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MULTICRITERION OPTIMIZATION OF PLASMA PROCESSES

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A new method of automatic multicriterion synthesis of plasma processes and apparatuses is proposed. The method is applied to multicriterion optimization of reduction plasma production with the recovery of blast-furnace gas in a direct steel-making process.

To optimize any device, apparatus or process, its mathematical model and an optimization method are required. The choice of the latter is a complex problem if only because they are numerous (according to some sources, 400–500, according to other sources, more than 2000). Each designer works with equations of a certain form. Since optimization purposes are especially practical, we must determine how the potentialities of the available methods correlate with the basic features and properties of real technical objects and processes reflected in their mathematical models. What is implied is the multicriterial nature, the multiparametric nature, and the parameter spread of real plasma systems.

The concept of a multicriterial nature came about because objects whose quality can be characterized with a sufficient degree of completeness by one index are extremely few. Most often there is the whole set of indexes (criteria), each characterizing one of the aspects of object operation. Accordingly the quality indexes can be technical, technological, economical, ecological, etc.

Consequently, the problem of optimization, too, should be considered with allowance made for the presence of contradictory requirements on many quality indexes, i.e., in a multicriterial statement.

The available multicriterion-optimization (multiobjective-optimization) methods can be arbitrarily separated into two classes. The first class is based on reduction of multicriterion problems to one-criterion ones by identifying the main criterion or through the formation of a generalized criterion from partial ones. These methods are widespread and seem very attractive since the one-criterion optimization methods are most developed and, which is of particular value, most formalized [1-3]. However, in this approach, one problem is practically replaced by the other, and the correctness of this replacement with respect to a real object is very doubtful.

The second class of methods is based on two successive procedures: first the Pareto set is identified by completely formalized methods, and then the optimum variant is chosen from this set by a decision-maker or a group of decision-makers [4]. The set of "good" points can turn out to be intolerably large for the decision-maker to be able to independently make the final choice. And, to reduce the Pareto set, additional information is needed, which must be obtained again from a highly skilled specialist.

In general, both classes of methods to solve multicriterion problems have one conceptual feature: the main responsibility for synthesizing the system is to be borne by a specialist. In the first class of methods, he, using his discretion, must choose one main criterion or formulate a generalized criterion using his personal knowledge and experience. In the second class of methods, he must choose one variant from the Pareto set presented.

Thus, the result of the optimization in both cases is almost fully predetermined by the level of skill, experience, and intuition of development engineers and experts and, naturally, is subjective.

Another important feature of real technical objects and processes that is reflected in mathematical models is their multiparameter nature. The presence of a large number of parameters that are related by some operators

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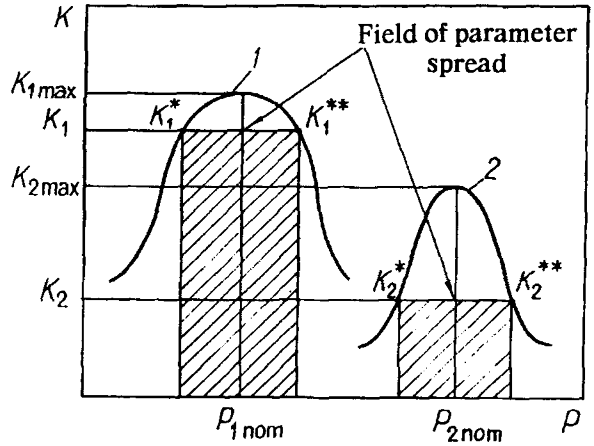

Fig. 1. Check of solution stability in one-criterion optimization.

to quality indexes is characteristic of complex technical systems, among which are plasma processes and the equipment to perform them.

If the parameters are numerous and their relationships with the criteria are complex and implicit, the principle of counterintuitiveness can come into effect when a man is unable to correlate and analyze all the information reflected in a mathematical model [5]. On the other hand, a complex model of an object can be too cumbersome even for solution on a computer. In the optimization methods available, it is proposed to overcome this so-called "curse of multidimensionality" using decomposition (separation) of a complicated comprehensive mathematical model into submodels. This ensures optimization with acceptable computer-time consumption. However, the procedures to decompose the mathematical model are very complicated methodologically. When submodels are separated it is impossible to avoid beakups and replacements of the relationships, and this leads to considerable errors in calculations. The procedures themselves are rather tedious; they call for a thorough analysis and a large consumption of the time of the most skilled specialists.

