattmeter.

The TE_{10} fundamental-mode wave from the rectangular waveguide produces also a TE_{10} fundamental-mode wave in the cylindrical waveguide, thus the electrical contact is not necessary between the aluminum rings and the waveguide lateral surface, because there are no electrical flows in this region.

This device features the advantage that the rectangular waveguide wider side is horizontal, thus it can be easily coupled to the other elements of the measuring line. However, because of its mechanical fragility, this device is used only for checking other measuring methods by comparison.

Among the **electric effects based devices**, fig.3 shows a Hall-effect measuring device. The U_H voltage induced in a semiconductor plate placed in a magnetic field is:

$$U_H = \frac{K_H}{b} \cdot \left| \vec{B} \times \vec{i} \right| \tag{6}$$

where K_H is the Hall coefficient, $\vec{B}$ is the magnetic induction vector and $\vec{i}$ is the conduction current intensity though the semiconductor plate.

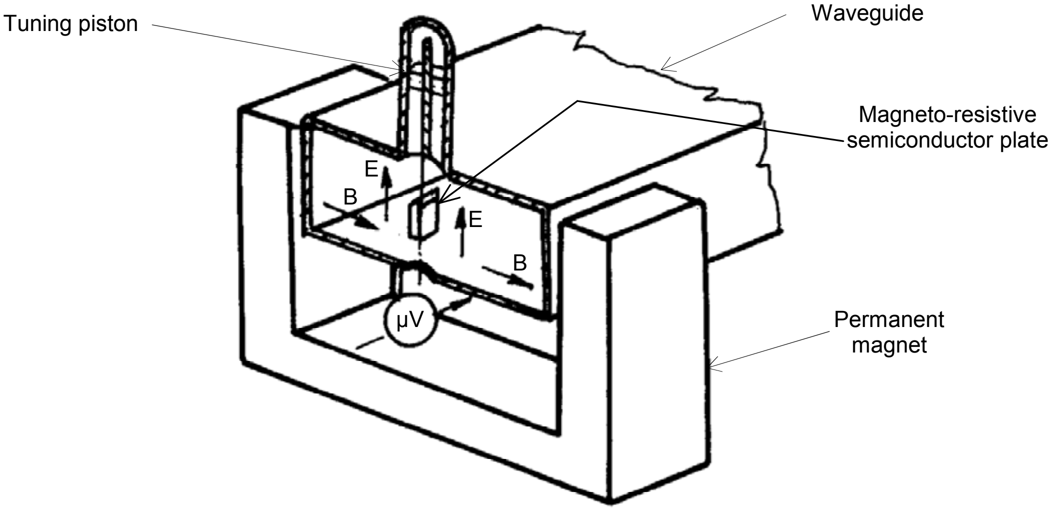

Fig.3. Hall-effect based microwave power measuring device – adaptable to rectangular waveguides.

The conduction current is proportional to the electric field intensity:

$$\vec{i} = k \cdot \sigma \cdot \vec{E} \tag{7}$$

where σ is the semiconductor conductivity and k is a proportionality factor; so

$$U_H = \frac{K_H}{b} \cdot k \cdot \sigma \cdot \left| \vec{B} \times \vec{E} \right| \tag{8}$$

The Hall voltage is proportional to the Poynting vector, which expresses the power density carried by the microwave electromagnetic wave. However, this device is difficult to use because of the numerous electric connections.

The measurement accuracy is influenced by various factors:

- connection waveguide losses;
- losses of the measuring device itself;
- mismatches.

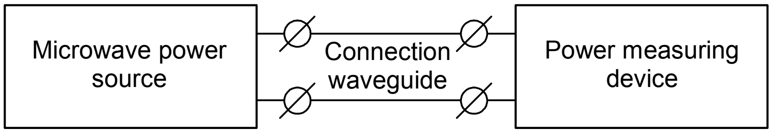

Fig.4. Electric diagram of the coupling between the power measurement device and the microwave power generator.

The connection waveguide losses must be taken into account for accurate power measurements (fig.4). It has been experimentally proven that the measurement cables attenuation is greater than 0.5 dB/m for frequency above 3 GHz.

