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IDENTIFYING THE OPERATIONAL CHARACTERISTICS OF AN AMMONIA SYNTHESIS COLUMN, TAKING INTO ACCOUNT CHANGES IN THE OPERATING PARAMETERS OF THE PROCESS PLANT

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This study explores the technological process of ammonia synthesis in a synthesis column as a complex multi-tonnage chemical and technological facility with a transport delay and variable state parameters. The task addressed relates to the lack of quantitative assessment of the impact of catalyst degradation on the dynamic characteristics of the facility, in particular on the transport delay and the stability margin, which complicates the determination of the limits of effective equipment operation and timely adoption of technological decisions.

As a result of analysis, it was established that a decrease in the synthesis gas flow rate by 10% leads to an increase in the transport delay time from 61 s to 67 s and a decrease in the stability margin in terms of modulus from 15.7 dB to 15.0 dB. It is shown that restoring the stability margin to the base level is possible by reducing the gain factor by 8%, which, in turn, is accompanied by an increase in the steady-state error to 8.39%, that is, a deterioration in the control accuracy and deviation of technological parameters from the set values.

The results are based on the use of the stability margin in terms of the modulus as an integral indicator sensitive to changes in the parameters of the object's state, which makes it possible to quantitatively link the degradation of the catalyst with the dynamic characteristics of the control system. The established patterns are explained by the fact that an increase in the transport delay causes an additional phase shift in the system and reduces the stability margin, while a decrease in the gain factor increases stability, but leads to an increase in the steady-state error, forming a compromise between stability and accuracy.

The practical value of the results is the possibility of their use for assessing the technical condition of the ammonia synthesis column, determining the limit modes of its operation, and substantiating the time of catalyst replacement. The application of the findings is appropriate under conditions of quasi-stationarity of the process, limited disturbances. and the use of linearized mathematical models of the object

Keywords: combined mathematical model, ammonia synthesis column, transport delay, stability margin, catalyst degradation, steady-state error

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1. Introduction

Ammonia production is one of the most energy-intensive processes in the chemical industry with a global volume of over 180 million tons/year and consumption of up to 1–2% of world energy. Even minor deviations in technological parameters (temperature, gas composition, pressure) at the level of 1–3% can lead to a decrease in the degree of conversion by 2–5% and an increase in specific energy consumption by 3–7%, which on the scale of multi-tonnage production causes significant product losses and an increase in cost.

One of the key features of the ammonia synthesis process is high inertia and the presence of transport delay, which complicates control and increases the sensitivity of the system to parametric disturbances. An important factor affecting the dynamic characteristics of the facility is the degradation of the catalyst, which under operating conditions leads to a decrease in its activity and changes in the operating modes of the apparatus. In particular, a decrease in catalyst activity necessitates an increase in the contact time of the gas mixture, which is accompanied by a change in the transport delay and characteristics of the control system.

The experience of operating modern chemical and technological productions indicates an increase in requirements for automation systems, in particular for automatic control systems, which ensure the maintenance of specified operating modes and the stability of the functioning of technological objects. Such systems effectively compensate for the influence of external disturbances characteristic of industrial processes. At the same time, their capabilities are limited in cases of changes in the internal parameters of the state of the object, caused by the course of physicochemical processes. In particular, a gradual decrease in catalyst activity leads to a change in the dynamic characteristics of the object, which cannot be fully compensated by standard means of regulation.

Under such conditions, there is a need to determine the limits of effective operation of the equipment and justify the moment of catalyst replacement based on an analysis of changes in the characteristics of the technological process. This renders relevance to research aimed at quantitatively analyzing the influence of changes in the parameters of the state of technological objects on their dynamic characteristics and performance indicators.

2. Literature review and problem statement

In [1], approaches to optimal control over chemical and technological processes are considered, in particular, the use of mathematical models of objects is proposed to form an optimization problem in the form of minimizing a functional that takes into account deviations in technological parameters (temperature, concentration) from set values and energy consumption of the process. The authors of [1] also analyze the application of optimal control algorithms for multi-coupled systems with constraints on control and output variables, which makes it possible to increase the accuracy of maintaining modes and reduce energy consumption by 3–5% in model examples. However, the proposed approaches are based on the assumption of the invariance of the object parameters over time and use stationary or quasi-stationary models. This means that the influence of degradation of state parameters (in particular, catalyst activity, which under industrial conditions can decrease by 5–15% per operating cycle) is not taken into account. As a result, such methods do not allow for a correct assessment of the change in the dynamic characteristics of the object (in particular, the transport delay and the amplification factor) and, accordingly, do not provide for the determination of the limits of effective operation of the equipment, which is critical for high-tonnage production.

