SCIENTIFIC-ENGINEERING APPROACH TO THE PROBLEM OF MODELLING AND OPTIMIZATION OF INDUSTRIAL PLASMOCHEMICAL DEVICES

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ABSTRACT

A method to analyze dynamic characteristics of plasmochemical processes is suggested. The problem formulation and the method for dynamic optimization of plasmochemical devices and its operation are exemplified by a typical thermal unbranched chain reaction of nitrogen oxidation entering into the total plasmochemical scheme of nitric acid preparation.

1. INTRODUCTION

The analysis and development of efficient plasmotrons for plasmochemistry with a high degree of the electric-to-thermal energy transformation ensuring the high degree of the desired chemical conversion, determine the necessity of dynamic characteristics studies. These characteristics represent a rather complicated complex of individual processes. The first step in dynamic studies is always the extensively studied problem of stability, and in this field many significant results have been obtained. But the necessary second step in these studies, that is the consideration of transition processes (usually referred to as the problem of transient performance) is still only at the initial stage of studying.

In the present communication the problems of determination of dynamic characteristics of plasmotrons associated with the possibility of approximated analytical interpretations of transition processes, have been studied in technological aspects. To obtain such characteristics, generalized dynamic parameters, that is criteria of process inertia, were introduced as the generalization of the concept of the object time constant to determine transfer functions and to reconstruct response functions in the approximately analytical form without partial-derivatives solutions of the differential equations which describe the process dynamics in plasmotrons, i.e. plasmochemical, thermal, gasdynamic and electrical processes. In high-power plasmotrons with a long electric arc the fundamental time of chemical gas or gas mixture reactions is of the same order as the gas transport time. A detailed mathematical description for the physical nature of the plasmotron process as a technological object[1,2,3] includes nonstationary material and heat balance equations, momentum, nonequilibrium and state equations and equations to describe the arc dynamics at small disturbances. The process dynamics was studied taking into account the electric arc radiation, whose contribution in high-power plasmotrons to the total electric balance is significant.

The plasmotron dynamics equations were completed by the external disturbance functions, taking into account the actual conditions of the plasmotron technological processes, in particular, that the distributed process in an interelectrode insertion plasmotron (IIP) is usually influenced only by local intermediate external disturbances imposed at several points. If one intermediate disturbance is considered, the problem is readily generalized for the case of several disturbances and the disturbance continuously distributed along the plasmotron. The external disturbance in a closed system of plasmotron control can be applied as the manipulated variable.

In general, all transition regimes are greatly dependent on the process prehistory, i.e. on the initial steady state. In our calculations (being in rather good agreement with experiment) the parameters of the static regime were taken close to the actual conditions for a model industrial plasmotron, type GNP-10. According to the experimental data, the arc current is 420 A, its voltage is 2200 V, the air flow rate for the first and second plasmotron regions is 40 and 50 g/s and the mean pressure at the starting length of the plasmotron channel is $4 \cdot 10^5$ Pa (4 atm). The gas flow rate along the plasmotron was distributed. Disturbances were taken so as the object under study was in a linear region, i.e. the disturbances were not higher than 10% of the static regime parameters. The problem linearization in these conditions was shown to be valid.

2. RESULTS

The suggested method of theoretical analysis of the plasmotron dynamics and of solution of its dynamic optimization consists of the following steps:

1) A general system of equations to describe the plasmochemical process dynamics is specified and expressed in dimensional parameters.

2) According to the known rules, the problem is linearized near the initial steady-state regime. Note that using the Volterra series, the problem can be applied for some strong-nonlinear processes[4].

3) Using the Laplace transform, it is possible to turn to the operator equations, not to be solved, however. The problem of determination of the solutions (required functions) is substituted by the determination of the totality of these functions moments (inertia) defining well the required solutions[4].

The relation of inertia with the power moments of the response function is expressed by the simple relationship:

$$n!S_n = C_n \quad , \quad C_n = \int_0^{\infty} \tau^n f'(\tau)\, d\tau .$$

4) The concrete determination of various order inertia S_n can be performed by one of the indirect methods:

a) Inertia calculation according to the accurate transcendental transfer function $F(P)$ found from the process equations, if this function is determined in the general form. Then

$$S_n = (-1)^n \cdot \frac{1}{n!} \lim_{P \to 0} \frac{d}{dP^n} F(P),$$

i.e. the inertia values are determined from the transfer function transformation to the Maclaurin's series.

b) Consequtive calculation of various order inertia S_0, S_1, S_2, S_3, S_4, ... directly by the recurrent system of differential inertia equations which is much more simple than the basic process equations, since it does not contain partial derivatives. This system is obtained from the given basic equations through simple differential and algebraic transformations according to the above relationship (a).