The errors caused by the losses of the measuring device are produced in the walls of the coupling flanges and depend on their construction.

The mismatch errors seldom cannot be expressed univocally; the basic notions are:

- conjugated mismatch attenuation: $A_c = 10\cdot\lg\left[\frac{|1-\Gamma_G\cdot\Gamma_L|^2}{\left(1-|\Gamma_G|^2\right)\cdot\left(1-|\Gamma_L|^2\right)}\right]$ (9)
- mismatch attenuation Z$_0$: $A_{Z_0} = 10\cdot\lg\left(\frac{|1-\Gamma_G\cdot\Gamma_L|^2}{1-\Gamma_L^2}\right)$ (10)

and the power that reaches the measuring device is:

$$P = P_0\cdot\frac{\left(1-|\Gamma_G|^2\right)\cdot\left(1-|\Gamma_S|^2\right)}{\left(1-\Gamma_G\cdot\Gamma_S\right)^2} \tag{11}$$

where P_0 is the maximal power emitted by the microwave generator when perfectly matched, Γ_G is the generator reflection coefficient and Γ_S is the load (measuring device) reflection coefficient.

Mismatch causes measurement errors because one part of the emitted power is reflected and does not enter the measuring device. Another part of the power to be measured, even if entered in the measuring device, is lost because of the losses in the inner conductive walls (caused by the induced high-frequency currents) and in the non-conductive parts (caused by the large dielectric losses $\mathrm{tg}\,\delta$).

These losses increase along with the frequency, so that signals of equal power and different frequency cause different device response, the smaller frequency signals being advantaged, which means that a certain non-linearity can be pointed out. Another cause of the frequency non-linearity is that the spatial distribution of the currents is also frequency-dependent. In order to characterize the calibrating transducers by using known DC or low-frequency power levels, the *effective transducer ratio* is introduced:

$$\eta_e = \frac{P_{cc}}{P_1} \tag{12}$$

where P_{cc} is the DC or low-frequency power that produces in the transducer the same effect as the incident microwave power P_1. Because of the above-mentioned losses, always $P_1 > P_{cc}$, so $\eta_e < 1$. It can be noticed that the effective transducer ratio is not influenced by the mismatch. Also, the input power is partially reflected by the transducer itself, so it cannot be entirely sensed and converted.

3. EXPERIMENTAL RESEARCH

For the first time in our country, the Microwave Collective from the University of Oradea succeeded to build a set of different power magnetrons (200W, 650W, 800W, 1500W), to which the authors have also contributed. The power measurement have been carried out by means of a measuring slotted line, waveguides and calorimetric wattmeters based on artificial water loads (fig.5), all of them designed and built at the University of Oradea especially on this purpose.

When bringing the magnetrons into service, the TZA-340 micro-wattmeter has been used to sense the oscillation state and to measure the parasite microwave levels. This measuring device is based on thermal effects and has 7 switchable measure ranges: 10, 30, 100, 300 mW, 1, 3, 10 mW. Also, this device was used as indicator of the measurement line made by the Microwave Collective for measuring the magnetron output parameters.

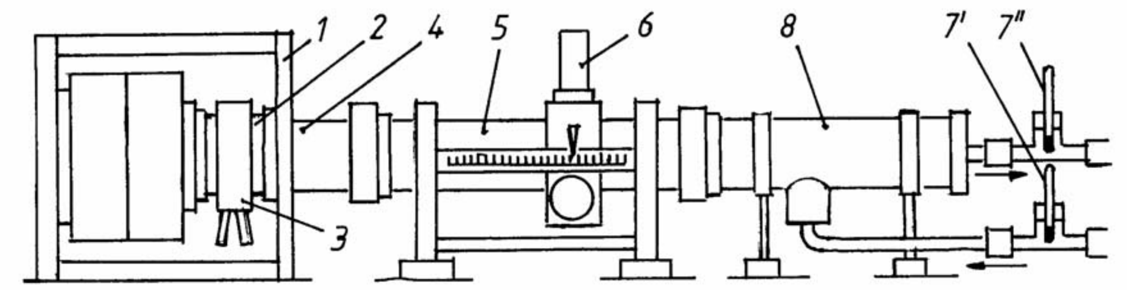

Fig.5. Measuring line for determination of the output magnetron parameters: 1 – electromagnet; 2 – magnetron; 3 – cooling sleeve; 4 –magnetron coaxial output; 5 – measuring slotted line; 6 – tester of the TZA-354 micro-wattmeter; 7', 7" – thermometers; 8 – coaxial artificial water load.