A very important feature of real technical objects and processes is the fact that they operate under conditions of constant variation of parameter values under the effect of various internal and external destabilizing actions.

The region of the values that each parameter can take in object operation is called the dispersion field. The magnitudes of the parameters are distributed in it in a random manner and obey a certain law. The number of destabilizing factors can include inaccuracies in manufacturing the plasma equipment, the errors of measuring instruments, feeders of loose materials and weighers of the initial reagents, supply-line voltage fluctuations and pressure fluctuations in gas- and water-supply lines, etc. These factors not only cause parameter spread but can also lead to qualitative changes in the behavior of the object [6].

Therefore, in the stage of search for the required values of the parameters, there arises the problem of allowing for deviations of the real magnitudes of the parameters from the calculated ones and ensuring the required quality of equipment operation and technological process under these conditions. Mathematically, this becomes the problem of the optimum's stability. Because of the presence of dispersion in the majority of cases the calculated variant cannot be realized. This often leads to the need for radical reprocessing of the results obtained.

As an illustration, we can give an example of one-criterion optimization for objects with one parameter (Fig. 1). For the first object (curve 1), the presence of parameter spread does not lead to a substantial change in $K_{1\max}$ (points K_1^* and K_1^{**}). But in the second variant (curve 2), the same spread takes the system far away from the maximum value of the criterion $K_{2\max}$ (points K_2^* and K_2^{**}), and the result of the solution of the optimization problem is practically reduced to zero. The situation is complicated further in the presence of a large number of criteria and parameters.

We can say that the methods that allow for the phenomenon of parameter spread in the known multicriterion-optimization methods do not satisfy the users. Having powerful optimization programs, a development engineer is often unable to obtain a solution that is of practical value.

Analysis of the problems that accompany the use of the known multicriterion-optimization methods suggests that fundamentally new approaches to the solution of these problems are needed.

A new concept developed by the authors eliminates the contradiction between the complication of the created systems and traditional approaches to their synthesis that make the development engineers responsible both for a tedious computer dialog and for decision-making. This is effected through a methodology in which all synthesis procedures are completely formalized and are performed on a computer in the automatic mode. The solution is correct since it is performed with allowance made for the requirements on criteria and with a priori allowance made for parameter dispersion. The human role reduces directly to the statement of the problem (what is implied is the step of creating a mathematical model and the step of developing a technical task as a set of the requirements on quality indexes of the object created).

To realize a completely computerized methodology for parameter search, we developed a method to construct a multicriterion mathematical model of special form. It presents a system of two functionally interrelated structures: a parameter space with a region within which all the requirements on quality indexes are met and a criterion space with a region limited by the requirements of the technical task. It forms the methodological basis for solution of multicriterion problems in which all procedures are automated. A model of special form can be applied to transform practically any initial mathematical model, since it requires no limitations on the number of parameters, the number of criteria, or the form of the equation of the relationship between them. When the initial mathematical model is very complicated and cumbersome, there is no need for its decomposition.

In designing a complicated technical system, it becomes possible to realize the principle of the unity of objectives in a multicriterion statement for all design steps. This enables us to do away with the disagreement of optimality conditions, since the requirements on the entire system and its subsystems are unified and are easily formed by the development engineer by completely formalized rules.

As a result of the solution of the design problem the development engineer obtains data to create the best technical task as regards the requirements rather than a more or less acceptable variant. Reliability of the results is ensured through the elimination of subjective aspects from the optimization procedures.

The method of computer synthesis of plasma systems is applied to solve the problem of choosing the composition of raw material in the step of generating reduction (H_2 + CO) plasma in a direct steel-making process [7].

A plasma with a high content of hydrogen and carbon monoxide is produced in plasmochemical pyrolysis of methane in the presence of oxygen (70% CH_4 + 30% O_2). When this plasma is used to reduce iron from the oxides, blast-furnace gas that is heated to a temperature of 600–800 K and, with a 50% use of the reduction plasma contains 31.65 vol.% of H_2, 17.48 vol.% of CO, 32.10 vol.% of H_2O, 16.35 vol.% of CO_2, and 1.8 vol.% of N_2 is discharged to the atmosphere from a melt unit [7].

