CALCULATION OF ABSORBED AND OUTPUT POWER FOR A 1 kW MICROWAVE GENERATOR

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Abstract. In variable electric fields (2,45 GHz frequency microwaves) we are faced with energy loss, especially because of the fact that electrical polarization does not vary in phase with electric field intensity – these losses are called losses by electrical polarization. These losses, thus due to the post electrical effect take place in epoxy resin subjected to the electrical microwave field. Maximum power in microwave field that covers the whole range of applications referring to epoxy resin polymerization is of about 1 kW. This power level in microwave covers the losses that appear from the generator to the applicator where the polymerization takes place. An important element of technology is the dielectric power measuring and reflecting in the polymerization processes of the electric epoxy resins insulations.

Keywords: epoxy resin polymerization, microwave process, magnetron, microwave power measurement

INTRODUCTION

Because of the post electrical effect that appears at the epoxy resin placed in microwave field, the polarization is phased with a δ_h angle, called loss angle by electric hysteresis. The expressions of the electrical field and electrical induction:

$$E(t) = E_M \cdot \sin \omega t \qquad (1)$$

$$D(t) = E_M \cdot \sin(\omega t - \delta_h) \qquad (2)$$

Represent the parametrical equations of the ellipse presented in Fig. 1, its A_h area being in proportion with the electric hysteresis losses.

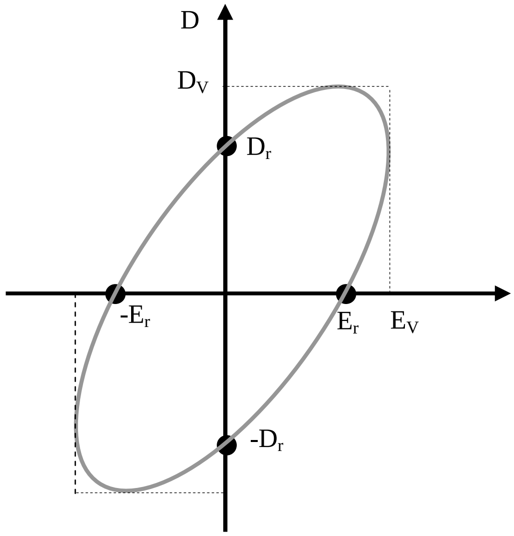

Fig. 1. Referring to the electrical hysteresis losses.

For an infinitesimal variation of the electrical field, microwave energy on the epoxy resin volume unit varies with:

$$dW_c = E \cdot dD \tag{3}$$

Variation speed on time span being:

$$P_{(t)} = \frac{dW_e}{dt} = \frac{E \cdot dD}{dt} = E \cdot I_d \tag{4}$$

In complex value we define the apparent power on the volume unit:

$$\underline{s_h} = E \cdot \underline{I_D^*} = p_h + jq_h \tag{5}$$

where:

1. p_h are the losses in a time span and the volume losses (heat build-up in the resin subjected to polymerization);
2. q_h is the maximum variation speed of the energy in the electric field in the volume unit of the resin subjected to polymerization.

We thus have:

$$p_h = \omega \cdot \varepsilon_0 \cdot \varepsilon_r'' \cdot E_{ef}^2 \tag{6}$$

$$q_h = -\omega \cdot \varepsilon_0 \cdot \varepsilon_r'' \cdot E_{ef}^2 \tag{7}$$

where:

ε_r'' - is loss factor in epoxy resin.

Total energy loss in the epoxy resin is obtained adding up:

$$p = p_h + p_c \tag{8}$$

$$q_c = q_h + q_c = q_h \tag{9}$$

which have the expressions:

$$p = \left(\omega \cdot \varepsilon_0 \cdot \varepsilon_r'' + \sigma\right) \cdot E_{ef}^2 \tag{10}$$

$$q = -\omega \cdot \varepsilon_0 \cdot \varepsilon_r'' \cdot E_{ef}^2 \tag{11}$$

if we keep in mind the relation:

$$-tg\delta_h = \frac{\varepsilon''}{\varepsilon'} \tag{12}$$

and if we note:

$$tg\delta = tg\delta_h + \frac{\sigma}{\varepsilon_0 \cdot \varepsilon_\omega'} \tag{13}$$

