Errors Caused by Microwave Part of the Microwave Heating System

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Abstract: *Principle of operation and construction of the system to scientific research of microwave heating are briefly presented in the paper. The error components caused by real parameters of microwave part of the measurement system as well as a RSS uncertainty of the system are analysed.*

1. Introduction

Determination of the microwave energy consumption in a heating process creates the difficult problem [1]÷[4]. An information about of output power P_{PG} of the microwave power generator applied in heating apparatus is insufficient to determine a power P_d delivered to the energy applicator input. Generator output power value can be changed not only while the temperature of generator increases but also while reflection coefficient Γ of the load is changed. Moreover, the reflection coefficient Γ can be changed during heating process because the dielectric properties of the heated material can be changed while the temperature is increased. It is evident from above that a continuous measuring of the forward power incident at applicator input as well as the reflection coefficient of the applicator input has to be performed during a heating experiment.

Manifold data have to be measured and calculated while the scientific researches of microwave heating processes are performed [5], but the determination of energy absorption in a material placed in high-power density microwave field is especially important to understand the heating process. Simultaneously, an estimation of the overall circuit efficiency of microwave heating equipment allows to appraise economical aspects of the microwave heating. Energy utilisation is of paramount importance in any application involving microwave power.

Measurement system for scientific research of microwave heating is presented in [6] and [7]. In this paper the error components caused by real parameters of microwave part of the measurement system as well as a root sum of squares (RSS) uncertainty of the system are analysed in detail.

2. A system for research of microwave heating

Simplified block diagram of the measurement system for research of microwave heating processes is shown in Fig. 1. Dual directional coupler, incident wave detector, and reflected wave

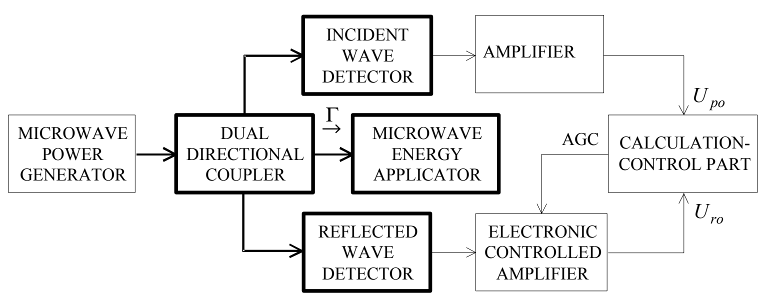

Fig. 1. Block diagram of the measurement system to research of microwave heating process.

detector represent a microwave part of high-power reflectometer. For square-law detection the output signals of detectors as D.C. voltages of U_p and U_r values are proportional to the incident P_p and reflected power P_r at the energy applicator input, respectively. The voltages U_p and U_r are amplified to the U_{po} and U_{ro} values, respectively, by the low-frequency voltage amplifiers. The calculation-control part of the system is composed of microprocessor controller, CPU of a computer, keyboard, monitor and printer. The microwave power generator contains a high-power microwave source, high-voltage and filament power supplies, radio interference eliminator and electronic switch-key.

Energy transmitted by electromagnetic field to a lossy material depends on a power dissipated in this material during exposure to electromagnetic field. The energy absorbed by material heated may be described as

$$W = \eta_a \int_{t_0}^{t_g} P_p(t) \cdot \left(1 - |\Gamma(t)|^2\right) \cdot dt \tag{1}$$

where η_a is an efficiency of the applicator used in the system, and $t_g - t_0$ is an exposure time interval to electromagnetic field of the heated material. The efficiency describes a ratio of the power dissipated in material heated to the power delivered to the applicator input. Time dependent values of the forward power incident at the applicator input P_p and reflection coefficient $|\Gamma|$ of the applicator have to be measured.

Equation (1) can be written as

$$W = \eta_a K_1 K_2 \sum_{i=1}^{n} \left(U_{po(i)} - K_0^{-1} U_{ro(i)} \Delta G_{r(i)}\right) \Delta t_{(i)} \tag{2}$$

where:

K_0 is a calibration coefficient which has to be equals 1 due to calibration of the reflectometer,

K_1 - power coefficient equals to a ratio of the power P_p incident at applicator input to the output voltage U_{po} of the voltage amplifier,

K_2 - scale coefficient (K_2 =1 if W[J], K_2 = 10^{-3} if W[kJ], and K_2 = 1/3600 if W[Wh]),

$\Delta G_{r(i)} \leq 1$ - ratio of a minimal gain value of the electronic controlled amplifier (while the input reflection coefficient of the applicator $|\Gamma| = 1$) to the actual gain value of this amplifier during a measurement of number *i*,

Δt - sampling time interval of microwave power delivered to the energy applicator input, $i = 1,2,3,....n$ - number of the measurement.

