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ALGORITHMIC TOOLS FOR OPTIMIZING THE TEMPERATURE REGIME OF EVAPORATOR AT ABSORPTION-REFRIGERATION UNITS OF AMMONIA PRODUCTION

A. Babichenko
PhD, Associate Professor*
E-mail: babichenko_a_k@ukr.net
Y. Kravchenko
Postgraduate student*
J. Babichenko
PhD, Associate Professor
Department of Thermal Engineering and heat engines
Ukrainian State University of Railway Transport
Feierbakha sq., 7, Kharkiv, Ukraine, 61050
I. Krasnikov
PhD, Associate Professor*
I. Lysachenko
PhD, Associate Professor*
V. Velma
PhD, Associate Professor
Department processes and devices of chemical-pharmaceutical industries
National University of Pharmacy
Pushkinska str., 53, Kharkiv, Ukraine, 61002
*Department of Automation engineering systems and environmental monitoring
National Technical University
"Kharkiv Polytechnic Institute"
Kyrpychova str., 2, Kharkiv, Ukraine, 61002

Проведено аналіз випарників абсорбційно-холодильних установок блоку вторинної конденсації виробництва аміаку як об'єктів керування. Визначені координати векторів стану, керування та зовнішніх збурень. Обґрунтована необхідність розв'язання задачі мінімізації температури охолодження циркуляційного газу у випарниках для підвищення енергоефективності виробництва. За результатами аналізу промислового апаратурно-технологічного оформлення блоків первинної і вторинної конденсації з'ясовані особливості умов роботи випарників, що зумовлюють параметричну невизначеність у функціонуванні об'єктів керування. Основна з таких невизначеностей пов'язана з керуючою дією витрати флегми.

Методом математичного моделювання за розробленим алгоритмом визначені закономірності керуючої дії витрати флегми на ефективність процесів теплообміну у випарниках абсорбційно-холодильних установок. Встановлено екстремальний характер залежності теплового потоку (холодопродуктивності) та температури охолодження циркуляційного газу від витрати флегми. Максимальна холодопродуктивність, а отже і мінімальна температура охолодження циркуляційного газу за певного температурного напору, обумовлені досягненням критичного режиму бульбашкового кипіння холодоагенту. Подальше збільшення температурного напору з підвищенням витрати флегми сприяє встановленню перехідного режиму і зниженню ефективності поверхні теплообміну. Визначені показники енергоефективності виробництва аміаку, а саме витрати природного газу в умовах зміни керуючої дії витрати флегми та значень координат вектора збурень. Розроблене алгоритмічне забезпечення дозволяє здійснити розв'язання задачі мінімізації температури охолодження циркуляційного газу безградієнтним способом крокового типу з використанням методів одномірного пошуку екстремуму. Показано, що за рахунок мінімізації температури охолодження циркуляційного газу річна витрата природного газу може бути знижена в середньому на 500 тис. нм³

Ключові слова: виробництво аміаку, абсорбційно-холодильна установка, випарник, витрата флегми, алгоритм оптимізації температури

1. Introduction

One of the main tendencies in improving the efficiency of production is to reduce energy consumption by introducing energy-technological systems that utilize the low-potential heat. Such an approach has led to renewed interest in the application of thermal absorption refrigeration units (ARU) in various industrial sectors where a refrigerant must be maintained at a temperature below 0 °C [1]. This led to the widespread use in the composition of large tonnage units of series AM-1360 of two ARU, which ensure cooling of a circulating gas (CG) in the low-temperature evaporators at a unit for secondary condensation of discharge of the ammonia synthesis [2].

The unit for secondary condensation, ARU in particular, is characterized by the wide use of apparatuses with air and water cooling. Given the large-tonnage production of ammonia and the existing hardware design of the unit for secondary condensation, changing the indicators of the environment predetermines not only the parametric uncertainty in the functioning of the object, but also leads to significant economic losses. According to the available studies, a rise in the atmospheric air temperature from −6 °C to 30 °C, despite the growth in the ARU cooling capacity from 2.44 MW to 3.25 MW, causes an increase in the temperature of cooling of CG from −8 °C to 4 °C [3]. However, raising this temperature even by 1 °C leads to a decrease in the energy efficiency of the unit for synthesis in general at the expense of the increased annual consumption of natural gas to an additional steam boiler by 307.3 thousand nm^3 in order to obtain water vapor of high pressure, which ensures the drive of a centrifugal three-body compressor for CG compression and a fresh nitrogen-hydrogen mixture at the synthesis unit [4]. Thus, minimizing the temperature mode of CG cooling at ARU evaporators through the creation of an automated system of optimal software control acquires special relevance for the overall process of improving the energy efficiency of large tonnage units for ammonia synthesis.