It was obtain power in microwave expression dissipated in the epoxy mass resin, that produces its polymerization as being:

$$p = \omega \cdot \varepsilon_0 \cdot \varepsilon' \cdot E_{ef}^2 \cdot tg\delta \tag{14}$$

1. THE MAXIMUM EFFECTIVE POWER AND THE ABSOLUTE POWER FROM MICROWAVE DEVICE

1.1. The maximum effective power for epoxy resin polymerization

Maximum power in microwave field that covers the whole range of applications referring to epoxy resin polymerization is of about 1 kW.

This power level in microwave covers the losses that appear from the generator to the applicator where the polymerization takes place [1]:

- losses in the metallic walls of the applicator, that are of about 5% of the whole power emitted by the generator, in the case of a correct dimensioning of the transport device and correct microwave use (wave guide and applicator);
- thermal losses by conduction and convection of the epoxy resin during polymerization, evaluated at about 10% of the power emitted by the generator.

1.2. The absolute absorbed power by the microwave generator from the electric supply network

In order to estimate the absolute absorbed power from the supply network the following parameters are taken into account:

- magnetron efficiency (η_m) – microwave emitted power – absorbed power relation $(\eta_m = 70 \div 75\%)$;
- magnetron supply source efficiency (η_s), (filament transformer and anode voltage transformer), $(\eta_s = 95\%)$

The absorbed power by the microwave generator:

$$P_{abs} = \frac{P_{microwave}}{\eta_m \cdot \eta_s} \cong 1{,}2kW \qquad (15)$$

The microwave generator in fig. 2 represents microwave energy source that is transmitted in an enclosure (applicator) for the purpose of thermal processing.

The constructive solution chosen for the microwave generator GM – 00 wants to line up as far as performance is concerned with the products of prestigious companies from this field. The microwave generator GM – 00 is conceived such that it has a large range of applications. In this respect, the microwave generator is fitted with a waveguide GM – 03 (to which the magnetron is connected) through which supplies microwave energy.

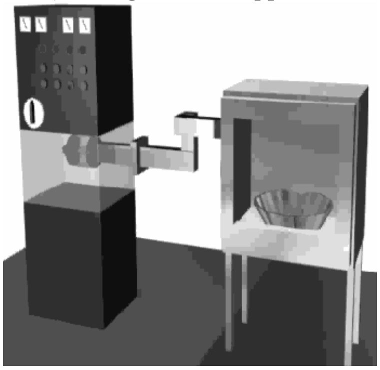

Fig. 2. Microwave generator

For designing the continuous adjustment of output power, the generator is fitted with an electronic device. [7]

For displaying the main parameters needed for the elaboration of a microwave technology, the generator GM – 00 is presented with appropriate measurement equipments on the dashboard. Thus, with the help of the three measuring units aligned on the generator dashboard the following parameters can be distinguished:

- *generator transmitted power* – adjusting the level of this power is done with the help of the electronic device available for GM – 00 by means of a fine adjustment button (multi-tour potentiometer) placed on the front board of the generator;
- *incidental power transmitted towards the thermal process load placed inside the microwave applicator* – incidental power, on the microwave path, respectively on the waveguide, is absorbed from the bidirectional oven with the help of a detection well and introduced inside the microwave generator with the help of a connecting cable with an connector afferent to the measuring device available on the panel for this purpose;
- *power reflected by the processing load or by the existence of a non-adaptation state between the generator and the applicator* – the reflected power is absorbed, like the transmitted incidental

power from the bi-directional coupler with the help of a detection well (other than the incident power) and introduced in the microwave generator GM – 00 with the help of a connecting cable with an connector afferent to the measuring device available on the panel for this purpose. The frontal panel of the microwave generator also presents signalling, functioning elements and on – off switches.

