

This paper has analyzed the functioning conditions for the technological system of secondary condensation (TSSC) in a typical ammonia synthesis unit of the AM-1360 series with the use of a system-control approach. The coordinates of control vectors and external disturbances have been determined. An algorithm has been developed for predicting the coordinates of the control vector for the subsystem of decision support under the conditions of external disturbances for such a complex inertial object with high metal consumption as TSSC.

The method of mathematical modeling was used to determine, based on the developed algorithm, the patterns and quantitative dependences of the influence of external disturbances such as the temperature of primary condensation and the flow rate of circulation gas on the efficiency of TSSC heat exchange processes. The regularity of increase in the heat flows and coordinates of control vector with an increase in the temperature of primary condensation has been established. The parametric sensitivity of the coordinates of the control vector under the conditions of change in the temperature of the primary condensation has been determined, which, compared with the circulation gas flow rate, exceeds it by more than six times.

The executed software implementation of the algorithm employing the MATLAB programming environment makes it possible, owing to the embedded client part (ORC client), free software access to the current data on the technological process. The functional structure of computer-integrated TSSC technology with the proposed correction subsystem under a supervisory control mode has been designed. Correction solutions involving the additional hardware and software based on the programmable logic controller VIPA and SCADA-system Zenon have been practically implemented.

The implementation of the developed system ensures the stabilization of the secondary condensation temperature at the regulatory level of -5°C , which reduces the consumption of natural gas by almost 1 million nm^3 per year

Keywords: ammonia production, secondary condensation, energy efficiency, decision-making subsystem, computer control

DESIGN OF AN INTELLIGENT SYSTEM TO CONTROL THE TECHNOLOGICAL SYSTEM OF AMMONIA PRODUCTION SECONDARY CONDENSATION

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1. Introduction

Modern ammonia production involves complex large-tonnage energy technological systems, which are built in almost all countries according to the unified ideology of the company "M. Kellogg & Co" (USA) [1, 2]. In the synthesis units of such production, a two-stage condensation system of production ammonia is most often adopted, which occurs due to the cooling of circulation gas (CG). For cooling at the stage of secondary condensation, the AM-1360 series assemblies employ economical heat-use absorption (ARU) and steam-ejector (SRU) refrigeration units [3, 4]. Their efficiency is ensured due to the possibility of utilization of heat of material flows of both low (about 140°C) in ARU, and

ultra-low (up to 90°C) in SRU, temperature potential. However, the use at the preliminary stage of primary condensation of air cooling devices predetermines the functioning of the technological system of secondary condensation (TSSC) under the influence of constant changes (seasonal and daily) in the external heat load from CG. That leads to significant fluctuations in the TSSC temperature regime and deviations in the temperature of secondary condensation from the rated norm of -5°C [5]. The increase in this temperature even by 1°C in the synthesis units AM-1360 causes a decrease in the energy efficiency of production by increasing the annual consumption of natural gas by 307.3 thousand nm^3 [6]. Therefore, it is necessary to stabilize the temperature regime of TSSC at the regulatory level.

The large-tonnage ammonia production also predetermines the significant metal consumption in the technological equipment, and, therefore, the excessive inertia of heat exchange processes in TSSC. All this greatly complicates the process of control. Therefore, research into the development of a high-quality and reliable control system for TSSC under the conditions of external disturbances is a relevant task for the overall process of improving the energy efficiency of ammonia production.

2. Literature review and problem statement

Paper [7] shows that the construction of high-quality computer-integrated control technology under the existing conditions of TSSC functioning is most effectively executed using a system approach. One of the main aspects of this approach is system-control. It should be aimed at studying TSSC under the conditions of external and internal disturbances to make decisions on stabilization of the secondary condensation temperature at the regulatory level of no more than $-5\text{ }^{\circ}\text{C}$.

It is known from [8] that the main element of the functional structure of such control technology for decision-making should be an identifier with an embedded TSSC mathematical model. The TSSC assembly is quite complex and contains a condensation column (CC), an auxiliary heat exchanger (AHE) a high-temperature evaporator (HTE) with SRU, and two low-temperature evaporators (LTE) with water-ammonia ARU [3]. Therefore, in the process of building a mathematical model that could predict the result or value of certain events (forecasts) of such a complex system, there are certain difficulties. They are associated with the processing and execution of multiple operations with a significant array of current information [9]. In addition, model construction is further complicated by the presence of uncertainties in the functioning of TSSC. This is due to the influence of external heat load from CG. The uncertainty, as found in [6], relates to the impossibility of continuous automatic control over ammonia concentration in CG, both at the TSSC input and output. There is also a change in the heat transfer coefficients in the system's devices. As shown in [10], this is caused by a change in the condensation thermal resistance and, mainly, by its dependence on the concentration of ammonia in CG at the input [6].

The range of change, at the TSSC input, of CG temperature and the concentration of ammonia in CG is $35\div 45\text{ }^{\circ}\text{C}$ and $8.6\div 13\%$ by volume, respectively. In such circumstances, the temperature of CG at the input of HTE, which is included in the scheme of ammonia SRU, would also change. Therefore, as shown in [11], it is necessary to use a system for stabilizing the temperature of CG at the level of $30\text{ }^{\circ}\text{C}$ in order to maintain the temperature of CG at the input of LTE at the level of $9\text{ }^{\circ}\text{C}$. Such a control system could also make it possible to stabilize the temperature of secondary condensation (CG at the output of LTE) at the regulatory level of no more than $-5\text{ }^{\circ}\text{C}$, regardless of the change in the external thermal load at the TSSC input.

The significant metal consumption by the equipment and the complexity of technological structure contribute to the excessive inertia of heat exchange processes. This is especially true of AHE and CC, the total weight of which is more than 400 tons and is characterized by feedback on CG. In such circumstances, to an even greater extent there is a

need to predict the regime parameters of the settings of the control system regulators. This is especially true of SRU, in which the change in refrigeration capacity, and, therefore, the consumption of refrigerant to HTE is carried out, as a rule, by auto-adjusting the position of the nozzle and air-cooled capacitors (ACC) [12, 13]. However, such auto-configuration, which is considered in the cited works, is too complex, time-consuming, and expensive to implement. In addition, in such large-tonnage industries, reservation must be implemented, that is, the installation of another ejector with auto-adjustment to improve the reliability of operation. Therefore, it is more expedient to equip HTE evaporators with much simpler ejectors (for example, three) without auto-tuning. That could ensure their selective inclusion in work according to the predicted value of a certain situation by the operator under a supervisory mode, which would definitely improve the reliability of control technology. At the same time, the consumption by one of these three ACCs is 200 kWh, which provides for the condensation of 10 t/h of ammonia vapor. However, the issues related to the development of particularly algorithmic software remained unresolved in modern literature and in production conditions. Therefore, the task of improving the reliability of control and the ability to prepare the operator for such changes under a supervisory control mode requires the construction of a mathematical model and algorithmic software for a decision-support subsystem. This approach makes it possible to establish both patterns and quantitative dependences of the influence of external heat load on the effectiveness of heat transfer processes in TSSC, information on which is practically absent in periodicals. Owing to these studies, it would be possible to assess in advance the forecasts of possible changes in the temperature of CG at the input of HTE under the conditions of existing uncertainties and, therefore, numerical indicators (U settings) for control vectors.