In work [2], an overview of dynamic models of the ammonia synthesis circuit is provided, in particular, models of the reactor, heat exchange equipment, circulating compressor and gas recirculation systems, as well as approaches to their use in control problems. The authors of [2] consider in detail the structures of mathematical models, methods of describing heat and mass transfer, synthesis kinetics and the relationships between pressure, temperature, and composition of the gas mixture. The practical value of the work is the systematization of existing models for simulation and synthesis problems of control systems. However, most attention is focused on the adequacy of the model structures and general approaches to control, while the issues of quantitative assessment of technological efficiency with a gradual change in the parameters of the object state, primarily the activity of the catalyst, are actually not considered. The work lacks an analysis of how catalyst degradation affects transport delay, stability margin, and limits of permissible operating modes, which limits the use of these approaches for diagnostics and decision-making in high-tonnage production.

In [3], an engineering review of model predictive control (MPC) methods is presented, within which the main schemes for constructing a predictor, setting the optimization problem, working with constraints on control signals and output coordinates, as well as the features of implementing MPC in industrial systems are analyzed. The authors of [3] show that MPC is effective primarily for multi-connected objects, where constraints on temperature, pressure, flow rates, control change rate, and permissible limits of output parameters are simultaneously in effect. At the same time, the review is mainly algorithmic in nature: the focus is on the controller architecture, forecast horizon, objective functions, and numerical optimization methods. The specifics of chemical and technological objects with transport delay, parametric degradation, and slow changes in the internal state are not disclosed at the level of formalized criteria of technological efficiency. As a result, work [3] does not provide an answer on how to relate the change in the parameters of the object model during operation to the change in the stability margin, the quality of regulation and the feasibility of mode adjustment.

In [4], modern approaches to process monitoring and diagnostics of deviations based on data are investigated, in particular, statistical methods, latent variable models, machine learning and tools for detecting anomalies in multidimensional industrial data. The authors show the high efficiency of such approaches for timely detection of violations of the normal regime, classification of process states and localization of possible causes of deviations. However, the logic of these methods is focused mainly on detecting the fact of deviation, and not on quantitative analysis of the impact of this deviation on the dynamic characteristics of the object and the subsequent formation of control actions. In particular, work [4] does not consider how the detected changes in the state of the object are reflected in the stability margin, the established error, or the limits of safe operation. Therefore, it is advisable to consider such approaches as an information support tool, but not as a complete method of analyzing the technological efficiency of high-tonnage production.

In [5], current approaches to sustainable ammonia production are considered, including energy cost optimization, decarbonization of technological schemes, use of low-carbon hydrogen and integration of the process with renewable energy sources. The authors focus on reducing specific energy consumption, reducing CO_2 emissions, and increasing resource efficiency of production as a whole. Such a macro level of analysis is important for strategic modernization of the industry, but it hardly covers the dynamics of individual technological objects and their behavior under current operational degradation. The work does not consider how changes in reactor or catalyst state parameters affect the stability of the local control system, the accuracy of maintaining the regime and product quality. Therefore, study [5] is valuable for assessing energy efficiency at the level of the technological scheme, but does not provide a tool for analyzing the dynamic technological efficiency of an individual multi-tonnage device.

In [6], the use of deep learning methods for modeling and controlling complex industrial processes is proposed, in particular, for approximating nonlinear dependencies, predicting object behavior, and building intelligent controllers. The authors show that neural network models are able to describe complex multidimensional relationships more accurately than traditional linearized schemes, especially in the presence of large amounts of historical data. At the same time, for responsible chemical and technological industries, the issues of interpretability, reliability, and guarantees of stability remain fundamental. Work [6] does not offer a formalized criterion that would link a change in the internal state of an object with dynamic stability and technological efficiency. In addition, such approaches depend on the completeness and representativeness of training samples and poorly explain the physical nature of the revealed patterns. This significantly limits their use as a means of determining the limits of effective equipment operation or a criterion for the feasibility of replacing a catalyst.

In [7], robust control methods for large-scale chemical processes with delays are investigated, focused on ensuring stability in the presence of parameter uncertainty and external disturbances. The authors focus on the synthesis of controllers that maintain the system's operability even under model variations and load changes, which is important for the safe operation of industrial facilities. However, robustness in this formulation is achieved mainly due to the conservatism of settings, and this does not answer the question of at what cost to product quality and control accuracy such stability is ensured. In [7], the trade-off between the increase in the stability margin and the increase in the steady-state error is not analyzed, and the criterion that would allow linking this trade-off with the technological efficiency of production is not introduced. That is why the approach of [7] is insufficient for solving the problem of assessing the limit modes of operation of a multi-tonnage facility.