Also, the Microwave Collective has made industrial installations as objects of research contracts (ovens, dryers etc). Their secure operation was ensured by adequate design (shielding, ferrite absorbent garnitures etc), as well as by measurements done in both normal and abnormal operating conditions, observing the fulfillment of the security normative in each case.

4. SAFE OPERATION WITH MICROWAVE EQUIPMENT

Because of the invisible and silent character of the microwave energy, the public has an easy-to-understand interest for safety standards. Various debates have arisen based on the safe operation of microwave installations, concerning the experimental results and the safety standards proposed on national scale.

By assessing the possible dangers concerning the use of microwave energy, it results that there are two main risk categories. The first risk category is of thermal nature, determined by the heating of human body as a result of exposure, and the second risk category is of non-thermal nature, referring to possible temporary and permanent effects.

A considerable research activity has been developed in many countries, concerning the establishment of a procedure code and, finally, of a legislation regarding the admissible microwave exposure levels.

The microwave heating installations must be properly designed and operated, so that they ensure a suitable protection against irradiation risks caused by microwave leakage. The operator must get access to the whole installation and mainly to the applicator, so it is necessary that they are provided with secured access means which can be locked and properly protected.

The microwave leakage per area unit must not exceed 50 W/m^2 (5 mW/cm^2) in any accessible place situated at 0.05 m of any installation part, in the normal operating conditions. In addition, the microwave leakage must not exceed 100 W/m^2 (10 mW/cm^2) in any accessible place situated at 0.05 m of any installation part also during malfunctions. These values must not be exceeded in any place situated at more than 0.05 m.

The above shown values have been checked by measuring the maximum microwave leakage by means of adequate measuring systems. Fig.6 shows the personnel microwave exposure standards, in several countries. If necessary, the above mentioned microwave leakage levels (5 mW/cm^2 respectively 10 mW/cm^2) may be replaced with lower values.

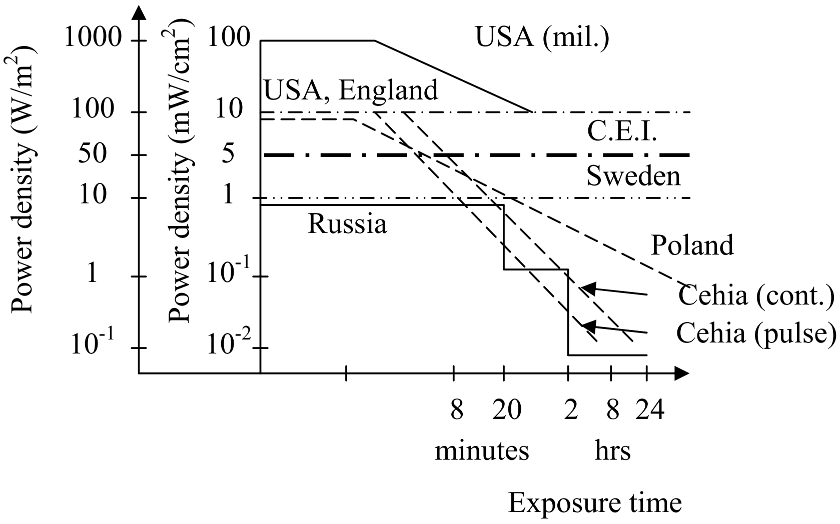

Fig.6. Personnel microwave exposure standards.

The microwave power leakage is measured with special instruments that fulfill several requirements:

- to reach 90% of the real value of microwave leakage in stabilized regime, when a step-shaped input signal is applied;
- to be fitted with an non-polarized radiation detector (antenna), capable of measuring leaks of 50 ÷ 100 W/m with ±5% accuracy at the working frequency of the installation.