3. Accuracy of energy measurement

To discuss the accuracy of the energy measurement a RSS error δW_i of the measured *i-th* energy sample first should be defined:

$$\delta W_i = \left[(\delta\eta_a)^2 + (\delta K_1)^2 + (\delta\Delta t)^2 + \left(\frac{\delta U_p}{1 - |\Gamma|^2}\right)^2 + \left(\frac{\delta U_r}{|\Gamma|^{-2} - 1}\right)^2 + \left(\frac{\delta K_0}{|\Gamma|^{-2} - 1}\right)^2 + \left(\frac{\delta\Delta G_r}{|\Gamma|^{-2} - 1}\right)^2 \right]^{0,5} \cdot 100\% \tag{3}$$

The δU_p and δU_r errors of the voltage U_{po} and U_{ro} measurement, respectively, result from the finite directivity of the coupler, offset voltage and noise signal of the voltage amplifiers as well as A/C conversion error of the voltages U_{po} and U_{ro}, respectively. The components of the errors δU_p and δU_r depending on finite directivity are the error-determining elements in a total uncertainty of the measurement system. The finite directivity causes a false signal at a coupled line output of the directional coupler. The voltages U_{po} and U_{ro} can be expressed as a function of directivity D_p and D_r, respectively, as follows:

$$U_{po} = \frac{P_{PG}\gamma_p G_p}{C_p} \left| 1 + \frac{\Gamma}{A_t^{0,5} D_p^{0,5}} \right|^2 \text{ and } U_{ro} = \frac{P_{PG}\gamma_r G_r}{C_r} \left| \frac{\Gamma}{A_t^{0,5}} + \frac{1}{D_r^{0,5}} \right|^2 \tag{4}$$

where γ is a low-level sensitivity (mV/μW) of the microwave detectors, G – a gain of the D.C. voltage amplifiers, C – coupling of the directional couplers, and A_t – attenuation of the main line of the dual directional coupler. The error components resulting from finite directivity can be described as

$$\delta U_{Dp} \cong 2 \frac{|\Gamma|}{A_t^{0,5} D_p^{0,5}} \quad \text{and} \quad \delta U_{Dr} \cong 2 \frac{A_t^{0,5}}{D_r^{0,5} |\Gamma|}. \tag{5}$$

The error components of the energy measurement corresponding to these errors are given as

$$\delta W_{Dp} = \frac{2|\Gamma|}{A_t^{0,5} D_p^{0,5}(1-|\Gamma|^2)}, \text{ and } \delta W_{Dr} = \frac{2A_t^{0,5}|\Gamma|}{D_r^{0,5}(1-|\Gamma|^2)}. \quad (6)$$

For high-power directional coupler the coupling C is very weak (40 dB) and $A_t \cong 1$, so the both expressions of (6) give almost the same result:

$$\delta W_D[\%] \cong \frac{2|\Gamma|}{D^{0,5}(1-|\Gamma|^2)} 100\% . \quad (7)$$

The relation (7) is presented in Fig. 2. For D=35dB and $|\Gamma| \leq 0{,}5$ the values of the considered measurement error $\delta W_D \leq 2{,}37\%$.

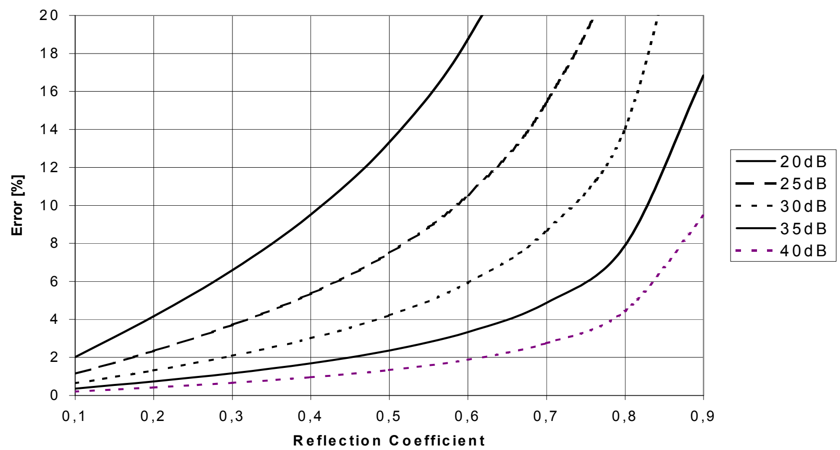

Fig. 2. Error component δW_D [%] for the constant values of the directivity of the energy measurement caused by finite directivity of one from two couplers of the reflectometer.