In [8], the practical implementation of the model in the control system for a methanol synthesis column using additive test methods and subsequent synthesis of a control system based on the model is considered. The authors demonstrate the possibility of obtaining an adequate mathematical model of a specific technological apparatus and its application for building control algorithms. The strength of the work is the applied focus and binding to a real object. However, the study is limited to a separate process and a separate configuration of the apparatus; it does not formulate a generalized criterion of technological efficiency that could be transferred to other multi-tonnage production. In addition, in [8], the gradual change in the parameters of the object's state over time and its impact on the stability margin and the limits of effective operation are not considered. Therefore, its results are useful as an example of modeling and control synthesis, but do not solve the problem of complex analysis of efficiency under degradation conditions.

In [9], the principles and stages of designing automatic control systems for complex technological processes using mathematical models are formulated, including building an information structure, identifying an object, forming a model, and integrating it into a control loop. The authors emphasize the methodology for designing a control system as an integrated engineering solution, which is important for automation practice. At the same time, the work focuses mainly on the procedural aspects of system synthesis and does not contain a quantitative criterion that would make it possible to assess the change in the technological efficiency of the object during its operation. In particular, it does not analyze how internal disturbances associated with changes in state parameters affect the margin of stability, the established error, and the limits of operability. Therefore, ref. [9] forms a useful methodological basis, but does not provide a tool for quantitative monitoring of the efficiency of multi-tonnage production in real time.

In [10], the current state of nonlinear control with a predictive model for complex chemical and technological processes is considered, in particular, the advantages of nonlinear models in comparison with linear MPC approaches, the issue of computational complexity and the prospects for practical application are described. The author shows that nonlinear MPC potentially allows for a more accurate account of the real physics of processes and provides better control quality in a wide range of modes. However, the study is mainly conceptual and theoretical in nature and almost does not reveal the specifics of multi-tonnage processes with slow degradation of state parameters, transport delay, and strict requirements for reliability under conditions of long-term operation. In [10], there is no approach to quantitatively linking the change in the internal state of the object with the change in the stability margin and technological efficiency. Therefore, despite the high theoretical value, this approach does not provide a ready-made solution for determining the limits of effective operation of real large-tonnage devices.

Thus, our analysis of current research reveals that existing approaches either focus on individual aspects (modeling, control, energy efficiency, diagnostics), or do not take into account the complex impact of changes in the parameters of the object's state on its dynamic characteristics and stability. The issue of quantitative analysis of the technological efficiency of high-tonnage production, which would simultaneously take into account changes in the parameters of the object, ensuring stability and the quality of the technological process, remains insufficiently studied. The criteria for the efficiency of the functioning of chemical and technological objects provide for the provision of such indicators as minimal overshoot, minimal settling time, and small steady-state error. These requirements are achieved by appropriate adjustment of the control system parameters. At the same time, the improvement of some indicators is usually accompanied by a deterioration in others, in particular, a decrease in the stability reserve of the regulated object. A decrease in the stability reserve is undesirable since it brings the system closer to the instability limit, increases sensitivity to disturbances, and can lead to violation of regulatory regimes and deterioration of product quality.

This problem becomes particularly important under conditions of changes in the state parameters of a technological object, in particular during catalyst degradation, which affects the dynamic characteristics of the system, including the transport delay time. Under such conditions, there is a need for quantitative analysis of the relationship between changes in the state parameters of the object, its dynamic characteristics and performance quality indicators. However, existing approaches do not provide a sufficiently complete and consistent consideration of these factors, which complicates the determination of the limits of effective operation of equipment and the justification of the parameters of the control system in conditions of changes in the state of the object.

The above allows us to conclude that it is necessary to conduct a study to determine the technological efficiency of high-tonnage chemical and technological productions in terms of ensuring stability, optimal operating modes, and high product quality.

3. The aim and objectives of the study

The purpose of our work is to determine features in the functioning of the ammonia synthesis column as a multi-tonnage chemical and technological object, taking into account changes in its state parameters. This will make it possible to assess the technical condition of the ammonia synthesis column, determine the limit modes of its operation, and justify the moment of catalyst replacement.

To achieve the set goal, it is necessary to solve the following tasks:

– to identify the mathematical model of the ammonia synthesis column and, on its basis, investigate the impact of changes in the state parameters of the object on its dynamic characteristics, in particular, the transport delay time and the stability margin;

– to assess the impact of changes in the control system pap rameters on the performance indicators of the object (stability margin, established error) and establish the relationship between stability and control accuracy under conditions of changes in state parameters.