It seems promising, both economically and ecologically, to recover part of the blast-furnace gas by feeding it to the inlet of the plasmatron together with methane and oxygen. The heat is recovered, the oxydizing elements reduce the process oxygen demand while the reduction elements ensure an additional decrease in energy consumption. Thus, we stated the problem of determination of the composition of the initial methane–oxygen–blast-furnace gas plasma-generating mixture that will ensure a composition of the target product, i.e., reduction plasma, at the outlet from the plasmatron at least that as good as and energy indexes of the process that are even better than those of the methane–oxygen process.

A preliminary thermodynamic analysis of the composition and characteristics of the methane–oxygen–blast-furnace gas mixture in the temperature range of 500–3000 K at normal pressure [8] enabled us to establish that as the concentration of the blast-furnace gas in the mixture changes from 20 to 60 vol.% and the oxygen concentration changes from 10 to 50 vol.%, the ranges of change in the characteristics of the methane–oxygen process can be completely covered for each concentration of the blast-furnace gas (Table 1).

The mole fractions of the additions X_{ox} and $X_{\mathrm{bl.g}}$ to the methane can be considered as the internal parameters of the process. As the output characteristics (quality indexes) of the process we took: the energy indexes K_1 and K_2 (kW·h/m^3) (the specific energy consumption per unit volume of the final product (H_2 + CO_2) and the initial mixture, respectively); composition characteristics of the reduction plasma: K_3 is the volume concentration

TABLE 1. Initial Parameters and Optimization Criteria for Reduction Plasma Production with Blast-Furnace Gas as an Oxidizer

No. of initial composition	$X_{bl.g}$	$X_{methane}$	X_{ox}	K_1	K_2	K_3	K_4	K_5
1	0.2	0.72	0.08	1.197	2.294	0.968	0.213	22.607
2	0.2	0.64	0.16	1.081	2.250	0.971	0.354	22.822
3	0.2	0.56	0.24	0.951	1.675	0.972	0.499	23.038
4	0.2	0.48	0.32	0.650	0.931	0.827	0.606	23.253
5	0.2	0.40	0.40	0.185	0.213	0.643	0.776	23.463
6	0.3	0.63	0.07	1.137	2.832	0.969	0.287	19.781
7	0.3	0.56	0.14	1.166	2.446	0.972	0.415	19.970
8	0.3	0.49	0.21	0.983	1.735	0.927	0.548	20.158
9	0.3	0.42	0.28	0.676	0.986	0.793	0.659	20.346
10	0.3	0.35	0.35	0.324	0.392	0.631	0.845	20.534
11	0.5	0.45	0.05	1.322	3.110	0.972	0.436	14.129
12	0.5	0.40	0.10	1.198	2.504	0.948	0.529	14.264
13	0.5	0.35	0.15	1.007	1.836	0.854	0.584	14.398
14	0.5	0.30	0.20	0.780	1.223	0.741	0.688	14.533
15	0.5	0.25	0.25	0.491	0.624	0.584	1.021	14.668
16	0.6	0.36	0.04	1.337	3.023	0.969	0.538	11.304
17	0.6	0.32	0.08	1.200	2.429	0.896	0.580	11.411
18	0.6	0.28	0.12	1.000	1.900	0.809	0.651	11.519
19	0.6	0.24	0.16	0.825	1.305	0.707	0.768	11.626
20	0.6	0.20	0.20	0.548	0.760	0.566	0.952	11.73

of $X_{H_2} + X_{CO}$ in the final product; K_4 is the ratio X_{H_2}/X_{CO}; K_5 (roubles) (the cost of 1000 m^3 of the initial mixture).

The problem of seeking optimum concentration relations for the initial reagents requires multiple computations. There is little sense in referring each time to a complicated thermodynamic computational model, but the results of a numerical experiment in the analyzed parameter region that are presented in Table 1 enable us to use regression analysis to create approximate equations for the relationship between the quality indexes for the process K_1-K_5 and its internal parameters X_{ox} and $X_{bl.g}$.

