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TECHNOLOGICAL RELIABILITY OF CHEMICAL ENGINEERING SYSTEMS*

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A significant part of the gross domestic product is lost because of hitches followed by long down-time periods in industrial systems. This is a common problem in the industry of developed nations. Analysis of causes of this phenomenon allows developing a conception of solving this problem and suggesting a method of studying the reliability (working capacity) of chemical-engineering systems. In this article we prove the need for technological reliability analysis tools in prefeasibility study to estimate the potential working capacity of the technology and to avoid the large costs of starts and stops.

Keywords: *dependability, reliability, working capacity, chemical engineering, process engineering, hitch.*

Introduction

An unpleasant phenomenon is observed in the industry: the loss of a considerable part of the gross domestic product because of sudden stops and the subsequent long non-productive times of industrial producing systems. Analyzing the reasons of this phenomenon allowed to formulate a concept of solving the problem and to suggest a method for studying the reliability (working capacity) of chemical-engineering systems (CES).

The suggested method of studying the reliability of CES is based on completely legitimate definitions:

1. A system is a set of interacting parts. Let us call the parts of CES chemical engineering, the processes and apparatuses of chemical technology and the equipment of chemical plants.

2. Reliability is working capacity in time [1].

3. Working capacity is the state of an object, at which the values of all parameters characterizing the ability of carrying out the preset functions conform to the requirements of normative-technical and/or design documentation [1].

The latter definition requires more exactness. In chemical industry, as a rule, the preset functions mean the *annual* productivity of CES with respect to the target product and the quality of this product.

The meaning of conformity of parameters of normative-technical and/or design documentation is as follows. Let us assume that Y_i is one of parameters characterizing the ability of a CES to perform the preset functions. Let us assume that Y_{i0} is the rated value of this parameter preset by the design, and ΔY_i is the range of deviations of this parameter from the rated value allowed by the developers. Let us assume that Y_i conforms to the requirements of normative-technical and/or design documentation, if

$$|Y_i - Y_{i0}| < \Delta Y_i$$

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In practice restrictions to the amplitude of deviation ΔY_i are asymmetric: either only at the right or only at the left (Figure 1). We will further refer to these parameters with restriction to the amplitude of deviation as to the *preset* parameters.

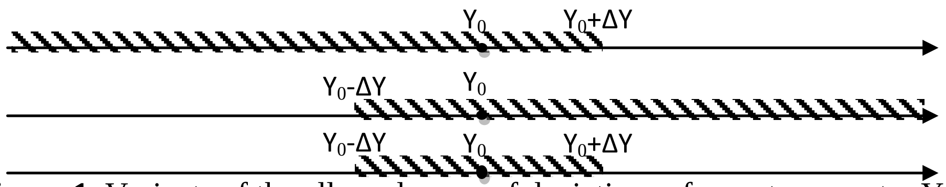

Figure 1. Variants of the allowed range of deviations of preset parameter Y_i

It follows from these definitions that CES is capable of working, when and if ALL the preset parameters (Y_i) are in the allowed interval of variation (ΔY_i). Therefore, CES is in a state of failure, when and if AT LEAST ONE preset parameter is beyond the allowed variation interval.

For example, let us assume that the nominal temperature of a gas flow at the inlet to the layer of a catalyst is 300 °C (thus, Y_{i0}=T=300°C). According to the technical specifications of the catalyst the allowed interval of changes $\Delta Y_i = \Delta T = \pm 20$°C. The physical justification of such interval is as follows. If the temperature of the gas flow in the catalyst layer becomes more than 320°C, destruction of the catalyst carrier will occur, the CES productivity will become zero, and the CES failure will happen. If the temperature of the gases becomes less than 280°C, the catalysis rate will significantly decrease, and in this case the CES failure will happen as well.

Historically, mechanic engineers started being engaged in reliability before anyone else. They investigate the destruction and degradation of matter under operating conditions of CES (corrosion, adhesion, abrasive wear, cyclic loading and aging, growth of non-uniformity in materials, change of strength properties). Studies of this field serve designers armed with the theory of strength of materials and engaged only in the destruction of apparatuses. This refers only to mechanical reliability.