Thus, the task of modeling and forecasting in order to automatically search for hidden patterns and relationships between variables in large data sets is a complex multi-stage process. All these tasks, as it is known [14], have all the features of the intelligent system.

The AM-1360 series assemblies employ the information and control system (ICS) TDC-3000 made by the United States [15]. This system covers both field and technological level of production management. However, its hardware and software were developed for the so-called "closed"-type systems. Such ICSs do not provide for the possibility of modernizing production based on the latest ammonia synthesis technologies without adding or integrating additional and auxiliary control systems. That is, the addition of new algorithms and automation tools is impossible. As a result, the modernization of such ICSs is significantly complicated.

Thus, the tasks of developing algorithmic software for the subsystem of decision-making support to the control system and retrofitting its hardware acquire special relevance in the overall process of increasing the efficiency of production by stabilizing the temperature of secondary condensation. There is an additional task to align existing control system with the specified subsystem.

3. The aim and objectives of the study

The purpose of this research is to design an algorithmic and hardware and software subsystem for decision support

under the conditions of uncertainty in the computer-integrated control technology of TSSC regarding the synthesis units of the AM-1360 series. This could ensure improved reliability and quality of process management under the conditions of uncertainty. Owing to that, the energy efficiency of production would increase due to the stabilization of the secondary condensation temperature at the regulatory level of no more than $-5\text{ }^\circ\text{C}$, regardless of external disturbances acting on TSSC.

To accomplish the aim, the following tasks have been set:

- to develop the algorithmic and program support for a decision-support subsystem given the existing uncertainties regarding TSSC;
- to determine the parametric sensitivity and coordinates of the control vector on the basis of the developed algorithmic software for real changes in the external heat load at the TSSC input;
- to define the functional structure and design the software and technical structure of computer technology for managing the contours of refrigerant flow rate to HTE and MEA solution to the SRU steam generator;
- to devise a structural-logical scheme of information flows of computer-integrated TSSC control technology of the "open" type.

4. The study materials and methods

The research was carried out by mathematical modeling. To this end, we used equations for the mathematical notation of the heat exchanger AHE, the evaporator HTE, the subprogram for calculating the coefficients of heat transfer and the concentration of ammonia in CG at the TSSC input $a_{\text{NH}_3}^{\text{IN}}$ and output $a_{\text{NH}_3}^{\text{AP}}$ according to the algorithms developed and tested for adequacy. The algorithms that are in STAB, STOCH, and DANI files were built on the basis of earlier studies [6, 16].

We determined the quantitative dependences of the setpoints for flow rate regulators of refrigerant consumption to the HTE and MEA solution to the PCO steam generator from the existing external perturbations at the TSSC input using a specially developed algorithm. The software implementation of the algorithm underlies the decision-support subsystem.

5. Results of studying the impact of external disturbances on the coordinates of the control vector and the development of the control system

5.1. Development of the algorithmic software for a decision-support subsystem

The generalized flowchart of the developed algorithm is shown in Fig. 1; the software implementation was realized in the MATLAB R2014a package (The MathWorks, USA).