2. Literature review and problem statement

Solving the task on minimizing (optimizing) a temperature mode of CG cooling aimed to improve economic efficiency of production requires, as is known from [5], the development of a specialized algorithm for the subsystem of optimization of control object. Regarding a low-temperature evaporator at the unit for secondary condensation, a problem on the synthesis of an optimization algorithm in a general form can be represented in the following way:

$$\varphi(\mathbf{X},\mathbf{Y},\mathbf{Z}) \to \min(extr) \Rightarrow \mathbf{X}^{OPT}(t), \tag{1}$$

$$\mathbf{X} = F(\mathbf{Y},\mathbf{Z}), \tag{2}$$

where φ is the objective function; $\mathbf{X}$, $\mathbf{Z}$ is the coordinate vector in accordance with the state of the object and perturbations of a certain dimensionality. $\mathbf{Y}$ is the vector of controlling influences; F is an operator of the mathematical model.

Vaporizers are the pipe-casing heat exchangers of the immersed type with U-shaped tubes. CG is cooled in a pipe space by ammonia, which boils in the intra-pipe space. According to the available experimental data [6], a special feature in the operation of low-temperature evaporators as the objects of control is associated with a constant influence of the seasonal and daily disturbances driven by two circumstances. The first is related to the use, at the stage of primary condensation of synthesis separation, of the air-cooled apparatuses. The second is due to the use, in an ARU cycle, of water and air cooling, respectively, in the absorber and in condenser. All this leads to a change in the coordinates of perturbation vector $\boldsymbol{Z}(t)$ of evaporators, namely, temperature $\Theta_{1CG}(t)$ of CG (13÷23 °C) and the concentration of ammonia $a_{NH_3}^{IN}(t)$ in CG (9÷12 % by volume), temperature $\Theta_X^{IN}(t)$ of the cooling agent (18÷38 °C) and concentration $\xi_X^{IN}(t)$ of the cooling agent at the inlet (0.993÷0.998 kg/kg), as well as pressure $P_{IP}(t)$ of boiling (0.296÷0.16 MPa) of the cooling agent.

Another feature in the operation of evaporators relates to the fact that a liquid refrigerant enters it with an addition of water. In order to prevent the accumulation of water, the evaporator is designed with the property of draining it in the form of a reflux with a certain consumption of M_R [7]. An analysis of the draining process reveals that on the one hand the excessive discharge of a reflux leads to the loss of a cooling agent, which can be evaporated. This can lead to a change in the state vector of evaporator $\boldsymbol{X}(t)$, namely to a decrease in the level $H(t)$ of a liquid cooling agent and an increase in the temperature of CG cooling $\Theta_{2CG}(t)$. The result is a drop in cooling capacity Φ_O. On the other hand, the insufficient drainage of the reflux contributes to the accumulation of water, reduces the concentration of boiling cooling agent ξ_R and increases boiling pressure P_{IP}. Such conditions will lead to an increase in temperature Θ_{2CG} and a decrease in cooling capacity Φ_O. Therefore, the consumption of reflux $M_R(t)$, along with the consumption of cooling agent $M_X^{IN}(t)$, are among the main coordinates of control vector $\mathbf{Y}(t)$, which define the optimal vector of state $\mathbf{X}^{OPT}(t)$. However, the scientific periodicals mostly consider variants on the expediency of reflux draining techniques from the evaporator, or to the absorber of the receiver, or to the generator-rectifier [1]. At the same time, there is almost no information on determining the quantitative dependences of influence of the flow rate on efficiency of the process of heat exchange in evaporator, particularly under conditions of action of a large number of external perturbations. Such an absence is predetermined by the wide use in ARU of only a periodic draining of reflux for the set temperature of CG cooling [8]. The downside to it is the low operational reliability under conditions of a possible simultaneous change in the above-specified external disturbances. Under these circumstances, it is impossible to uniquely identify the preset CG temperature Θ_{2CG}, and, therefore, the moment of the onset of the periodic reflux drainage. In this case, the process of periodic reflux draining disrupts the regime of ARU and, if using it improperly, can stop its operation [9]. In addition, commonly used are such ARU, particularly at households and processing sectors, which have a small cooling capacity, in which the effect of the process of reflux drainage on economic efficiency is not so significant [10]. For ARU with a large cooling capacity, over 3 MW, exploited in the production of ammonia, such an effect can be quite considerable. Therefore, the problem on determining the quantitative dependence of control action $M_R(t)$ on the optimal vector of state $\mathbf{X}^{OPT}(t)$ for ARU with a large cooling capacity, as well as constructing an algorithm for the optimization subsystem, is of special importance.

3. The aim and objectives of the study

The purpose of this study is to build a subsystem for the optimal software control over low-temperature evaporators in absorption-refrigeration units at a secondary condensation unit in the production of ammonia. That would enable solving the task on minimizing the temperature of CG cooling and on improving the energy efficiency of production by reducing the consumption of natural gas.