Let us note a specific feature of these studies. Studying the processes of degradation and destruction of matter under the operating conditions of CES gives recommendations in the characteristic time scale: years. However, the practice of operation of many CES shows that failures happen more often before degradation and destruction begin. Therefore, it is necessary to study reliability in other, smaller time scales.

For an industrial large-capacity installation it was necessary to create a physico-mathematical model of the processes dynamics. Processing this model by the methods of generalized analysis [2], more precisely, by the method of the theory of natural scales [3], showed that natural time scales $\tau_{\#}$ of all processes in CES are in the range from 10^{-3} to 10^{3} sec. Therefore, when changing an external action within several hours (10^{3} sec), the CES will come to a new stationary state. During 10^{3} sec faster processes will have already come to the end. Therefore, the theory of parametrical reliability should be considered in this time scale: hours.

The suggested method of studying the reliability of CES is based on two prerequisites:

1. The method does not consider organizational and social causes of CES failures.
2. The physico-chemico-process mathematical model of CES (referred to hereafter simply as model) is developed in the stationary approximation (see Figure 2)

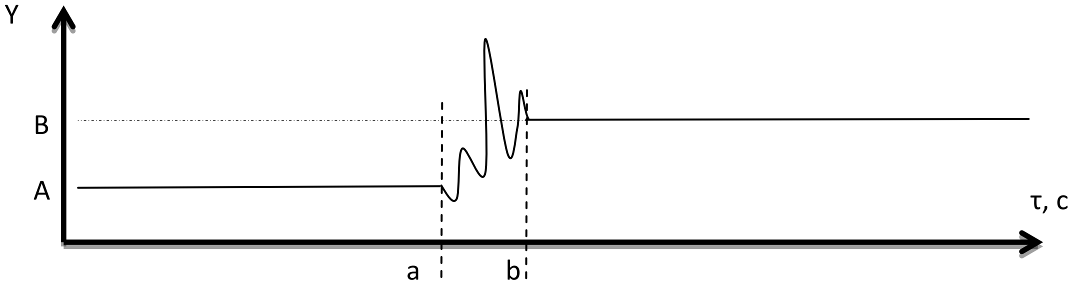

Figure 2. Illustration of the stationary consideration of CES states.
Point *a* is the point where a stepwise change of external influence occurred.
Point *b* is a point where a new stationary state emerged. [c means s (seconds)]

At $\tau < a$ the CES was in a stationary state A. At $\tau > b$ a new stationary state B was implemented. The time of reorganization of the CES b–a = (3–5)$\tau_{\#}$, where $\tau_{\#}$ is the maximum natural time scale of CES. So, the stationarity of the consideration of processes in CES means considering states A and B and studying the preset parameters in these states.

Actually, the concept of stationarity of CES requires deeper and detailed understanding. Indeed, let us consider a situation when we succeeded in developing an adequate model of dynamics of the whole CES taking into account the automatic control system. Let us apply the procedure of studying stability [4] to this model. That is, let us find the coordinates of equilibrium points in the phase space (including the infinity). Then let us determine their local topological structure. Among all the equilibrium points there can be rough and not rough states. грубые и негрубые состояния Among the rough states there can be stable and unstable ones. Not rough states are of bifurcational nature [5]: they can come apart into several rough ones or simply disappear from the phase space. Therefore, plural equilibrium states are obtained. Besides a part of them are not physically implemented. Only rough stable equilibrium states are theoretically implemented, and each such state is characterized by its own set of initial conditions and its own trajectory of start-up.

Thus, the hypothesis of stationary consideration upon creating the model of a CES means the following: the coordinates of a nominal rough stable equilibrium point are known, the initial conditions and the trajectory of attaining this equilibrium point are known.