It is evident from expression (3), that energy measurement error component caused by an inaccurate determination of the calibration coefficient K_0 of microwave reflectometer depends also on $|\Gamma|$ values.

$$\delta W_{K0} = \frac{\delta K_0}{|\Gamma|^{-2} - 1}. \quad (8)$$

During the calibration procedure a standard termination with well-known reflection coefficient Γ_S is used. The error δK_0 of determination of the calibration coefficient K_0 depends not only on inaccurate knowledge of Γ_S but also the values of the $|\Gamma_S|$ as well [9].

$$\delta K_0 = \delta|\Gamma_S| + \frac{1}{D_r^{0,5}|\Gamma_S|} + \frac{(1+\delta|\Gamma_S|)^2}{D_p^{0,5}}|\Gamma_S|. \quad (9)$$

The value of δK_0 is highly sensitive on finite directivity D_r. For a small values of the $|\Gamma_S|$ the error δK_0 is decreasing while $|\Gamma_S|$ is increased, but if $|\Gamma_S| \geq 0{,}6$ the δK_0 value is practically independent on the actual $|\Gamma_S|$ values, and for $\delta|\Gamma_S| = 5\%$, $D_p = D_r \geq 35$dB the value of $\delta K_0 \leq 9{,}14\%$. From (8) we have $\delta W_{K0} \in (0{,}1 \div 3)\%$ for $|\Gamma| \in (0{,}1 \div 0{,}5)$. If $D_p = D_r \geq 40$dB, for $|\Gamma| \in (0{,}1 \div 0{,}5)$, the δW_{K0} values will be smaller than 2,44%.

If a strongly dissipative material is heated the value of efficiency of the applicator will be $\eta_a \cong 1$ and if we put up $\eta_a = 1$ in expression (2) we get $\delta W_\eta = \delta\eta_a \cong 1 - \eta_a$. If a heated material sample is small and the material has low dissipativity the efficiency η_a has to be determined. It can be done with some error $\delta\eta_a$ depending on the system calibration procedure. A rapid practical method of efficiency determination of the microwave energy applicator based on the calculation and measurement of temperature of the well-known heated material can easy to reach a 6,1% RSS calibration error [8].

The power coefficient K_1 is determined during the measurement system calibration procedure while the power P_M is measured by a power meter connected to the dual directional coupler instead of incident wave detector. The value of K_1 is calculated as

$$K_1 = \frac{C_p P_M}{U_{po}} . \tag{10}$$

The RSS error of K_1 can be calculated as:

$$\delta K_1 = \left[(\delta C_p)^2 + (\delta P_M)^2 + (\delta U_{po})^2 \right]^2 , \tag{11}$$

where δU_{po} one can be find using the first expression of (5).

For $A_t \cong 1$, $D_p > 35dB$ the δU_{po} value is usually smaller then 2%. If the coupling C_p is known with the 0,1dB error of attenuation measurement, the δC_p will be equals 2,33%. Power meter accuracy δP_M is typically lower then 2%. Finally, for all above mentioned data we get $\delta W_{K1} = \delta K_1 = 3{,}66\%$.

4. Conclusions

Energy measurement error analysis shows the strong dependence of the discussed errors on the impedance mismatch of the applicator input. It is shown that the first of two error components (7) and (8) are decreasing while the mismatch is improved. It is quite opposite situation when the change of the error components caused by finite coupler directivity (while relectometer is used to an impedance mismatch measurement) when for a small $|\Gamma|$ values the error is decreasing while measured $|\Gamma|$ increases. For reflection coefficient of energy applicator input $|\Gamma| \leq 0{,}5$, the RRS error measurement of the energy delivered into this port can be smaller than 5,8%, and it can be reached 8,4% for energy dissipated in a small material sample. Well-matched applicator gives not only a better stable operation of the power generator and a better watt-hour efficiency of microwave system, but also a better measuring accuracy of microwave energy consumption in a heating process.

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