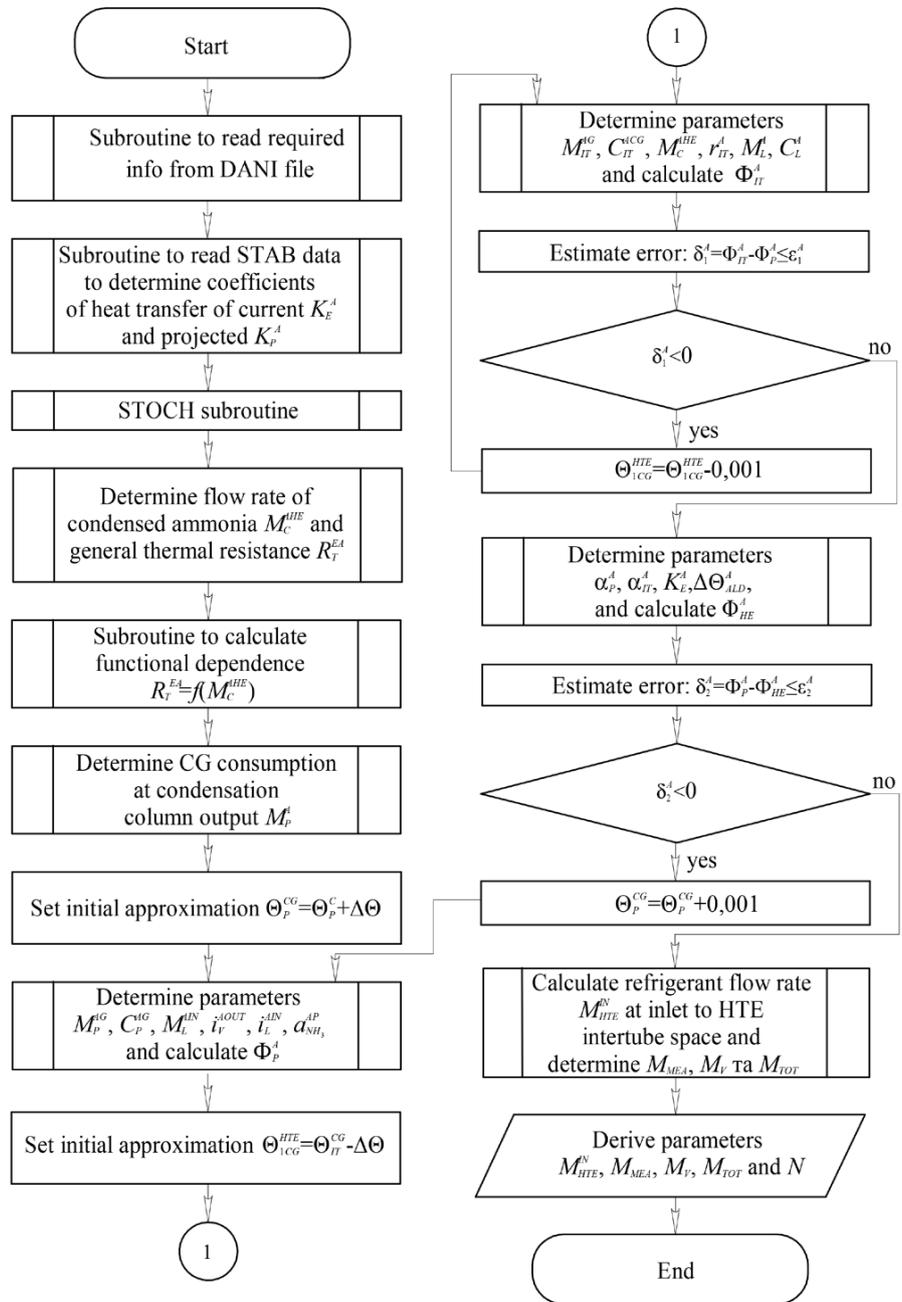


Fig. 1. Flowchart of the research algorithm for numerical assessment of the setpoints for flow rate regulators

Designations in Fig. 1 correspond to the following physical quantities: K_E^A , K_D^A – the heat transfer coefficients for AHE, respectively, current and calculated according to the

formulas adopted during design, $W/(m^2 \cdot K)$; M_C^{AHE} – flow rate of condensed ammonia in the flow of CG of the intertube space of AHE, kg/s; M_p^A , M_p^{AG} , M_L^{AN} – consumption, respectively, of the total CG, the gas mixture of CG at the outlet, and liquid ammonia at the input of the AHE pipe space, kg/s; C_p^{AG} – average heat capacity of the gas mixture CG, kJ/(kg·K); $a_{NH_3}^{IN}$, $a_{NH_3}^{OUT}$ – accordingly, the enthalpy of liquid ammonia at the input and ammonia vapor at the outlet of the AHE pipe space, kJ/kg; $\Theta_p^C = 17,5$ °C – the temperature of the CG at the input of the AHE pipe space, which is provided by the temperature of the CG at the input of the CC at the level of $\Theta_{2CG}^{HTE} = 30$ °C and the temperature of the CG at the output of the LTE $\Theta_p^{LTE} = -5$ °C; $\Delta\Theta$ – approximation step, °C; $a_{NH_3}^{AP}$ – volumetric concentration of ammonia in the CG at the outlet of the AHE pipe space, % by volume; Θ_{IT}^A – CG temperature at the outlet of the pipe space AHE, °C; Φ_p^A , Φ_{IT}^A – respectively, the heat flow from the pipe and intertube space of the AHE, MW; Θ_{IT}^{CG} , Θ_{1CG}^{HTE} – accordingly, the temperature of the CG at the input and output of the intertube space AHE, °C; M_{IT}^{AG} , M_L^A , M_C – accordingly, the amount of gas mixture at the output of the intertube space of AHE, condensed and liquid ammonia in the intertube space of AHE, kg/s; C_p^{ACG} , C_L^A – respectively, the average heat capacity of the gas mixture of the CG of the intertube space of AHE and liquid ammonia, kJ/(kg·K); r_{IT}^A – specific heat of ammonia condensation in the intertube space of AHE, kJ/kg; $\Delta\Theta_{ALD}^A$ – average logarithmic temperature difference AHE, °C; α_p^A , α_{IT}^A – coefficients of heat transfer, respectively, from the pipe and intertube space of the AHE, calculated according to the Krausold equations adopted during design, $W/(m^2 \cdot K)$; Φ_{HE}^A – heat flow due to heat exchange in AHE, MW; M_{HTE}^{IN} , M_{MEA} , M_V – flow rate, respectively, of the refrigerant at the input of the intertube space of the HTE, the MEA of the solution to the SRU steam generator and working vapor per SRU ejectors, kg/s; M_{TOT} – the total amount of ammonia vapor per air capacitors of SRU (working vapor and refrigerant vapor), kg/s; Φ_{HTE} – heat flow (cold productivity) of HTE, MW, N – consumer power of electricity on the drive of ACC fans for condensation of working steam and refrigerant vapor in SRU, kWh.

The algorithm contains convergence cycles that provide measurement of heat flows from the pipe space Φ_p^A , and intertube space Φ_{IT}^A and in the process of heat exchange Φ_{HE}^A of the AHE apparatus to determine the temperature of the CG at the output of its intertube space Θ_{1CG}^{HTE} . In this case, the STAB subroutine algorithm makes it possible to form a stable information array of current data and exclude transition modes. That provides the possibility of calculating the actual heat transfer coefficient K_E^A . Further, using the STOCH stochastic approximation subroutine, the conditions of stationarity, the reproducibility of the process, and the hypothesis of the normality of the empirical distribution are checked. According to the results of such a check, functional dependences are established for the numerical assessment of the uncertainties of volumetric concentrations of ammonia in the CG at the input $a_{NH_3}^{IN}$ and output $a_{NH_3}^{AP}$ of TSSC. At the same time, the numerical assessment of the uncertainty of the total coefficient of thermal resistance R_T^{EA} , taking into consideration condensation, was carried out according to the resulting array of experimental data. In the process of approbation of the algorithm, the following functional dependences were used to numerically assess these uncertain-

ties obtained according to experimental data of industrial operation of TSSC from earlier works [3, 6], namely:

$$a_{NH_3}^{IN} = 22.068 - 0.6272P_{PC} + 0.05245\Theta_{PC}; \quad (1)$$

$$a_{NH_3}^{AP} = -7.78 + 0.0244V_{NHM} + 0.01176V_{IT}^{CG} + 0.0327(\Theta_p^{LTE} + 273) + 0.085a_{NH_3}^{IN} - 0.0635P_{CG}; \quad (2)$$

$$R_T^{EA} = \left[\begin{matrix} 76.64 - 9.40232M_C^{AHE} + \\ + 1.66742(M_C^{AHE})^2 \end{matrix} \right] \cdot 10^{-5}, \quad (3)$$

where V_{NHM} , V_{IT}^{CG} is the flow rate of nitrogen-hydrogen mixture and CG at the TSSC input, nm^3/s , respectively; P_{CG} – CG pressure at the TSSC input, MPa; M_C^{AME} – consumption of condensed ammonia, t/h.

