

## ON MEASUREMENTS APPLIED IN SCIENTIFIC RESEARCHES OF MICROWAVE HEATING PROCESSES

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### 1. INTRODUCTION

Microwaves frequencies occupy the three decades of the electromagnetic spectrum (300MHz to 300GHz) that lie between VHF radiowaves and the far infrared. Their application fall into two categories, depending on whether the wave is used to transmit information or just energy. The first category includes terrestrial and satellite communication links, radar, radioastronomy, microwave thermography, material permittivity measurements, and so on. In all cases, the transmission link incorporates a receiver whose function is to extract the information, that in some way modulates the microwave signal. The second category of applications is the subject of this paper. As a whole it is called a microwave heating. Here, there no modulating signal and the electromagnetic wave interacts directly with solid or liquid materials known as lossy dielectrics, among which water is of particular interest.

Microwave heating as an industrial process is a technique which was originally conceived above forty years ago [1], [2], [3]. The microwave oven was born as American patent No. 2495 429 of 24 January 1951. The use of microwaves on the industrial and domestic scenes has increased dramatically over the past thirty years. Microwave ovens in the home have become commonplace and major contributions are made by microwaves in the food industry. Microwaves are currently used for drying, vulcanizing, polymerizing, melting, sintering, hardening, cooking and backing, thawing, blanching, pasteurizing and sterilizing, and many other processes of lesser importance. In the last two decades microwaves have been employed in medicine for treating cancer and other clinical conditions. In Poland, a successful trying of the microwave vulcanization in gum industry has been made in the beginning of the seventieth [4]. Presently, a laboratory investigation of the microwave devulcanization of waste rubber is carried and leads to promising results [5]. Appropriated for laboratory use, microwave mineralizers are presently in polish serialized production.

The main advantages of microwave heating are the uniformity of heating and precise control of the temperature. Microwaves transfer energy directly into all volume of the material heated, which is heated from the inside. The heating process can be immediately ended or resumed by an instantaneous off or on operations of the microwave power generator.

The heating by microwave energy is essentially an interaction between the molecules of the material to be heated and the electric field component of microwave energy. In an energy-efficient heating system transfer of energy from generator to workload (input of the device for applying microwave energy to a product) must clearly be achieved with minimum loss. A microwave heating system has unusually high transfer efficiency, limited by two factors.

First, energy is absorbed in the walls of the transmission waveguide I<sup>2</sup>R heating. In most cases this is a very small proportion of the transmitted power and is negligible.

Second, power is reflected from the load if "optimum matching" has not been achieved. The concept of optimum matching for maximum power transfer from a source to a load is well known and load impedance should be the complex conjugate of the generator internal impedance, seen in feeding waveguide end used to connect the load to the source.

In terms of the reflection coefficient  $\Gamma$  and its conjugate value  $\Gamma^*$ , the power delivered to the workload (input of an applicator, e.g., heating chamber of the microwave oven) is given by

$$P_d = P_p(1 - \Gamma \cdot \Gamma^*), \quad (1)$$

where  $P_p$  is the forward power incident at the load, and  $\Gamma$  is a reflection coefficient of the load, (load impedance value is related to the characteristic impedance  $Z_0$  of the feeding waveguide). The energy

absorbed by a workload depends on the power delivered  $P_d$  value and the access time of microwave signal at workload input, which is equal to an exposure time of material heated to electromagnetic field.

A matching tuners are inserted in the applicator input to adjust the impedance to the conditions when maximum value of the forward power incident at the applicator input as well as stable operation of the generator is achieved. In practice it is not the condition  $|\Gamma|=0$ , when applicator input impedance equal the characteristic impedance of the connecting waveguide. A microwave generator will change its efficiency with the complex voltage reflection coefficient of the workload so that more forward power may be obtained under certain “impedance mismatched” loading condition (see a Rieke diagram of microwave power tubes). Usually an industrial microwave applicator is designed to have an input standing wave ratio (VSWR) smaller than 3 [6] over the operating range of frequencies of the generator, giving a maximum of about 25% reflected power. The distribution of energy is optimized by an empirical adjustment of feeding waveguides.

A literature information [1], [2], [3] on microwave energy consumption in a heating process is an inaccurate. A knowledge of the output power,  $P_{PG}$ , of microwave power generators applied in heating apparatus is important in evaluating the mains power  $P_m$ , transformed to microwave power  $P_{PG}$ , useful for described industrial heating process. The information on a number of well-known magnetrons used in a power generator of the heating system, or even the knowledge of the power  $P_{PG}$  value, is insufficient in accurate determination of power  $P_d$ , delivered to the applicator input, as well as power  $P_w$ , dissipated in the material heated. Generator output power  $P_{PG}$  can be changed not only while the temperature of generator is changed but also while reflection coefficient  $\Gamma$  of the load is changed. Moreover, the reflection coefficient  $\Gamma$  value can be changed during heating process, because dielectric properties of heated material can be changed while the temperature is increased. It is evident from above that the continuous measuring of forward power incident at applicator input and the reflection coefficient of applicator input have to be performed during a heating experiment carried out for fundamental research.

Scientific research of microwave heating requires an accurate on-line measurement of the microwave energy absorbed by material. Determination of the energy absorption during heating is especially important to understand the heating process of the material placed in high-power density microwave field. Transformation of microwave energy changes the temperature and creates new physical and chemical effects in the heated material. Therefore continuous and accurate measurement of the energy absorption during the experiment can help to explain and to control of the material transformation process. Simultaneously, an estimation of the overall circuit efficiency of microwave heating equipment allows appraise economical aspects of the microwave heating. Energy utilisation is of paramount importance in any application involving microwave power.