Concept of the method for studying the working capacity of CES

1. The system for producing raw materials, semi-products, consumer goods in combination with the social and organizational system form the macrosystem, in which the CES is being developed and in which it will operate.
2. The macrosystem perturbs the CES at all its life stages from the development to the dismantlement. These perturbations are considered as a field of elementary accidental events.
3. The quantitative parameters of CES quality (working capacity, prime cost, profit, rate of profit, ecological safety, etc.) are considered to be complex accidental events over the field of elementary ones.
4. A chemical-engineering installation is considered as a system. Its system properties, their effect on the behavior of its parts, the nature of the interaction of the parts of the installation will be distinguished by modeling and numerical experiment.

Algorithm of the method for studying the reliability of CES

Block I: collecting initial information. Here initial minimum necessary information means documents: "Basic data for design", "Chemical operating procedure" etc.

Block II: studying the operating procedure and establishing the set of predetermined parameters; tabulating the predetermined parameters with the following columns: No., Name and physical sense, Designation in the model, Dimension in SI system, Reference value, Allowed interval of deviations, Reference to information source.

The practice of studying operating and projected industrial CES's shows that the number of preset parameters is ~ 10^1.

Block III: model building for each technological process stage and apparatus. It is necessary to start by recording the conservation laws. The model should be closed, i.e., the number of equations in the model should be equal to the number of sought quantities. A basic feature: each "exit" of the CES part should be "entrance" to the following technological process stage or apparatus according to the flow chart. Following these rules makes the whole set of models of the parts a closed model of the whole CES. Thus, the necessary condition of correctness of the whole task is attained.

Block IV: establishing the set of external actions. In order to do this, it is necessary, considering each equation, to separate the sought quantities (functions). The other quantities in the equations form the set of external actions.

Then the table of external actions is created with the following columns: No, Name and physical sense, Designation in the model, Dimension in SI system, Reference value, Allowed interval of deviations, Reference to information source.

In practice the total number of external actions was of the order of 10^2.

The whole set of external actions upon CES can be divided into three subsets according to their origin.

Subset 1: supply streams and their parameters. Of course, the nominal value of the supply stream in the CES is known from the operating procedure. However, the accuracy of raw materials supplying is determined by the dosing apparatus accuracy. The accuracy class index of a dosing apparatus is established by the developers of instrumentation and automated control systems on the basis of requirements specification. In the context of this study it is important only that the mass flow of raw materials is accidental, and its average value and dispersion are known at start-up operations and during the CES operation.

The composition of the raw stream and its parameters – humidity, chemical composition, dispersion, porosity, etc. – are also accidental.

Power flows in CES – the expense and composition of natural gas, fuel oil, coal – are also included in this group of external actions. In the practice of CES operation many cases are known when an installation is first supplied by Tyumen gas, then by Astrakhan gas, or by their various mixtures. Often nobody even warns the CES operators about this, and the installations come to a state of failure.

In the same way parameters of water vapor supplied for technological needs (steam pressure, its state – overheated, saturated or wet – temperature) change. This is also the case with parameters of recycle water of the plant where the CES will be installed.

Parameters of power supply of the CES – voltage jumps, current frequencies, lack of power supply – are also included in this group of external actions.

Subset 2: linear sizes, areas and volumes for heat and mass transfer. When producing equipment at an engineering plant, the actual geometrical parameters differ from those specified in working documentation, at best, within the limits determined in standards. At worst, they differ much more. And these differences are usual external actions.

There is one more circumstance increasing the number of external actions. In order to decrease the investment cost CES developers try to use standard types of equipment as often as possible. This equipment is produced batchwise by engineering plants and, therefore it is rather cheap. This tendency is especially widely implemented for heat exchange equipment. First, heat exchange surface meeting the requirements of chemical engineers is calculated, and then a heat exchanger with the next standard surface larger than required is installed.

In modern CES, heat exchangers make not less than 35–40% of capital investments [6]. Besides, in most cases their heat exchange surface is overestimated. Of course, this perturbs the parameters of the production line away from the reference values.

Subset 3: information noise, inaccuracy, uncertainty of research information.

First of all, it is necessary to include in this subgroup of external actions the whole set of routes of chemical reactions determined by an expert, chemical engineer. It is clear that choosing another set of routes changes the whole basis of the CES, i.e., the concentrations of components in the production line, heat and mass evolution, the rate of transformations, thermal properties, etc. Note that the experience of the authors does not show a single fact of developing the same type of CES with a different set of routes of chemical and phase transformations. This set is once appointed by an expert, and then the whole huge process of development and creation of CES is started.