At the end, based on the set temperature Θ_{1CG}^{HTE} determines sequentially the settings of regulators. Among them are the following: refrigerant consumption M_{HTE}^{IN} , (kg/s) at the input of the HTE intertube space; working ammonia vapor M_V (kg/s) to SRU ejectors; MEA solution M_{MEA} (kg/s) to obtain this vapor; the total load on the ammonia vapor M_{TOT} (kg/s) on SRU air capacitors. We determine these flow rates according to the following formulas:

$$M_{HTE}^{IN} = \frac{M_p^{HTE} C_p^{CGG} (\Theta_{1CG}^{HTE} - \Theta_{2CG}^{HTE}) + M_C^{HTE} r_C + (M_L^{HTE} - 0,5M_C^{HTE}) C_L^{HTE} (\Theta_{1CG}^{HTE} - \Theta_{2CG}^{HTE})}{r_R - (\Theta_{R1} - \Theta_{R2}) C_{NH_3}^L}; \quad (4)$$

$$M_{MEA} = \frac{M_V r_V}{C_{MEA} (\Theta_{MEA1} - \Theta_{MEA2})}; \quad (5)$$

$$M_V = M_{HTE}^{IN} / u; \quad (6)$$

$$M_{TOT} = M_V + M_{HTE}^{IN}, \quad (7)$$

where C_p^{CGG} , C_L^{HTE} – respectively, the average heat capacity of the gas mixture CG and liquid ammonia of the pipe space of the HTE, kJ/(kg·K); r_C , r_R – heat of condensation and vaporization of ammonia in the pipe and intertube space of HTE, kJ/kg; M_C^{HTE} – flow rate of compressed ammonia in the pipe space of the HTE, kg/s; $\Theta_{R1} = 35$ °C, $\Theta_{R2} = 24$ °C, $\Theta_{MEA1} = 85$ °C, $\Theta_{MEA2} = 75$ °C – the temperature of the refrigerant (ammonia) at the input of the HTE, the boiling of the refrigerant in the intertube space of the HTE, the input and output temperature of the MEA solution [3]; $u = 0.4$ – injection coefficient [3]; r_V – specific heat of ammonia vapor formation at a temperature of 65 °C and a pressure of 3 MPa, kJ/kg; C_{MEA} – specific heat capacity of MEA solution, kJ/(kg·K); $C_{NH_3}^L$ – specific heat capacity of liquid ammonia, kJ/(kg·K).

At the final stage of the algorithm, an array of current PSPR data of the decision support algorithm is formed, regarding M_V , M_{MEA} , M_{HTE}^{IN} , M_{TOT} and N .

5. 2. Determining the parametric sensitivity and coordinates of the control vector under real external disturbances

The assessment of parametric sensitivity regarding the influence of such perturbing factors as the temperature of the primary condensation and the flow rate of the CG to the parameters of the regulators' settings was carried out using the dimensionless coefficient K_{Zi} , which is determined from the following formula:

$$K_{Z_i} = \frac{(M_{i1} - M_{i2}) \cdot Z_{i1}}{M_{i1} \cdot (Z_{i1} - Z_{i2})}, \quad (8)$$

where M_{i1}, M_{i2} is the coordinate of the control vector, respectively, under the perturbing factor Z_{i1} and Z_{i2} .

Mathematical modeling according to the developed algorithm makes it possible to investigate the patterns of influence of the most characteristic for industrial conditions of variable vectors of external perturbations $Z(t)$ on the vector of control $Y(t)$ in order to stabilize the temperature of secondary condensation at the regulatory level of -5°C . Proceeding to the variable space, these vectors take the following form:

$$Z(t) = \begin{bmatrix} \Theta_{PC} \\ V_{IT}^{CG} \end{bmatrix};$$

$$Y(t) = \begin{bmatrix} M_{HTE}^{IN} \\ M_{MEA} \\ M_V \\ N \end{bmatrix}. \quad (9)$$

It should be noted that the limitations in research are due to the range of changes in coordinates in the process of developing a mathematical model of TSSC. Fig. 2 shows separate results of studies on the effect of the temperature of the primary condensation Θ_{PC} on the efficiency of the heat transfer process in TSSC on the coordinate indicators of the control vector under the following restrictions: nm^3/h ; $P_{PC} = 22 \text{ MPa}$ – CG pressure; $a_{\text{H}_2\text{O}}^{IT} = 55.7\%$ by volume; $a_{\text{CH}_4}^{IT} = 8.4\%$ by volume; $a_{\text{N}_2}^{IT} = 18.9\%$ by volume; $a_{\text{Ar}}^{IT} = 6.9\%$ by volume; $a_{\text{NH}_3}^{IT} = 10.16\%$ by volume; $V_{NHM} = 174 \cdot 10^3 \text{ nm}^3/\text{h}$; $\Theta_{NHM} = 35^\circ\text{C}$; $\Theta_p^c = 17.5^\circ\text{C}$, $\Theta_{2CG}^{HTE} = 30^\circ\text{C}$, $\Theta_p^{LTE} = -5^\circ\text{C}$, $\Theta_{IT}^c = 9.2^\circ\text{C}$ – accordingly, the temperature of CG at the input of the pipe space of AHE, at the input of CC, at the output of LTE, and at the outlet of the intertube space of CC [3].

Fig. 3 shows the results of studies on the impact of CG consumption at the input of AHE V_{IT}^{CG} on the efficiency of the heat transfer process in TSSC and the coordinate indicators of the control vector. The results of the studies are valid under the above restrictions, temperature $\Theta_{PC} = 36^\circ\text{C}$, pressure $P_{PC} = 22 \text{ MPa}$.

Table 1 gives the results of the assessment of parametric sensitivity of coordinates of the control vector to the change in perturbing factors, performed using (8).