4. The study materials and methods

The object of our study is the technological process of ammonia synthesis in a synthesis column as a complex multi-tonnage chemical and technological object with a transport delay and variable state parameters. The main characteristics of the object are the amplification factor, the transport delay time, as well as the parameters that determine the quality of the product, in particular the temperature and concentration of ammonia at the outlet of the column.

The principal hypothesis of the study assumes that the technological efficiency of multi-tonnage production can be assessed by analyzing the dynamic characteristics of the technological object, in particular the stability margin and the transport delay time, taking into account changes in its state parameters, such as catalyst activity.

The following assumptions are adopted in the study: parameters of the technological object change slowly in time, which makes it possible to use a quasi-stationary approach to analysis, and the influence of external disturbances is compensated by existing automatic control systems. The structure of the object and its main dynamic properties remain unchanged during the studied time interval.

The simplifications accepted in our study include the use of linearized mathematical models to describe the dynamics of the process and the reduction of a complex multi-parameter object to an equivalent transfer function with lumped parameters. Only the main parameters that determine the stability and quality of the process (gain coefficient and transport delay time) are taken into account, without a detailed description of all physicochemical phenomena.

Theoretically, a control object is stable if, with a limited input, its output value is limited and tends to be a constant value over time.

In mathematical form, this is written as

$$\lim_{t\to\infty} y(t) = \text{const},$$

where $y(t)$ is the initial parameter of the object.

However, this theoretical interpretation does not take into account the form of the trajectory of the transient stabilization process. However, for real industrial objects, the form of the trajectory along which the object approaches a stable value over time is often an extremely important indicator. Parameters such as overshoot or stabilization time will characterize the amount of products of inadequate quality (defective), and, as a result, material losses. The nature of these processes is largely determined by the value of the object's amplification factor.

At the same time, it should be noted that, as a rule, equipment of high-tonnage chemical and technological productions are systems with a complex structure of interconnected parameters. Some external or internal disturbances can cause long-term oscillatory transient processes. Under such conditions, a decrease in the ω degree of stability of the object is unacceptable.

Thus, the control system must provide optimal operating modes of the equipment without reducing the given level of stability of the technological object.

To solve this problem, first of all, an indicator is selected that will be used as a stability criterion.

Frequently used indicators of the stability of a regulated object are its phase margin and modulus margin. They are easy to calculate and convenient to use.

Phase margin is a value determined at the frequency at which

$$\left|GH(j\omega)\right| = 1,$$

where $G(j\omega)$ is the transfer function of the technological object; $H(j\omega)$ is the feedback transfer function.

The feedback transfer function shows how much additional negative phase shift is permissible in the system before it reaches the stability limit (the Nyquist diagram will pass through the point with coordinates (–1, +j0).

The modulus margin is a value determined at a phase shift of – 180° and shows how many times the system gain can be increased before it reaches the stability limit (the Nyquist diagram will pass through the point with coordinates (–1, +j0).

For objects with a small gain and/or transport delay, it is not always possible to calculate the stability margin by phase.

If the gain is very small and the condition is met for all frequencies

$$\left|GH(j\omega)\right| < 1,$$

then the system does not cross the level 0, dB.

In this case, the cutoff frequency does not exist, and the phase margin cannot be determined.

In the presence of transport delay, the objects have a transfer function of the form

$$G(s)=G_0(s)e^{-s\tau},$$

where τ is the delay time.

The phase of such an object is

$$\varphi(\omega)=\varphi_0(\omega)-\omega\tau.$$

In this case, with a sufficient gain, the phase drops quickly and reaches –180° earlier than the cutoff frequency.

The modulus stability margin is determined for objects with a delay, as well as for objects of the second and higher orders. It is to such objects that the vast majority of multi-tonnage chemical and technological objects belong.

Therefore, it is the modulus stability margin that is chosen as a criterion for the stability of a technological object.

If, for various reasons, a technological object approaches the stability limit, there is a danger of self-excitation (instability). In this case, any violation of the stability of the technological process of a multi-tonnage device will necessarily have a negative impact on the entire technological chain.

Ensuring an increased level of stability of the technological process is implemented by reducing its gain. However, this leads to a deterioration of its dynamic properties in the form of an increase in the steady-state error. And this can be a very significant negative factor from the point of view of the technological efficiency of the object.

Thus, a situation arises when, on the one hand, it is necessary to maintain the stability of the technological object, and, on the other hand, it is necessary to ensure certain parameters of the technological process and, accordingly, product quality.

An unambiguous solution to this dilemma in general is impossible, since in each case there is a large number of influencing factors. And first of all, these are the physicochemical and technological features of the object under study. Without analyzing these factors, taking into account their interaction, it is impossible to determine ways to ensure the technological efficiency of the object under study. An approach is proposed using the example of an ammonia reactor in ammonia production.