The maximal microwave leakage in any place situated at 0.05m from any microwave installation side must be measured on all power ranges and for all kinds of materials to be treated in normal operating conditions.

The measurement must be carried out at all doors, with all lids and access ways opened, except those that block microwaves in order to prevent microwave emission during measurement. The doors, lids and access ways must be set in the worst case operating conditions. The measurements are repeated with the empty applicator, with the microwave generator set at maximum allowed power level. In all cases, the maximum microwave leakage level must not exceed 5 mW/cm^2 in any place situated at 5 cm from any side of the installation.

Concerning the electromagnetic field exposure, eight physical quantities are used:

1. **contact current** I_c between a person and an object, expressed in amperes (A); a conductive object in an electric field can get charged by this field;
2. **current density** *J* is defined as the current that crosses an are a unit perpendicular to the current flux in a conductive body, as the human body or a body part, and is expressed in amperes per square meter (A/m^2);
3. **electric field intensity** *E* is a vectorial quantity that corresponds to the force exerted by the field over a charged particle, no matter of its movement in space, ad is expressed in volts per meter (V/m);
4. **magnetic field intensity** *H* is a vectorial quantity that, together with the magnetic induction, defines a magnetic field in any point in space, and is expressed in amperes per meter (A/m);
5. **magnetic induction** *B* or the magnetic flux density is a vectorial quantity defined as the force exerted over charged particles in motion, and is expressed in tesla (T); in free space and in biological matter, the magnetic induction and the magnetic field intensity can be each used instead of the other by means of equivalence $1\ A/m = 4\pi 10^{-7}\ T$;
6. **power density** *S* is the adequate quantity to measure the very high frequency power , when the field penetration is low; this represents the radiant power quantity perpendicular incident over an area unit, and is expressed in watts per square meter (W/m^2);
7. **specific absorption** *SA* of energy is defined as the energy absorbed by the biologic tissue mass unit and is expressed in joules per kilogram (J/kg); within these standards, this is used to limit the non-thermal effects of the pulsed microwave radiation;
8. **specific absorption rate** *SAR* average over the entire body or a specific body part, is defined as the ratio at which the energy is absorbed by the biological body tissue mas unit and is expressed in watts per kilogram (W/kg); *SAR* over the entire body is a widely accepted quantity for establishing the relations between the thermal effects and the radiofrequency exposure; localized *SAR* values are needed along *SAR* average on entire body in order to evaluate and limit the excessive energy accumulation in small body zones in special exposure conditions, as grounded person exposed to low frequency RF or persons exposed to antenna field in close proximity.

The following restrictions for electric, magnetic and electromagnetic fields in the range of 0 Hz ÷ 300 GHz were approved for Romania by Order of the Health Ministry nr.1193/29.09.2006:

Tab.1. The maximal admissible values of electric, magnetic and electromagnetic fields.

Frequency range	Magnetic field induction [mT]	Current density – effective value $[mA/m^2]$	SAR average on entire body [W/kg]	SAR localized – head and cap şi trunchi [W/kg]	SAR localizată – membre [W/kg]	Densitatea de putere $[W/m^2]$
0 Hz	40	-	-	-	-	-
până la 1 Hz	-	8	-	-	-	-
1 ÷ 4 Hz	-	8/f	-	-	-	-
4 Hz ÷ 1 kHz	-	2	-	-	-	-
1 kHz ÷ 100 kHz	-	f/500	-	-	-	-
100 kHz ÷ 10 MHz	-	f/500	0.08	2	4	-
10 MHz ÷ 10 GHz	-	-	0.08	2	4	-
10 GHz ÷ 300 GHz	-	-	-	-	-	10

5. CONCLUSIONS

Due to its high efficiency, the microwave usage makes possible the rational use of primary energy sources and the short-term investment recovery, but the limited generator lifetime, the particular safety measures and the requirements of high-qualified personnel point out that microwave energy should be used with much caution. Special attention must be paid to the general and particular safety standards.

When starting up the microwave installation, as well as during use, it is required that measurements are carried out in order to detect any microwave leakage that may occur because of access systems inadequate tightness and of the improper operating conditions (overload, no-load, overheat etc).

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