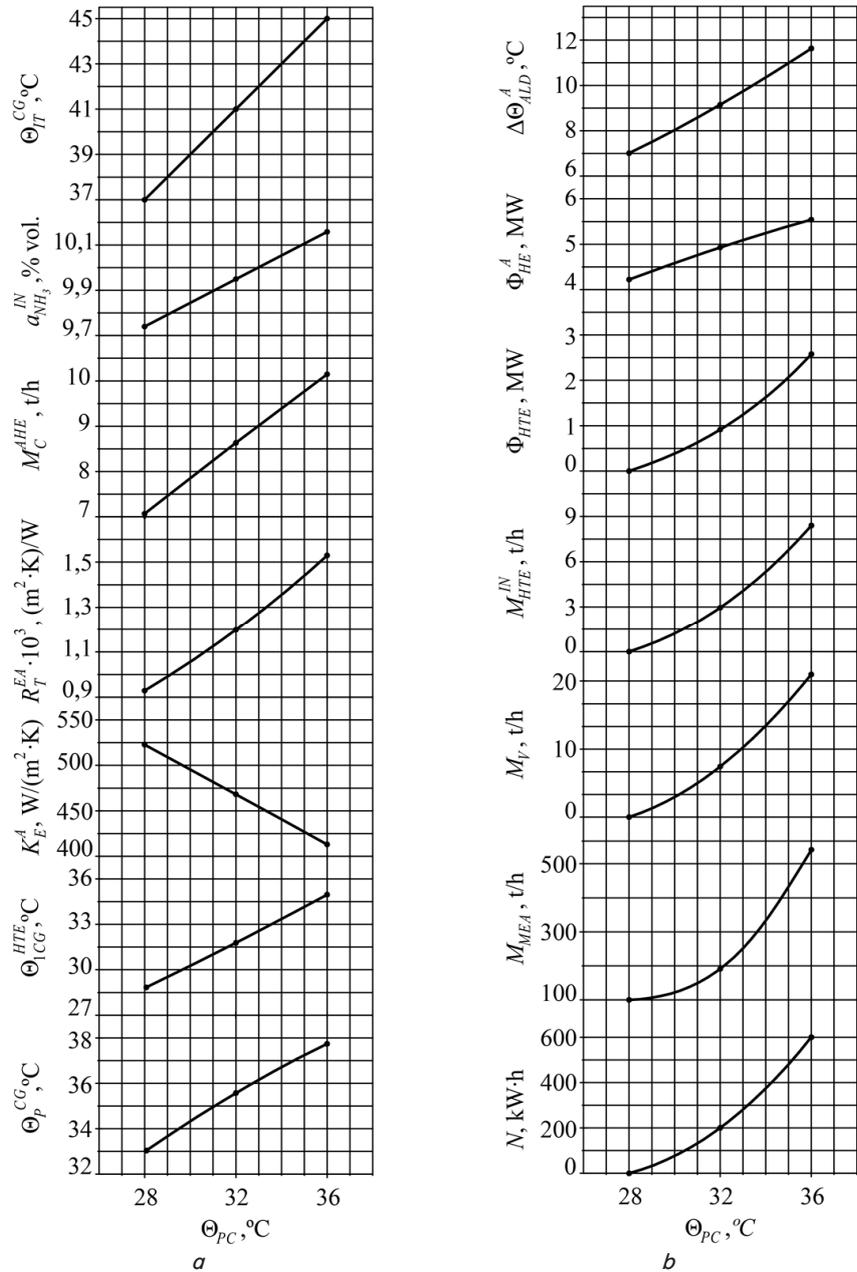


Fig. 2. Dependence of heat exchange efficiency indicators of the technological system of secondary condensation and coordinates of the control vector on the changes in temperature Θ_{PC} : *a* – the temperature Θ_{IT}^{CG} of the circulating gas at the input of the intertube space of the additional heat exchanger, the concentration of ammonia $a_{\text{NH}_3}^{IN}$ in the circulation gas at the input to the system, the consumption of condensed ammonia M_C^{AHE} in the flow of circulating gas of the intertube space of the additional heat exchanger, the total coefficient of thermal resistance R_T^{EA} , the actual coefficient of heat transfer K_E^A , the temperature of the circulation gas at the outlet of the intertube space of the additional heat exchanger, the temperature of the circulation gas at the outlet of the pipe space of the additional heat exchanger Θ_p^{CG} ; *b* – the average logarithmic temperature difference $\Delta\Theta_{ALD}^A$ of the additional heat exchanger, the heat flow Φ_{HE}^A due to heat exchange in an additional heat exchanger, the heat flow (refrigeration capacity) Φ_{HTE}^A of a high-temperature evaporator, refrigerant consumption at the input of the intertube space M_{HTE}^{IN} of a high-temperature evaporator, consumption of working vapor M_V for ejectors of steam-ejector refrigeration unit, consumption of monoethanolamine solution M_{MEA} to the steam generator of steam ejector refrigeration unit, consumer power of electricity N on the drive of fans of air cooling devices for condensation of working steam and refrigerant steam in steam ejector refrigeration unit

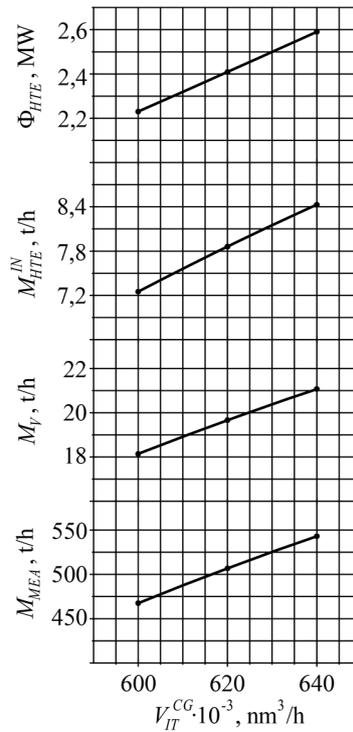


Fig. 3. Dependence of the required refrigeration capacity and coordinates of the control vector on the change in the flow rate of circulation gas at the input V_{IT}^{CG} at a constant temperature of primary condensation $\Theta_{PC}=36^\circ\text{C}$, characterizing the severest summer season of heat load

Table 1

Parametric sensitivity of the coordinates of the control vector M_i to the change in the coordinates of the perturbation vector Z_i

Coefficient of parametric sensitivity	Boundaries of changing the coordinates of the control vector according to the corresponding coordinates of the perturbation vector Z_i		
	$\Delta M_{HTE}^{IN} (2,96\div 8,41) \text{ t/h},$ $\Delta M_{MEA} (191\div 541.3) \text{ t/h}$	$\Delta M_{HTE}^{IN} (7.25\div 8.45) \text{ t/h},$ $\Delta M_{MEA} (467.5\div 543.1) \text{ t/h}$	$\Delta N (200\div 600) \text{ kW}\cdot\text{h}$
	$\Delta \Theta_{PC} (32\div 36)^\circ\text{C}$	$\Delta V_{IT}^{CG} (600\div 640) \cdot 10^3 \text{ nm}^3/\text{h}$	$\Delta \Theta_{PC} (32\div 36)^\circ\text{C}$
K_{Zi}	14.7	2.43	16

At the same time, the boundaries of changing the coordinates of the perturbation vector were chosen at the level most characteristic of the summer and winter seasons of TSSC operation.

5.3. Development of the functional and software-technical structure of the control system for a technological system

The implementation of computer control technology of TSSC realized on the basis of a three-level hierarchical structure. The general structure of the contour management system for the flow rate of material flows and electricity is shown in Fig. 4.