2. SPECIAL CONSTRUCTION PROBLEMS.

Constructing the GM – 00 microwave generator will be done on the basis of the documentation that constitutes the main issue of this phase of the project. The construction of the generator does not pose special problems, with the exception of the waveguide, observing the technical conditions formulated in the GM – 03 documentation [2], consequently of the aluminium parts welding of which it is made. On this purpose we must mention that the wildings must not induce buckling of the interior of the waveguide. Also, the interior finish must be high quality.

The functioning of the adjusting output in microwave power electric block must not be affected by the disturbing signals from the microwave leakages.

In practice in the polymerization processes of the epoxy resin based insulations, measuring the microwave power that is transmitted from the generator towards the load and of the power reflected (unabsorbed) by the load that is propagated from the load to the generator, must be done during the functioning of the microwave installation.

In this case the measuring process must not influence (disturb) power transmission and must not produce reflections on the waveguide.

For these measurements, one may use directional coupling devices, detection wells and instruments. In fact, directional coupling devices can be made in many ways, the versions differing from the functioning principles to the manufacturing technologies.

For any of the versions made in practice the performances that can be obtained are just close, not really identical with the ones of the ideal directional coupling device theoretical model [3]. The real directional coupling timings differ among themselves by performance, measuring where their behaviours are close to the ones of an ideal coupling device. Furthermore, in practice the problem of the frequency band and the coupling performances are maintained at an acceptable level; the larger the band, the more numerous applications where it can be employed.

If for a directional coupling device we note with 1 – entering gate; 2 – transmission gate; 3 – insulated gate; 4 – coupled gate we can introduce the next definitions:

1. *Coupling attenuation of the coupling device* – represents the attenuation of the power between gates 1 – 4, when all the gates are adapted (see fig. 3).

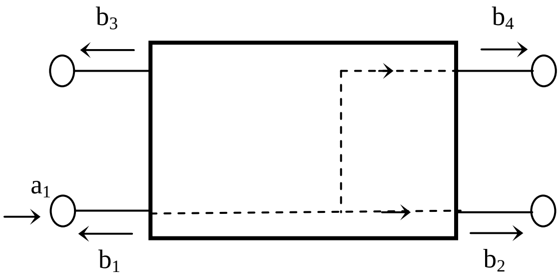

Fig. 3. Notations used for the directional coupling device.

Coupling attenuation has the relation:

$$A_c = \left.\frac{P_1}{P_4}\right|_{ad} = \frac{|c_1|^2 - |b_1|^2}{|b_4|} \qquad (16)$$

sometimes instead of the attenuation we use the under-unit measurement called „coupling”:

$$c = \frac{1}{A_c} \tag{17}$$

Other times we use the power division ratio notion:

$$K_p = \left.\frac{P_4}{P_2}\right|_{ad} \tag{18}$$

Coupling attenuation as well as the coupling is usually expressed in decibels:

$$A_c[dB] = -c[dB] = 10\,log\frac{P_1}{P_4} \tag{19}$$

2. *Directivity* (D) – of a real oven is the ration between the transmitted power at the coupled gate and at the insulated gate when adaptation at all gates is finalized:

$$D = \left.\frac{P_4}{P_3}\right|_{ad} \tag{20}$$

Expressed in decibels, the directivity of a coupling device is given by the relation:

$$D[dB] = 10\,log\frac{P_4}{P_3} \tag{21}$$

3. *The adaptation* of the real oven is appreciated by the adaptation of its gates. This adaptation can be characterised by the module value of the reflection coefficient of the gate, when all the other gates are finished adapted. For instance gate 1 adaptation is given by:

$$|\Gamma_1|_{ad} = |S_{11}| \tag{22}$$

Sometimes the term attenuation of the reflection is used (or reflection loss):

$$R_L = \frac{1}{|S_{11}|}\ sau\ R_{L_1}[dB] = -20\,log|S_{11}| \tag{23}$$

4. *Nominal frequency* (f_0) – is the frequency that the coupling device was calculated for.

5. *Band* (B) – is the frequency range inside which coupling performances remain optimum.