The third group of external actions includes experimental errors of determining the values and dependences of the equilibrium constants on the thermodynamic state parameters for each reaction from the general set of routes, pre-exponential factors and activation energies, if the Arrhenius equation is used, as well as the values of energy release (absorption) in each reaction.

The third group also includes the uncertainty of scientific information generated by specialists in the processes and apparatuses of chemical engineering. Indeed, the accuracy of determining the heat-exchange coefficient at convective transfer in homogeneous media is not better than 20–30%, and in case of phase transfers (boiling or condensation), not better than 50–100%. This accounts for the overestimation of the calculated heat exchange surface and for the tendency of choosing a standard heat exchanger larger than required in order to be on the safe side. The problem of phase transfers for multi-component systems is one of the most difficult and poorly known ones in chemical engineering. When reading monographs, one gets the impression that everything depends on everything, and everything interacts with everything, but engineering use of theories does give good quantitative dependences. Therefore, the error is great and urges to include the parameters of these dependences in the general list of external actions.

The situation is similar in hydraulics: the accuracy of determining local coefficients of resistance and coefficients of friction is not higher than 40%. The accuracy of creating the characteristics of a draught system and pumping equipment at a plant is also low. Thus, their approximation in the form of polynoms required for developing a model of CES hydrodynamics is also extremely inexact.

Block V: developing an algorithm and program for calculating each preset parameter in the function on all external actions with the use of a personal computer.

Block VI: verifying the model, algorithm for calculating the preset parameters and the program. For operating CES's adequacy can be stated if calculated and measured values coincide within the accuracy of the instrumentation and automated control systems of the plant. For projected CES's adequacy of a model can be stated if calculated values coincidence with the same values in the process procedure.

Block VII: developing a program for calculating functionalities for sets of accidental external actions; carrying out a procedure of random trial of the Monte-Carlo type.

Thanks to the experience of practical application of the method for studying the reliability of CES the most interesting and timely results for chemical engineers and developers of chemical production procedures were found:

1. Applying the method to several operating or projected industrial CES's showed that the probability of working capacity P_{CES} was always less than 0.5 [7]. Note that for any CES there is probability of working capacity P_{CES}, below which the creation of the CES is economically inexpedient.

2. The above method of studying the reliability of CES allows estimating quantitatively the quality of development only by chemical engineers, i.e., calculating an estimation of P_{chem}. This is done simply algorithmically: the transfer processes and the equipment are considered not to be the cause of CES failure.

If one understands that chemical engineers are the first to start creating the technology and developing the flow chart, it is obvious that $P_{CES} < P_{chem}$. Taking into account also the process parameters and the specificity of the applied equipment will only reduce the probability of working capacity as compared to P_{chem}. This circumstance shows the dominating role of chemical engineers in the creation of reliable CES's [8].

3. In old [9] and modern textbooks on "General chemical engineering" [10, 11] the word “reliability” is never found. This term is mentioned only once in the introduction of [12]. Therefore, a popular belief is widespread among chemical engineers that chemical technology has no concern with CES reliability.

In 1992 the scientific community and production engineers had an opportunity of getting acquainted with the book [13] by scientists and teachers of Moscow State University of Fine Chemical Technologies named after M.V. Lomonosov. It is postulated in [13]: "The tasks of creating and improving the industry of the basic organic synthesis should be solved on the ground of the system approach based on consideration of the studied object in interrelation with the objects surrounding it.", "… When creating and designing any industry, the system approach gives a chance to consider it as a whole when its parts are being developed and designed, as well as to choose a method of combining these parts". Therefore, the authors of [13] declare WHAT to do, and the method of studying the reliability of CES suggested by us describes HOW to do it.

The authors of [13] presented a whole chapter: "System regularities in the technology of basic organic synthesis". The last two sections of this chapter have the titles "Reliability of operation of separate apparatuses and chemico-technological systems" and "Estimation of the working capacity of a system".