The hierarchical structure of the system to control the contour of the flow rate of material flows and electricity predetermines the use of existing hardware

and software at the first and second levels. At the third level, the human-machine interface unit consists of three modules. These modules provide process correction and modeling and are connected to a real-time database.

Fig. 5 shows the software and technical structure of the automated control system of TSSC with a correction subsystem.

Data exchange is ensured through the use of “open” information technologies OPC and ODBC. This makes it possible to built a subsystem for correcting the modes of functioning and integrating it into a single information and control system.

Thus, the software-technical structure of a typical automated control system for TSSC with a correction subsystem takes the form depicted in Fig. 5.

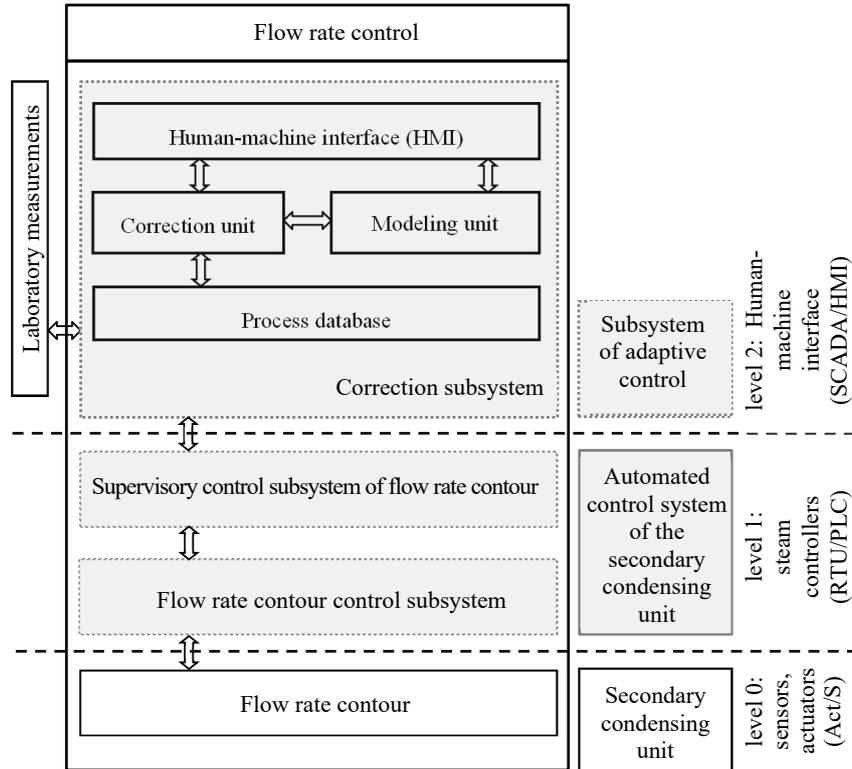


Fig. 4. The general structure of the system to control the contour of the material flows consumption M_{HTE}^{IN} , M_{MEA} , M_V , and electricity N

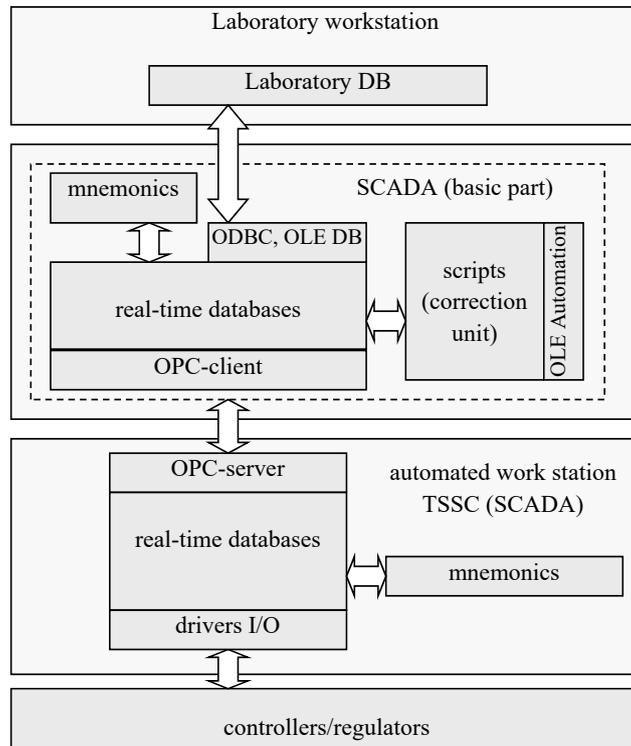


Fig. 5. Software and technical structure of the automated control system for the technological system of secondary condensation with a correction subsystem

5. 4. Development of the structural-logical scheme of information flows for a computer control system of the “open” type

The functioning of the information interaction between the main nodes that ensure the quality of the product

is shown in Fig. 6 in the form of a diagram of network information flows of a fragment of computer-integrated technology for TSSC. The structure of the scheme, which is illustrated in Fig. 6, provides an opportunity to clearly demonstrate the exchange of data between nodes on the

network, as well as the mechanisms and technologies used in its implementation.

According to Fig. 6, information streams connect the nodes of the correction subsystem, database, and laboratory to the

upper level using the Ethernet local area network. At the same time, the subsystem receives primary data from the TDC-3000 control system and an additional VIPA controller using a serial RS-485 interface using special network equipment.