5. Results of investigating the influence of state and control parameters on the characteristics of the ammonia synthesis column

5. 1. Determining the influence of changes in the state parameters of the object on the dynamic characteristics of the ammonia synthesis column

The production of ammonia was chosen as the object of application of the approach to the analysis of technological efficiency of multi-tonnage production. The technological scheme of production is shown in Fig. 1.

Process conditions: pressure 20–30 MPa, temperature in the reaction zone 400–500°C, synthesis gas flow rate F_{sg} as a control effect. A typical iron-containing industrial catalyst (Fe-K-Al-Ca), typical for ammonia synthesis units, was used as a catalyst. The scheme parameters correspond to medium-power industrial installations and are consistent with literature data [2] and modeling results [9].

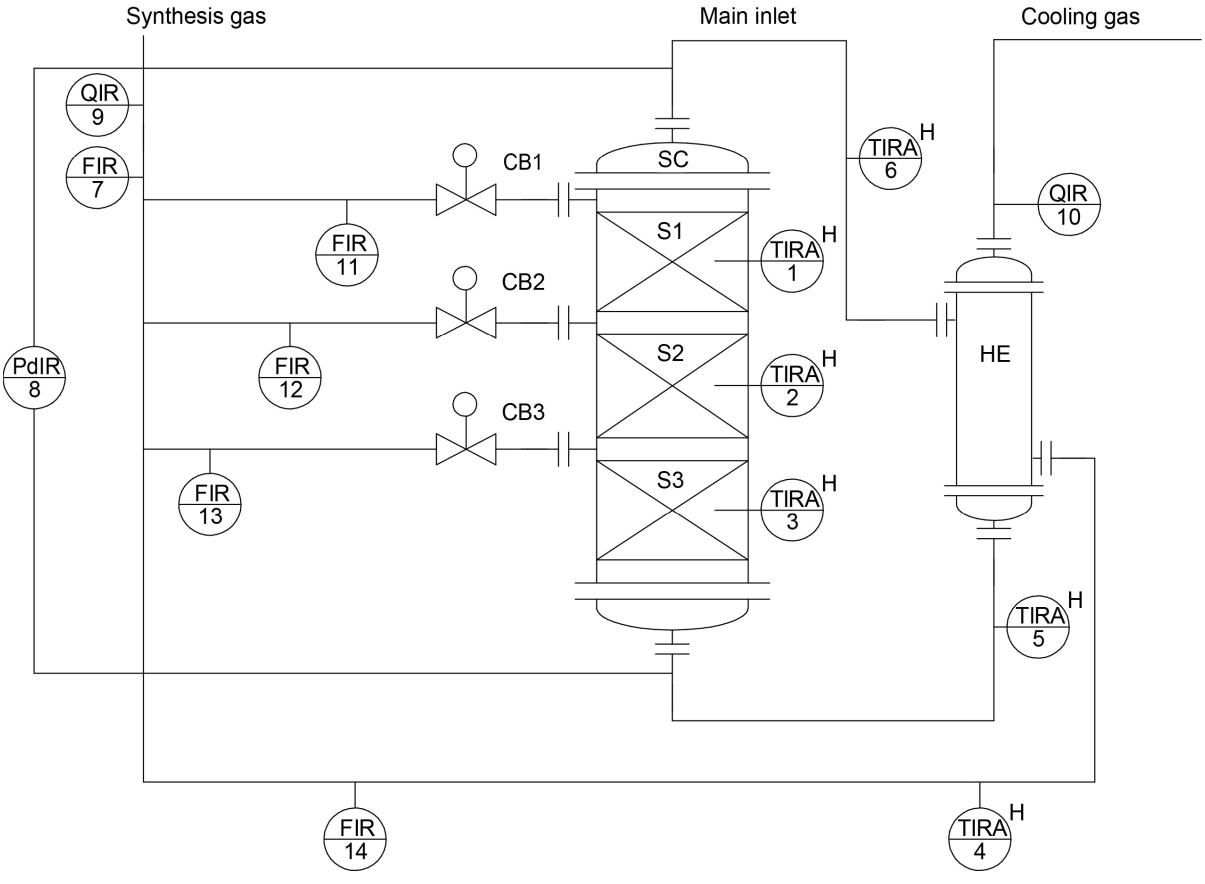

Fig. 1. Technological scheme of ammonia production with a functional automation scheme: SC – synthesis column, HE – recuperative heat exchanger, S1–S3 – shelves with catalyst

The reactor operation is organized as follows. Circulating gas with a temperature of about 160°C at the column inlet is divided into two streams: main and cold bypass. The main stream passes through a built-in heat exchanger, where it is heated by the heat of the return gases to approximately 280°C, after which it is fed to the first shelf of the reactor. The cold bypass is divided into three parts and is simultaneously fed to three shelves of the reactor. Its function is to maintain the temperature on the shelves within 310–330°C.