4. ERRORS IN THE MEASUREMENT OF THE POWER IN MICROWAVE IN EPOXY RESINS POLYMERIZATION PROCESSES.

From the dielectric power measuring and reflecting in the polymerization processes of the electric epoxy resins insulations we have an important element of technology. However, we may experience many independent sources of errors that affect direct and reflected power measuring. The most important are:

1. errors of un-adaptation that are due to the reflections that appear at load and generator, that have as effect the fact that the available power emitted by the microwave generator is not completely transferred to the electrical insulation or to the measure decoder of the direct and reflected power;
2. measuring devices errors used that affect the precision with which the continuous powers are measured or errors of low frequency substituted to the microwave power;
3. Errors due to the losses of the decoders due to the dissipation in the walls of the wells of the power in microwave that are transmitted in vacuum.

4.1. Un-adaptation errors due to the reflections

Transmission regime of the power in microwave through waveguides depends to a great extent on the essence of the reflections. When a direct wave of power (P_0) that propagates on the guide meets a discontinuity characterized by a reflection coefficient ρ, it separates itself into two components:

– a reflected wave that transports energy contrary to the direct wave propagation:

$$P_r = P_0 \cdot |\rho_s|^2 \tag{24}$$

– a direct wave that further carries energy, above the point where reflection appears:

$$P_d = P_0 \left(1 - |\rho_s|^2\right) \tag{25}$$

Thus, a load absorbs the whole direct power only when it does not produce any reflection on the wave-guide, that is, when it presents an impedance characteristic to the line [4].

Not only the impedance ratios influence the value of the power absorbed by the load, but also the ones at the generator.

P_o power of a direct wave, that is, the one the generator transfers into the guide, is maximum when the input impedance of the guide is complexly conjugated with the output impedance of the microwave generator. If we refer to the absorbed power by the epoxy resin at rank P_A that the microwave generator supplies to an adapted line we have:

$$\frac{P}{P_A} = \frac{1 - |\rho_s|^2}{[1 - \rho_G \cdot \rho_s]^2} \tag{26}$$

where ρ_s and ρ_G are the reflection coefficients (in complex value) at the load and generator [5].

We may notice that the denominator depends not only on the absorbed values of the reflection coefficients, but also on their phases at a point on the wave-guide.

The relation between the absorbed power by the epoxy resin and the maximum P_M that the generator supplies in optimal transfer conditions:

$$\frac{P}{P_M} = \frac{\left(1 - |\rho_s|^2\right) \cdot \left(1 - |\rho_G|^2\right)}{|1 - \rho_G \cdot \rho_s|^2} \tag{27}$$

The un-adaptation error may be reduced by controlling ρ_s and ρ_G. When the reflection coefficients are known only in absolute value we may establish a superior limit of the error with respect to the relation:

$$1 - |\rho_G \cdot \rho_s| \le |1 - \rho_G \cdot \rho_s| \le 1 + |\rho_G \cdot \rho_s| \tag{28}$$

Thus, if the stationary wave coefficient towards the load and the generator have the value:

$$\sigma = 1{,}4$$

$$|\rho_s| = |\rho_G| = \frac{1 - \sigma}{1 + \sigma} = 0{,}167 \tag{29}$$

so it follows that if the direct measured power is P, we will have:

$$P_M = 1{,}06 \cdot P \pm 2{,}8\% \tag{30}$$

Determining the power absorbed by the epoxy resin is done using a comparative method, for which in identical conditions instead of the resin we connect the power measuring device. For the result to be correct the measuring device must present the same impedance with the load. Otherwise, we must establish the correction which is done with the relation:

$$\frac{P_1}{P_s} = \frac{\left(1 - |\rho_1|^2\right) \cdot \left(|1 - \rho_G \cdot \rho_s|^2\right)}{\left(1 - |\rho_s|^2\right) \cdot \left(|1 - \rho_G \cdot \rho_s|^2\right)} \tag{31}$$

The un-adaptation error can be cancelled if $\rho_s = \rho_1$.

4.2. Measuring devices errors

Usually an insulator is introduced between the microwave generator and the load that allows for the passage of waves (only from the generator towards the load, or in the absorber with the purpose of separating the load from the generator so that its functioning regime is independent from certain load variations).

Avoiding the effect of the reflection coefficient of the generator is done interpolating a directional coupling device that includes a detector in the secondary arm that indicates the level of the direct wave.