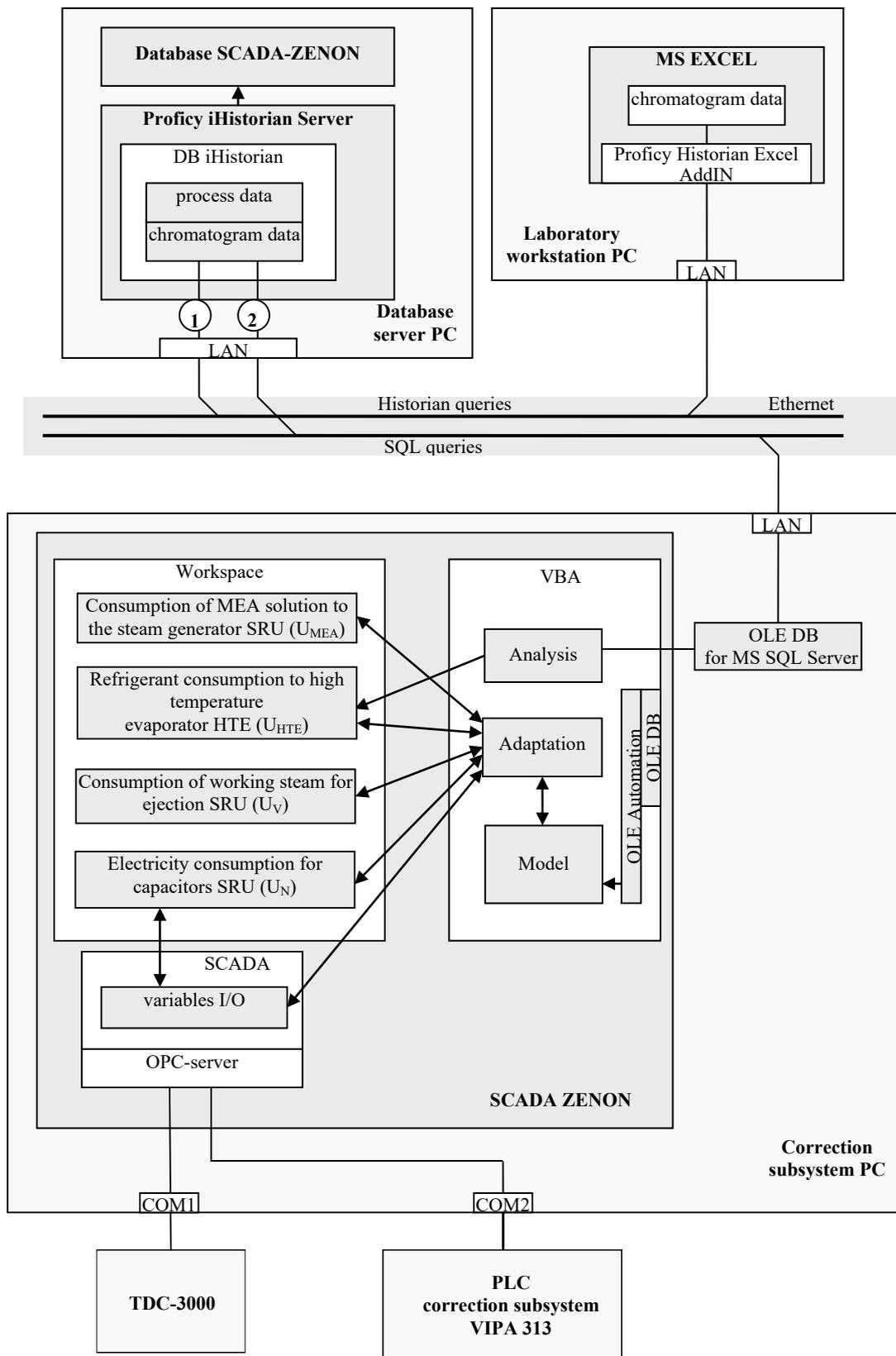


Fig. 6. Diagram of network information flows in a fragment of the computer-integrated technology for secondary condensation system

6. Discussion of results of studying the influence of the coordinates of the perturbation vector on the coordinates of the control vector

According to the results of our study by the method of mathematical modeling based on the developed algorithm (Fig. 1), we derived dependences, shown in Fig. 2, which characterize the effect of the temperature of the primary condensation Θ_{PC} of on the TSSC thermal load. At the same time, the increase in Θ_{PC} simultaneously affects both the increase in the concentration of ammonia $a_{\text{NH}_3}^{\text{IN}}$ in CG according to equation (1) and the temperature of CG at the input $\Theta_{\text{IT}}^{\text{CG}}$. In addition, the latter increases even more due to the compression of CG with a compressor located between the stages of primary and secondary condensation.

For example, with an increase in the temperature Θ_{IK} from 32 °C to 36 °C, the temperature $\Theta_{\text{IT}}^{\text{CG}}$ increases from 41 °C to 45 °C, and the concentration of ammonia in CG – from 9.95 % by volume to 10.16 % by volume. The increase in the latter causes, according to equation (2), an increase in the concentration $a_{\text{NH}_3}^{\text{AP}}$ at the output of the AHE pipe space from 3.69 % by volume to 3.71 % by volume. In turn, the increase in $a_{\text{NH}_3}^{\text{IN}}$ leads to an increase in the amount of condensed ammonia M_C^{AHE} in a CG stream passing through the intertube space of AHE, from 8.63 t/h to 10.15 t/h. Due to this, according to equation (3), there is an increase in the total thermal resistance R_r^{EA} from 0.001197 (m²·K)/W to 0.001531 (m²·K)/W, which causes a decrease in the heat transfer coefficient K_E^A from 468.13 W/(m²·K) to 413.11 W/(m²·K). In such circumstances, the temperatures at the outlet of the intertube space of the AHE $\Theta_{\text{ICG}}^{\text{HTE}}$ and the pipe space Θ_p^{CG} increase, respectively, from 31.78 °C to 34.97 °C, and from 35.58 °C to 37.74 °C, that is, by 3.19 °C and 2.13 °C. With such a temperature distribution, despite a decrease in the heat transfer coefficient, the average logarithmic temperature difference Θ_{ALD}^A increases significantly from 9.15 °C to 11.63 °C, which ensures an increase in the heat flow Φ_{HE}^A from 4.93 MW to 5.54 MW.

An increase in the temperature of CG $\Theta_{\text{ICG}}^{\text{HTE}}$ at the input of HTE to stabilize the temperature of CG $\Theta_{\text{2CG}}^{\text{HTE}}$ at the output of HTE at the level of 30 °C requires an increase in the refrigeration capacity of HTE from 0.91 MW to 2.58 MW. In turn, this causes the need to increase the flow rate of refrigerant $M_{\text{HTE}}^{\text{IN}}$ to HTE from 2.96 t/h to 8.4 t/h. To ensure such an increase $M_{\text{HTE}}^{\text{IN}}$ the consumption of working vapor M_V should be increased from 7.41 t/h to 21 t/h per ejector, which requires an increase in the consumption of the MEA solution M_{MEA} from 191 t/h to 541.34 t/h to the SRU steam generator. At the same time, the total load of ammonia vapor M_{TOT} on SRU air capacitors would increase from 10.37 t/h to 29.4 t/h, which makes it necessary to increase the number of ACC fans operating from one to three. As a result, electricity consumption N should be increased from 200 kWh to 600 kWh, that is, all three ACC air fans would be enabled. In case of lowering the temperature Θ_{PC} to 28 °C, which is observed at an atmospheric air temperature of less than 5 °C, the operation of SRU should be stopped at all. In such circumstances, cooling the CG to the operating temperature $\Theta_p^{\text{LTE}} = -5$ °C would be provided only in the evaporators of LTE with ARU.