In these sections the authors use the terminology and method of the element approach [14, 15], i.e., the classic method of calculating the probability of CES failure via the failures of "mutually independent" parts. In monograph [7, pp. 35–39] is it shown that the element approach is obviously incorrect for a number of reasons including the impossibility of searching initial data for its correct application. Besides, the mutual independence of parts assumed by the authors of [14–18] is not in accordance with the conservation laws and with the system approach postulated by the authors of [13]. Unfortunately, the authors of [13] did not notice the publication of the first article on this method of study in 1981 [19] and the article in "Theoretical foundations of chemical engineering" magazine in 1989 [20] concerning the subject of CES reliability.

4. The antagonisticity of these categories becomes obvious at the intuitive level of understanding the ratio of economic efficiency without considering stops and reliability. Moreover, applying the technique of studying reliability showed that in all the studied cases the higher is calculated efficiency, the lower is the reliability indicator.

On one hand, it makes no sense to create unreliable installations, because this gives nothing except expenses of resources and time. On the other hand, production should not be unprofitable. Some compromise is necessary. A compromise is offered by the method for studying the reliability of CES. Indeed, it is shown above that it is possible to calculate an estimation of any functionality on the basis of CES parameters. Let us choose the prime cost of the target product of CES as such functionality. Moreover, in this case it is not very difficult to find out what external actions and what preset parameters increase prime cost most of all. This allows controlling the prime cost of the product by means of the method for studying reliability.

Let us note here in addition that the calculation of prime cost in the modern design organizations is incorrect, because it does not consider the cost of repair after the CES failure and the reduction of annual production rate because of idle times or manufacturing defects. Let us write the prime cost formula based on [21]:

PC = ALL EXPENSES / ANNUAL QUANTITY OF PRODUCT

Therefore, the actual prime cost at the design stage can be determined only if the cost of accidents and idle times is included in the expenses, and the product not obtained because of stops or manufacturing defects is subtracted from the quantity of the product. The total formula in this case is

PC = (ALL EXPENSES (calculated) + COST OF ACCIDENTS) / (ANNUAL QUANTITY OF PRODUCT (calculated) – LOSSES BECAUSE OF ACCIDENTS)

The method of improving reliability presented in [3] on the basis of the suggested method of studying applied to CES can enable increasing reliability. On one hand, this will lead to growth of investment cost. On the other hand, the cost of eliminating the consequences of accidents and losses of production because of accidents will be reduced. In addition, the more reliability indicator grows, the more total expenses (capital cost in the form of amortization, as well as operating costs) increase. This means that in the beginning, as reliability increases, prime cost decreases due to the reduction of losses and costs of accidents. However, at some point of time the increase of reliability indicator will start leading only to prime cost growth. That is, there is a minimum of actual prime cost, and it is attainable.

5. At first sight, the description of the algorithm of the method for studying the reliability of CES seems rather difficult. Indeed, the practice of applying the method to industrial large-capacity CES’s shows that the procedure of the method is rather labor-consuming and very science-based. Workers of most different professions must have the highest proficiency and big erudition, but, above all, they must have the skill of mathematical formalization of their knowledge.

Conclusions:

1. It is necessary to distinguish mechanical and technological reliability of CES. Certainly, the importance of both is enormous, but the reliability of the system in one of these meanings does not guarantee the reliability in the other meaning.
2. Scientists and engineers have realized recently the need of calculating the reliability of CES and of system approach to this problem. Unfortunately, the conventional methods do not allow performing this calculation correctly. A technique allowing to do this is given in this article.
3. Calculating the probability of working capacity of a CES allows finding obviously inoperative technologies at the predesign stage.
4. The article shows for the first time that for each CES there is a reliability indicator, below which implementing the CES is economically inexpedient.
5. Besides, the article shows for the first time the existence of a minimum of actual prime cost and the possibility of attaining this minimum according to the method of increasing reliability presented in [3].
6. It is necessary to introduce (as a separate course) the study of technological reliability into the educational process of teaching magisters studying chemical technology.

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