The exothermic reaction of ammonia synthesis occurs directly on the shelves. The gas leaving the third shelf enters the built-in heat exchanger, where it transfers its heat to the gas fed into the column.

The basic parameter that determines the efficiency of the column is the concentration of ammonia in the synthesis gas at the outlet Q_f. For a given object, the concentration of ammonia at the outlet is uniquely determined by the temperature regime along the height of the ammonia synthesis column. The temperature regime also determines the temperature of the gas at the outlet of the column T_f. Thus, the gas temperature at the outlet of the column uniquely characterizes the efficiency of its operation.

The control parameter of the ammonia synthesis column is the flow rate of synthesis gas at its inlet F_{sg}.

Methods for obtaining an adequate mathematical model of the ammonia synthesis column are given in [9].

The model of such a column takes the following form

$$G(s)=\frac{K}{\tau_2\cdot s^2+\tau_1\cdot s+1}\cdot e^{-\tau_{TD}\cdot s}.$$

An analysis of the technological efficiency of such an object was conducted.

The research was based on information obtained from real ammonia production at PrAT "Severodonetsk Association "AZOT"" (Ukraine).

At the first stage, the parameters of the model subject to control and adjustment were determined: this is the amplification factor of the technological object K and the transport delay time τ_{TD}.

After identifying the parameters of the ammonia synthesis column, an initial or basic model of the technological object was obtained

$$G_{bas}(s)=\frac{1}{2724\cdot s^2+249\cdot s+1}\cdot e^{-61\cdot s}. \quad (1)$$

Next, the initial value of the stability margin was calculated according to the modulus of the basic technological object (Fig. 2).

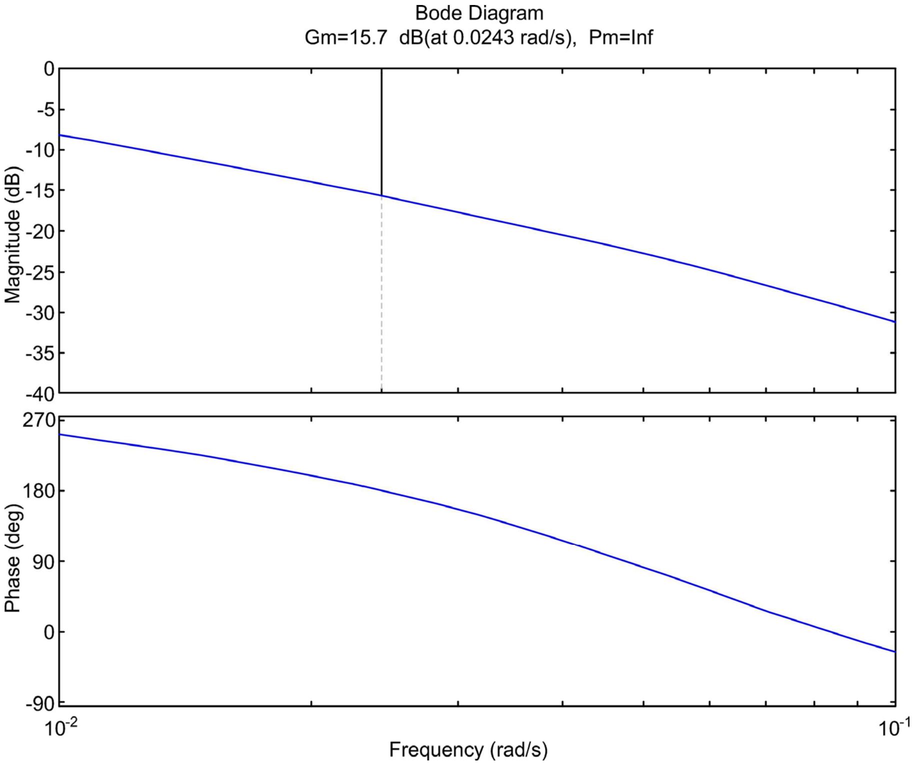

Fig. 2. Bode diagram for calculating the modulus of stability margin for an ammonia synthesis column

The stability margin of the technological object in terms of modulus is G_{mbas} = 15.7 dB, the stability margin in terms of phase is not determined since there is no cutoff frequency ω_c.

5. 2. Determining the influence of changes in the control system parameters on the performance of the ammonia synthesis column

In the column of the ammonia synthesis gas reactor, the activity of the catalyst decreases over time. Therefore, to ensure the required degree of conversion of the synthesis gas with the formation of ammonia, it is necessary to increase the time of its contact with the catalyst. This can be achieved by reducing the speed of passage of the gas mixture through the catalyst bed, that is, by reducing the gas mixture flow rate. In turn, this will lead to an increase in the transport delay time in the column.