The consumption of CG at the input $V_{\text{IT}}^{\text{CG}}$ due to possible production requirements for changes in the

performance of the ammonia synthesis unit also affects the thermal load of TSSC. As shown in Fig. 3, under the conditions of increasing the flow rate of CG $V_{\text{IT}}^{\text{CG}}$ from 600 thousand nm³/h to 640 thousand nm³/h, the coordinates of the control vector of the flow rate M_{MEA} , M_V and $M_{\text{HTE}}^{\text{IN}}$ increase, respectively, by 75.57 t/h, 2.93 t/h, and 1.18 t/h. This is due to the need for a slight increase in the cooling capacity Φ_{HTE} by 0.36 MW in the HTE evaporator due to an increase in the temperature $\Theta_{\text{ICG}}^{\text{HTE}}$ at its input by only 0.4 °C. Such slight increases in the listed indicators are associated with a slight increase in the amount of condensed ammonia M_C^{AHE} by 0.25 t/h, an increase in the total thermal resistance R_r^{EA} by 0.00007 (m²·K)/W, and a decrease in the heat transfer coefficient K_E^A by 4.9 W (m²·K). The nature of the impact of these indicators has been sufficiently justified by a preliminary explanation, and, therefore, Fig. 3 does not show these dependences. In such circumstances, the operation of SRU should be carried out under a maximum load; this is especially true for fans with ACC.

The analysis of the study's results, shown in Fig. 2, 3 and given in Table 1, explains the excessive amount of parametric sensitivity of the control vector under the conditions of changes in the temperature of the primary condensation, which, compared with the CG consumption at the input of TSSC, exceeds more than six times.

Designed to predict the modes of operation of such metal-intensive, and, therefore, too inertial objects as TSSC under the conditions of changing the coordinates of the perturbation vector allow it to be used in the subsystem of decision support under the existing uncertainties. This subsystem is one of the main components in the general technical structure of computer technology for controlling the process of secondary condensation of ammonia production [11]. However, the implementation of this structure requires the improvement of the existing control system based on the TDC-3000 with available hardware and software of the "open" type.

The unit of HMI (Fig. 4) includes three modules. The module for entering new data makes it possible to modify data tables for new components in a convenient form for the operator. The model configuration module is designed to manually enter the necessary structural data on evaporator, condensation column, and heat exchanger and start the process of checking the complete adequacy of models. Graphic screens provide a more detailed analysis of all information on the secondary condensation process intended only for the subsystem operator.

The separation of correction units and modeling units in the structure of the correction subsystem takes into consideration their final implementation since the model software is developed in the form of user libraries. The human-machine interface unit should provide the configuration of the subsystem and analysis of its work, as well as the construction and maintenance of the process database – the collection, processing, storage, and management of data on the technological process.

That has made it possible to develop a functional scheme of computer-integrated technology for TSSC, which is identical to the one built and reported in [6]. At the same time, a client-side module (OPC client) is embedded using the MATLAB programming environment, which provides free software access to the process data (Fig. 5). Regulators of technological parameters and classical regulators

in cascading circuits are implemented as a separate control subsystem. The values of settings for control vectors are formed by the correction subsystem. However, the operator can independently make decisions and change them due to the level of supervisory control. This mode is especially important in the process of changing the flow rate of working steam M_V and electricity N by changing the number of working ejectors and ACC fans.

The proposed correction subsystem is based on the functional structure to control the quality and amount of resulting product. Its structure includes the following components:

- real-time databases (functionally, it is a process database);
- algorithmic part (functionally, it is a correction unit and a modeling unit);
- human-machine interface.

The configuration windows of all components, as well as display mnemonics schemes for the operator's work, vary depending on the structure of the entire secondary condensation system. At the same time, the first and third components are the main elements of the SCADA system, which makes it possible to implement a subsystem based on an existing tool.

Thus, the correction subsystem can be implemented by a separate network node within the system or integrated into the SCADA node of the secondary condensation system, as shown in Fig. 6. This subsystem is developed on the basis of the SCADA-program Zenon [17, 18]. Connections of data sources depend on the method of connection of real-time databases (ACS of secondary condensation, laboratory workstation, etc.). In this case, OPC technology and ODBC technology are used [19].

Taking into consideration the requirements for the openness of the system, it is proposed to use the most common open communication technologies. These are the so-called OPC technologies.

The result of the use of the developed computer control technology for TSSC provides a decrease and stabilization of the secondary condensation temperature to -5°C . Such a decrease causes a decrease in natural gas consumption, as already noted, in an additional steam boiler by almost 1 million nm^3 per year. Further work will aim at the further improvement of the technology to control condensation processes in order to reduce the load on the compressor system of ammonia synthesis department.

7. Conclusions

1. We have developed an algorithm for the subsystem of decision support to the computer technology of TSSC control under the conditions of uncertainty, whose software implementation was carried out using the special MATLAB programming environment. This approach, owing to the client part embedded using the MATLAB environment (OPC client), provides free software access to the current data on the technological process.

2. A method of mathematical modeling based on the developed algorithmic software helped determine the regularity and quantitative dependences of the influence of external heat load on the performance indicators of heat exchange processes of TSSC under the established restrictions. These quantitative indicators make it possible to forecast the coordinates of the control vector in order to stabilize the temperature of secondary condensation at the regulatory level. Among these indicators, we distinguished the heat flows, a heat transfer coefficient, and the coordinates of the control vector. The regularity of increasing heat flows with an increase in the temperature of primary condensation has been established. As a result, there is a significant increase in the temperature load and coordinates of the control vector, despite some increase in ammonia in CG at the input of TSSC and a decrease in the heat transfer coefficient. The parametric sensitivity of the coordinates of the control vector from the change in the temperature of the primary condensation has been determined, which, compared with the change in the CG flow rate at the input of TSSC, exceeds by more than six times. We have built dependences of the coordinates of the control vector on the change in the external thermal load at the input of TSSC and determined the limit value of the primary condensation temperature at the level of 28°C . At this temperature, it is possible for the operator to decide to stop the operation of SRU within TSSC.

3. We have designed a functional structure of the computer technology to control the contours of refrigerant flow rate to HTE and MEA solution to SRU steam generator, which uses the controller of free programming VIPA and SCADA-system Zenon.

4. Based on the use of "open" technologies, the hardware and software support to the computer-integrated control technology of TSSC was developed. This approach provided an opportunity to integrate it into the structure of the existing TDC-3000 control system and implement it in the form of automated operator's workplace of the decision-support subsystem.

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