Polynomial dependences of various kinds serve as approximating expressions while the specific form of the approximating polynomial is substantiated by methods of mathematical statistics [9]. The process is most adequately described by the models:

$$K_1 = 0.614 + 2.305\,X_{bl.g} + 4.330\,X_{ox} - 1.586\,X_{bl.g}^2 -$$

$$- 10.024\,X_{bl.g}X_{ox} - 10.850\,X_{ox}^2,$$

$$K_2 = 3.588 + 1.032\,X_{bl.g} - 7.719\,X_{ox},$$

$$K_3 = 4.526 + 5.070\,X_{bl.g} + 3.479\,X_{ox} - 1.442\,X_{bl.g}^2 -$$

$$- 6.884\,X_{bl.g}X_{ox} - 6.112\,X_{ox}^2, \quad (1)$$

TABLE 2. Nominal Values and Possible Parameter Spreads for a Weigher Error

Parameters	Nominal value	Deviation from nominal value			
		5%		10%	
		lower	upper	lower	upper
Mole fraction of blast-furnace gas in initial mixture – $X_{bl.g}$	0.245	0.234	0.257	0.220	0.269
Mole fraction of oxygen in initial mixture – X_{ox}	0.249	0.237	0.261	0.224	0.274

TABLE 3. Nominal Values and Possible Quality-Index Spreads for a Weigher Error

Quality indexes	Nominal value	Deviation from nominal value			
		5%		10%	
		lower	upper	lower	upper
Specific energy consumption to heat initial raw material – K_1, $kW \cdot h/m^3$	0.879	0.841	0.906	0.800	0.932
Specific energy consumption to produce reduction plasma – K_2, $kW \cdot h/m^3$	1.386	1.310	1.450	1.240	1.510
Content of reduction elements in plasma – K_3	0.915	0.897	0.927	0.878	0.937
Relation of reduction elements in plasma – K_4	0.565	0.548	0.588	0.531	0.611
Cost of 1000 m^3 of raw material – K_5, roubles	21.55	21.30	21.80	21.00	22.10

$$K_4 = -0.134 + 0.994\, X_{bl.g} + 1.833\, X_{ox}\,,$$

$$K_5 = 26.825 - 24.775\, X_{bl.g} + 3.155\, X_{ox}$$

In multicriterion optimization, it is proposed to solve the problem of synthesis, i.e., to determine the values of the internal parameters that ensure the required output quality indexes. For this process, we should determine the X_{ox} and $X_{bl.g}$ that ensure the following requirements on the quality indexes

$$\begin{gathered} 0 \le K_1 \le 1.9\,, \\ 0 \le K_2 \le 1.1\,, \\ 0.85 \le K_3 \le 1\,, \\ 0.35 \le K_4 \le 0.65\,, \\ 0 \le K_5 \le 25\,. \end{gathered} \tag{2}$$

The presence of mathematical model (1) and the requirements on the process enabled us to begin solving the problem using immediately a program module in which all the procedures are performed on a computer in the automatic mode.

As a result of the solution in the parameter space a region is determined within which simultaneous fulfilment of the requirements on the entire set of the quality indexes of the process is guaranteed:

$$0.210 \le X_{\text{bl.g}} \le 0.280\,,$$
$$0.200 \le X_{\text{ox}} \le 0.285\,. \tag{3}$$

From the viewpoint of requirements (2), all the variants that are included in this region are equally good. If one variant is needed, we can propose

$$X_{\text{bl.g}} = 0.245\,, \;\; X_{\text{ox}} = 0.249\,. \tag{4}$$

as the nominal value. When the calculated variant is realized deviations from the nominal value under the action of destabilizing factors are possible. In the solution, we allowed for the level of possible deviations from the nominal value that occur because of the error of the weighing equipment in feeding the initial reagents. We calculated two variants: for errors of 5% and 10% (Tables 2 and 3). It turned out that the spread in $X_{\text{bl.g}}$ and X_{ox} does not fall outside the boundaries of the region of permissible values even for a 10% error, and there is no need to install weighing equipment of higher precision.

The calculation permitted a variant of a direct steel-making process whose energy indexes were improved by 20%.

Furthermore, about 30 problems from various fields have been solved by the developed method: linear arc-burning optimization in a plasmatron, calculation of the dynamic system of a balancing machine, choice of a production process for fused-cast refractories, design synthesis of an automatic-control system of the regulatory type for a gas-turbine plant, etc.

Experience with these objects confirmed the efficiency and correctness of the basic principles of the proposed method for solving the multicriterion problems of synthesis of technical objects and processes.

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