The transport delay time in the column was calculated from the following formula

$$\tau_{TD}=K_{RC}\cdot\frac{V_{app}}{F_{sg}}, \quad (2)$$

where τ_{TD} – transport delay time of synthesis gas movement;

K_{RC} – resistance coefficient of the catalyst layer on the reactor shelves;

V_{app} – volume of the apparatus;

F_{sg} – synthesis gas flow rate.

It was assumed that due to the decrease in catalyst activity, synthesis gas flow rate decreased by 10% from the initial value. According to (2), the transport delay time increased by 10% and was τ_{TD2} = 67 s.

Calculation of the column stability margin by modulus based on the Bode diagram for the current value of the transport delay time τ_{TD2} gives the value G_{mcurr} = 15.0 dB. Thus, the stability margin by modulus decreased by

$$\Delta G_m = G_{mbas} - G_{mcurr} = 0.7\left[\text{dB}\right].$$

If the decrease in the stability reserve by the modulus by value ΔG_m exceeds some permissible value $\Delta G_m \geq \Delta G_{mperm}$, then it is necessary to adjust the column gain factor. The determination of the ΔG_{mperm} value is carried out by production technologists and approved by the production management in accordance with the current technological standards and regulations (as a rule, 3–5 dB according to the regulations).

In order to determine the new value of the column gain factor, the value of its decrease ΔK was calculated. According to the definition of [dB], the coefficient of reduction in the stability reserve by the modulus was determined as

$$\Delta K = 10^{\frac{\Delta G_m}{20}} = 10^{\frac{0.7}{20}} = 1.084.$$

The adjusted gain value for the current time was defined as

$$K_{curr} = \frac{K}{\Delta K} = \frac{1}{1.084} = 0.92.$$

After adjustment, the current mathematical model of the technological object took the form

$$G_{curr}\left(s\right) = \frac{0.92}{2724 \cdot s^2 + 249 \cdot s + 1} \cdot e^{-67 \cdot s}. \tag{3}$$

Verification by constructing a Bode diagram for the model with the corrected value of the gain coefficient (3) gave the result of a stability margin of modulus –15.7 dB, which corresponds to the base (initial) value.

At this stage, such an important indicator of the technological object as its stability was provided.

At the next stage, another indicator of technological efficiency was considered, namely, the change in the value of the steady-state error of the initial parameter of the technological object. In this case, this is the temperature of the gas mixture at the outlet of the ammonia synthesis column, which characterizes the degree of conversion of synthesis gas with the formation of ammonia.

To compare the steady-state errors of the initial state of the technological object and the object with corrected parameters (after changing the state parameter – catalyst activity), their transient characteristics were constructed (Fig. 3).

The obtained data are summarized in Table 1.

Table 1

Analysis of reactor parameters

Gain coefficient K	Module reserve G_m	Transport delay time $\tau_{del.}$	Steady-state value	Established error, %
1.0	15.7 dB	61 s	0.9959	0.415
1.0	15.0 dB	67 s	0.9958	0.42
0.92	15.7 dB	67 s	0.9161	8.39

Table 1 give the results of a comparative analysis of the reactor parameters for three states: base, current (with reduced catalyst activity), and corrected after changing the gain factor.

The presented values of the gain factor, transport delay time, stability margin in terms of modulus, steady-state value of the output parameter, and steady-state error make it possible to comprehensively assess the impact of changing the parameters of the object state on its technological efficiency.

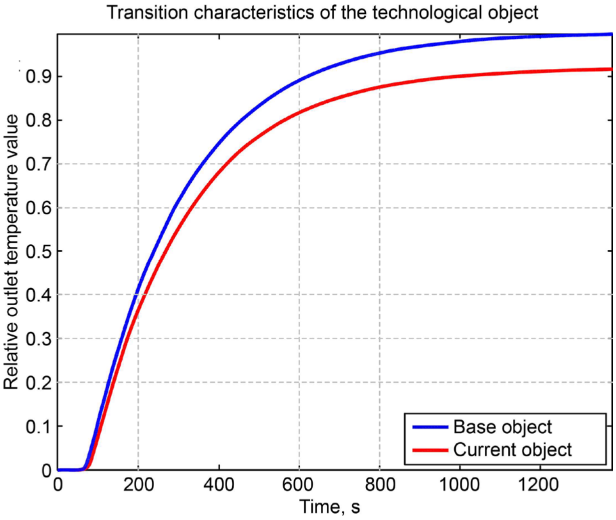

Fig. 3. Transition characteristics of the base and current states of the ammonia synthesis column: blue – base; red – current

The data given in Table 1 indicate that a decrease in catalyst activity leads to an increase in the transport delay time, which, in turn, causes a decrease in the stability margin of the technological object. This confirms the need to adjust the control system parameters.