5) The thus found dynamic inertia parameters represent the total solution of the problem. According to these parameters the required solution of the problem can be constructed (reconstructed), i.e. to obtain transfer and response functions of the process with any required accuracy[1,4]. In this case the transfer function can be represented by the Bürmann-Lagrange series:

$$F(P) = \sum_{n=0}^{\infty} d_n \left(\frac{P}{P+\lambda}\right)^n, \text{ where } d_n = \sum_{m=0}^{n-1} (-1)^{n-m} C_{n-1}^m \lambda^m S_{n-m},$$

$$\lambda_\alpha = \lim_{n \to \infty} \frac{S_{n-1}^\alpha}{S_n^\alpha} \simeq \frac{S_{n-1}^\alpha}{S_n^\alpha}, \quad C_{n-1}^m = \frac{(n-1)!}{m!\,(n-m-1)!}$$

The symbol α marks a given individual process.
The corresponding response function of the process is:

$$f(\tau) = f(\infty) + e^{-\lambda\tau} \sum_{n=1}^{\infty} d_n \mathcal{L}_{n-1}(\lambda\tau), \quad f(\infty) = S_0,$$

where $\mathcal{L}(\lambda\tau)$ is the Laguerre polynomial.

Note that for a special quasi-orthogonal system of polynomials[4] the transformation coefficients can be expressed in a quite simple way, namely $d_n = \lambda^n S_n$. All obtained approximations very quickly converge. Taking into account of two-three terms of the transform is quite enough for practical purposes and the fourth approximation, as a rule, does not practically differ from the third.

To estimate the plasmotron dynamic properties in designing with or without a control system, the concept of a transmission band can be used, also determined according to various order inertia. The dynamics of a multirelated system which is a plasmotron, can also be accounted for in designing by studying its response to the test disturbances.

If one considers the designing of a plasmotron as a technological object, the estimate of its dynamics will be the ability to filter disturbances (f) and to transmit the control pulses (u).

Then the functional

$$\mathcal{Y} \simeq a_1 \sum_{k=0}^{n} (C_k^u)^2 + a_2 \frac{1}{\sum_{k=0}^{n} (C_k^f)^2}$$

characterizes the object dynamics and takes the maximum value with changing variable construction parameters. Here the values C_k^u and C_k^f are the coefficients of transformation to the Fourier-Lagrange series of the pulse response functions which can be expressed through various order inertia (in the mathematical sense through the function moments); a_1 and a_2 are the weight coefficients, herewith $a_1 + a_2 = 1$, $a_1 \geqslant 0$ and $a_2 \geqslant 0$.

The application of disturbing functions of the distributed and the concerted character ensures the possibility for wide variations in the plasmotron technological regimes. It also allows for additional ways to change the technological regime and the efficiency of plasmotrons.

The plasmotron transmission band functional, as a first approximation, can be expressed through the first-order inertia

$$\mathcal{Y}_1 \approx b_1 S_1^1 + b_2 \frac{1}{S_1^2},$$

where b_1 and b_2 are the given weight coefficients; and S_1^1 and S_1^2 are the first-order inertia in the controlling and controlled channels.

The established property of the first-order extremal inertia can be used in designing plasmotrons to choose the parameters ensuring their maximum controllability.

To solve these problems, the following procedure for a step-wise study is suggested:

1) Using the basic transfer processes, the zero- and the first-order inertia are determined in the respective regions of plasmotron parameters variations depending on the coordinates χ_i of the points of disturbing function application.

2) The demands imposed on the construction and operation regime parameters restrict the region of the generalized parameters variation and the choice of the above coordinates for the application of disturbing functions (external disturbances).

3) In the admitted region of parameters variation the values are chosen ensuring the best controllability at a

given plasmotron point.

The decisive factors for the choice of optimal criteria can be construction, technological or operation characteristics.

The construction factors are: limitations regarding the plasmotron type, i.e. with transverse or longitudinal arc flowing, high-current and sectioned by interelectrode insertions; material limitations for cathode, anode and other plasmotron components depending on the media agressivity, etc. Among the technological factors are: maximum and minimum arc current and strength, gas flow rates, thermophysical properties of plasma and regularities in their variation with the temperature and pressure. The operation characteristics can be the efficiency of continuous plasmotron operation and the intensity of cathode erosion.

In the case of a large number of generalized plasmotron parameters and their associated relations, the problem of choice of the optimum parameters is advantageously solved by the methods of nonlinear programming [3,4]. The effectiveness function in this problem should be chosen according to the techico-economical aspects of the process.

3. CONCLUSION

The suggested method of plasmotron dynamic optimization with chemical reactions and imposed external disturbances can be applied for the analysis of plasmochemical devices. Herewith external disturbances of the distributed and concerted character can exert different influence on the reaction channel (Plasmochemical reactor) and the hardening device. This disturbance can be aimed at the stabilization of optimum regimes and the simultaneous enhancement of the extremum inertia values. Note that the output parameters of the plasmotron and reaction channel will be respectively the input parameters of the reaction channel and of the hardening device.

The above method for the analysis of the dynamic characteristics of plasmochemical devices solves the problem of their dynamic optimization. In this case an important property of the spatial distribution of the process significantly influencing the dynamics character is taken into account. The main advantage of these methods is that in the formulation of optimization problem the dynamic criteria are readily determined as functions of the plasmotron parameters and operation regime. Herewith the parameters are combined into dimensionless complexes whose number can be reduced to minimum, which simplifies analytical and graphical studies. Thus two practically important problems are solved:

1) Determination of the optimum parameters of plasmochemical devices and operation regimes with taking into account the stability criteria of the operation regime without automatic control.

2) Determination of the optimum parameters as the main stage of automatic control.

In addition, the obtained results can be used as a basis for an efficient solution of the problem of development of the control systems to control chemical technological processes in plasmotrons.

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