## 2. MEASUREMENT SYSTEM TO RESEARCH OF MICROWAVE HEATING

A simplified block diagram of the measuring system to scientific research of the microwave heating process is shown in Fig.1. The construction of this system is presented in details in [7].

The dual directional coupler used in a reflectometer set-up to sample the high-level signal of power  $P_p$  and  $P_r$ , makes sure the high transfer efficiency of energy from generator to the applicator contained a heating chamber. For coupling coefficient 40dB the efficiency can be 99% [8]. The weak coupling is required to reduce the input power level of the microwave detectors, working with square-law detection of the signal.

The voltages  $U_p$  and  $U_r$  are amplified by the voltage amplifiers of the ratiometer and control system block. The signal G is used to control the temperature of the microwave energy applicator. The STOP signal is used to turn off the microwave power generator in a distress situation. An actual condition of the measuring system is shown on the liquid crystal display and can be changed by means of numerical keyboard.

The computer set-up contains: the central processing unit, keyboard, monitor, and printer. It is used to present and analyse the measurement results as the time function graphs as well as to display the messages on the actual state of the measurement system and errors of its incorrect operation.

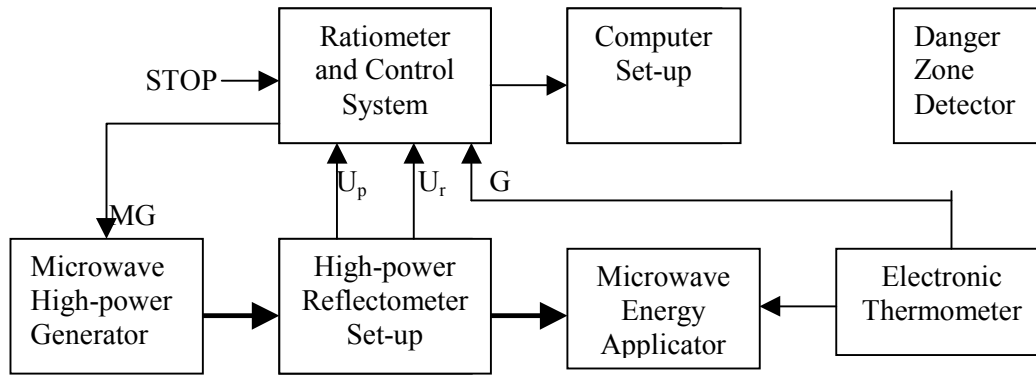


Fig. 1. Simplified block diagram of the measurement system to research of microwave heating.

A different kind of operation of the system can be applied to research of heating process which can be programmed to end the heating after a fixed time interval, or when a steady-temperature of the chamber or heating rate values are reached.

### 3. MEASURED AND CALCULATED RESULTS

The voltages  $U_p$  and  $U_r$ , directly proportional to the forward power, incident at the applicator input  $P_p$ , and reflected power  $P_r$ , respectively, are measured by ratiometer. Energy transmitted by electromagnetic field to a lossy material heated is calculated as

$$W = \eta_a K_1 \int_{t_0}^{t_g} U_p(t) \cdot (1 - K_0^{-1} |\Gamma(t)|^2) dt \quad (2)$$

where  $t_g - t_0$  is an exposure time interval to electromagnetic field of the heated material,  $\eta_a \cong 1$  is an efficiency of the applicator,  $K_0$  and  $K_1$  are the system calibration coefficients.

An average temperature  $T$  of the material heated is calculated as

$$T = \frac{3600W[Wh]}{cm} + T_0, \quad (3)$$

where  $c[J/(kgK)]$  is a specific heat,  $m[kg]$  - mass, and  $T_0$  - initial temperature of the material heated. The values of  $m$  and  $T_0$  are entered into the controller memory at the beginning of the measurement procedure. The relation (3) can be used to calculation of the unknown material  $c$  value.

A measure of the intensity of heating of a material is a heating rate  $I$ , which describes the energy absorbed per unit mass. It is defined as

$$I = \frac{W[J]}{m[kg]}. \quad (4)$$

Magnitude of the reflection coefficient and VSWR of the applicator input are calculated as

$$|\Gamma| = \sqrt{\frac{U_r}{K_0 U_p}}, \quad (5)$$

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}. \quad (6)$$

The power incident at applicator input is calculated as  $K_1 U_p$ , while the value of  $|\Gamma|^2 \cdot 100\%$  describes the reflected power as a percent of the incident power.

Measurement error of the system depends on the accuracy of determination of the voltages  $U_p$  and  $U_r$ , as well as on the accuracy of system calibration, while the  $K_1$  value is determined and the value  $K_0 = 1$  is adjusted. The contribution of the others error components to an overall root sum of squares (RSS) energy uncertainty can be neglected. Mentioned above error components are mostly dependent on the directivity of the reflectometer [9], [10], [11].

For coupler directivity bigger than 35 dB,  $|\Gamma| = 0,5$ , the overall RSS uncertainty of the system can be estimated as 6,15%.

#### 4. CONCLUSIONS

Measurement results of the voltages  $U_p$  and  $U_r$ , delivered energy, measurement energy error, expected average temperature of the material heated, heating rate, incident wave power, percent reflected power, and VSWR can be presented as the graphs on the computer monitor or printed on the colour printer.

The knowledge of the heating rate is useful to prediction of the power demand which is required for a transformation the heated material. The continuous measurement of the incident wave power at the applicator input is used to the energy determination. Displaying of this power value or voltage  $U_p$ , on the monitor screen, brings good results of the current control the non-failure operation of the microwave power source. Similarly, the measurement and displaying of the applicator reflection coefficient or voltage  $U_r$ , gives a certain information on the heated material permittivity change, typical during the heating process.

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