After adjusting the gain factor, the stability margin is restored to the initial level, which confirms the effectiveness of the applied approach to adjusting the control system parameters.

Therefore, the results given in Table 1 confirm the existence of a compromise between ensuring the stability of the technological facility and maintaining high product quality. Reaching the limit value of the established error can be considered as a criterion for the need to replace the catalyst or change the operating mode of the equipment.

6. Discussion of results based on investigating the influence of state and control parameters on the characteristics of the ammonia synthesis column

Our results are explained by the influence of changes in the dynamic characteristics of the technological object, which is confirmed by the data in Table 1, as well as the results of frequency analysis (Fig. 2) and transient characteristics (Fig. 3). In particular, an increase in the transport delay time from 61 s to 67 s, calculated from formula (2), led to a decrease in the stability margin in terms of the modulus from 15.7 dB to 15.0 dB, which indicates that the system is approaching the stability limit. This is consistent with the provisions of the theory of automatic control, according to which the presence of a delay causes an additional phase shift and reduces the stability of the system.

Restoring the stability margin by reducing the gain allowed its value to return to the initial level (15.7 dB), which is confirmed by the results of frequency analysis. At the same time, as shown in Table 1 and Fig. 3, this is accompanied by a significant increase in the steady-state error (up to 8.39%), which is explained by a decrease in the static transmission coefficient of the system. Thus, the results of the study confirm the existence of a compromise between ensuring stability and control accuracy for inertial objects with transport delay.

The obtained dependences make it possible to quantitatively assess the impact of changes in the parameters of the object's state, in particular the activity of the catalyst, on its dynamic characteristics and performance indicators. Unlike approaches focused solely on optimizing modes or ensuring robustness, our study establishes a relationship between the change in transport delay, the stability margin, and the steady-state error, which makes it possible to assess the limits of effective operation of the technological object.

The practical significance of the results is the possibility of their use for assessing the technical condition of the ammonia synthesis column and determining the limit modes of its operation. In particular, reaching a certain level of steady-state error can be considered as an indicator of the need to adjust the operating modes or replace the catalyst. This approach makes it possible to link the parameters of the control system with the technological indicators of the process and justify the adoption of operational decisions.

However, the limitations of our results should be taken into account. We used a linearized mathematical model, which limits the accuracy of the process description with significant deviations of the operating parameters. In addition, the analysis was carried out assuming quasi-stationarity of the process and immutability of the structure of the object, which may not fully correspond to real operating conditions. The influence of nonlinear effects and the interaction of several state variables was also not taken into account.

Further research should be directed at refining object models taking into account nonlinear process properties, expanding the list of state parameters taken into account, and verifying the obtained results under industrial conditions. This will increase the accuracy of the assessment and expand the scope of application of the derived dependences.

7. Conclusions

1. The mathematical model of the ammonia synthesis column has been identified and the effect of changing the state parameters of the object on its dynamic characteristics was investigated. It was found that a decrease in the synthesis gas flow rate by 10% (as a result of catalyst degradation) leads to an increase in the transport delay time from 61 s to 67 s and a decrease in the stability margin in terms of the modulus from 15.7 dB to 15.0 dB. The results confirm the sensitivity of the dynamic characteristics of the object to changes in its internal state.

2. The effect of changing parameters of the control system on the performance indicators of the object was assessed and the relationship between the stability margin and the control accuracy was established. It was shown that restoring the stability margin to the base level (15.7 dB) by reducing the gain by 8% (from $K = 1.0$ to $K = 0.92$) is accompanied by an increase in the steady-state error from 0.415% to 8.39%. This confirms the existence of a compromise between ensuring stability and control accuracy and makes it possible to use the level of steady-state error as an indicator of the limit operating modes for the facility.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

AI model and number GPT-5.3 from OpenAI. Used to select literature sources in section 2. Using AI tools, relevant literature was found. The authors independently reviewed the literature sources. The use of AI does not affect the conclusions of the study.

Authors' contributions

Petro Yeliseyev: Methodology, Writing – original draft; **Maryna Loriia:** Conceptualization, Formal analysis, Data Curation; **Olexii Tselishchev:** Validation, Investigation; **Liudmyla Karpyuk:** Investigation, Writing – original draft; **Oleksandr Duryshev:** Formal analysis, Investigation; **Yevgen Kobzarev:** Visualization, Project administration.

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