The errors introduced by the directional coupling device's imperfection are inferior to the ones resulted from microwave un-adaptation generator. Fig. 4 schematically shows the solution presented above.

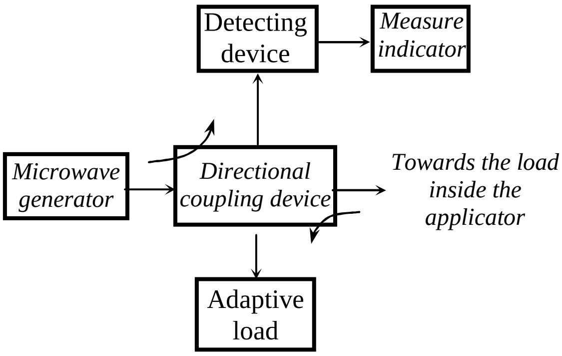

Fig. 4. Design for eliminating the errors resulting from generator reflection.

4.3. Errors due to the coaxial measuring wells for direct and reflected power.

The coaxial wells used for measuring the microwave power should transfer the whole power to the measuring element, element that should respond identically to same powers.

Well productivity is the ratio between the microwave power dissipated in the coaxial well and the whole power existing in the guide where the well is situated. The effective productivity is the ratio between the substituted power (continuous or low frequency) absorbed by the coaxial well and the whole power in microwaves inside the auxiliary guide of the directional coupling device. The etalon factor represents the ratio between the substituted power (continuous or low frequency) absorbed by the coaxial well and direct power.

Fig. 5 represents the scheme of a design for measuring the direct and reflected power in the case of an epoxy resins polymerization process.

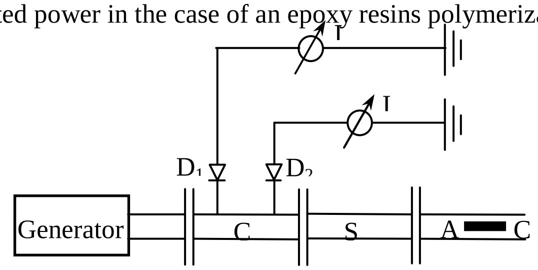

Fig. 5. Scheme of a design for measuring the direct and reflected power in the case of a epoxy resins thermal processing, where: G – microwave generator ; CD – directional coupling device; D_1, D_2 – detection diodes; I_1, I_2 – measuring devices; SA – impedance adaptor device; A – microwave with adjustment device.

Signals applied to the measuring devices I_1 and I_2 is in fact proportional with the length of the well $"I"$ introduced in the guide [6].

If this length varies with $\Delta 1$ the systematic error of the measuring devices will be:

$$\varepsilon_l = \frac{\Delta l}{l} \qquad (32)$$

where $\Delta 1$ is the deviation takes place also because of the upper wall thickness variation, upper wall that forms the secondary guide of the directional coupling device.

The length of the well introduced in the guide is of 5–10% of the height of the section of the rectangular guide. For an error less than 1% on the measuring devices I_1 and I_2, it is necessary that:

$$\Delta l \leq \frac{l}{100} \leq 0{,}05mm \qquad (33)$$

The upper wall of the guide must have thickness and parallelism variations of less than 15 mm. If the admissible error lowers from 1%, the tolerance in manufacturing the corresponding exterior to the upper wall becomes $\pm 0{,}75\mu m$. The length of the well inside the guide must not surpass 5 – 10% of the height of the $"b"$ guide because it raises the echoes due to the reflection. Reducing the well length to less than 5 – 10% from $"b"$ is not advisable because this leads to increasing the relative error $"\varepsilon_1"$ up to 3%.

CONCLUSIONS

In this paper we presented an interesting polymerisation method of epoxy resins employing microwave technology that has its own unique advantages, the most important being the substantial reduction of processing duration and obtaining a product of higher quality.

In the same time we could not leave aside the constructive issues that appear inside the microwave unit. Finally we presented some methods of reducing the errors for microwave power measuring during epoxy resins polymerisation; these methods are effective and experimentally validated.

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