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

– to establish patterns in the control action related to the consumption of reflux on efficiency of the processes of heat exchange at ARU evaporator;

– to determine the impact of control action related to the consumption of reflux on energy efficiency of the production of ammonia under conditions of a change in the coordinates of a perturbation vector;

– to develop software tools in order to provide for the minimization of the objective function and numerical estimation of the optimal vector of the evaporator state.

4. Materials and methods to study influence of the consumption of reflux on efficiency of the processes of heat exchange at evaporator

In our research, we applied method of mathematical modeling. To this end, we employed a mathematical model of the ARU evaporator; its adequacy was tested and substantiated based on the results of previous studies [6].

We determined quantitative dependences regarding the establishment of patterns in the influence of reflux drainage intensity on efficiency of the processes of heat exchange at evaporator using a specially constructed algorithm. A principal flowchart of this algorithm is shown in Fig. 1; its software implementation was executed in the Matlab package.

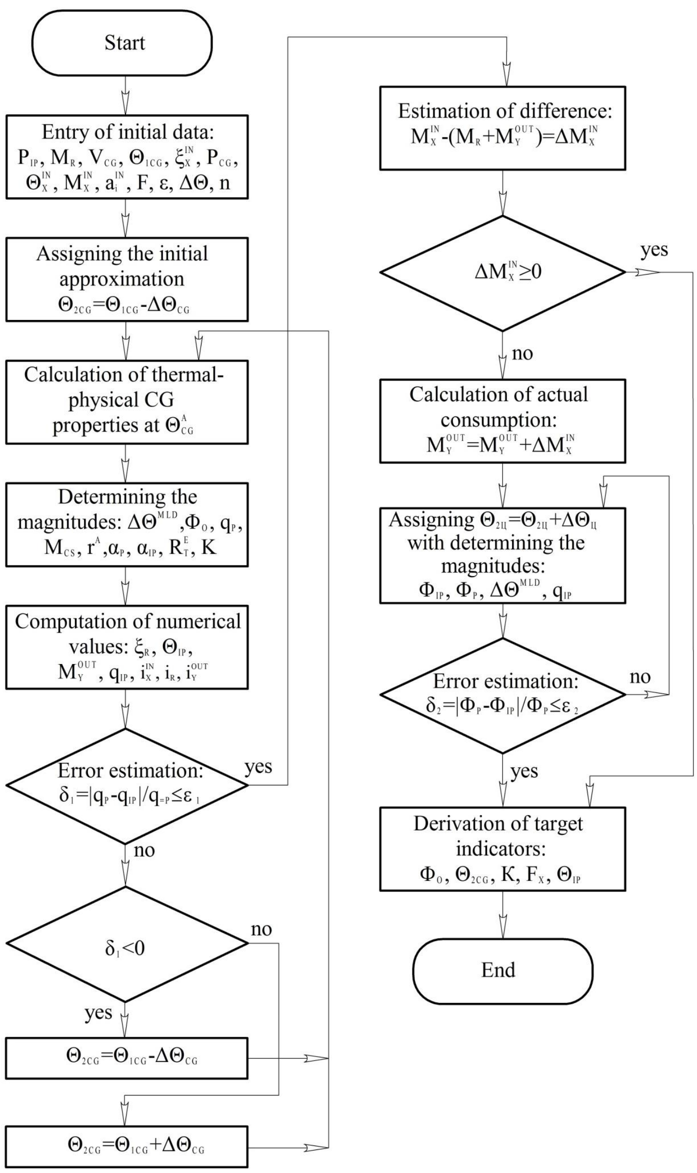


Fig. 1. Generalized flowchart of the algorithm to study the evaporator

Denotations that are given in Fig. 1 correspond to the following physical quantities: V_{CG} is the volumetric flow rate of CG, nm^3/s; a_i^{IN} is the volumetric concentration of the constituent components of CG at the inlet, % by volume, F=520 m^2 is the total surface of heat exchange; ε=0.2 % is the preset error of calculation; $\Delta\Theta=0{,}1$ °C is the step of change in the temperature; Θ_{CG}^A is the mean CG temperature, °C; $\Delta\Theta^{MLD}$ is the average logarithmic temperature difference, °C; q_P, q_{IP} are, respectively, the specific heat flow from the side of the pipe and intra-pipe space, W/m^2; M_{CS}, M_Y^{OUT}, M_X^{IN} is the mean flow rate, respectively, of the condensed ammonia from CG, of the cooling agent vapor at the outlet from the evaporator, and of the liquid cooling agent to the receiver of the condenser, kg/s; r^A is the mean heat of ammonia condensation, kJ/kg; α_P, α_{IP}, K are coefficients, respectively, of the heat transfer from CG, of the cooling agent, and the overall coefficient of heat transfer, W/(m^{2}K); R_T^E is the total thermal resistance, (m^{2}K)/W; P_{CG}, P_{IP} is the pressure, respectively, of CG and a boiling cooling agent, MPa; ξ_R is the weight concentration of reflux, kg/kg; Θ_{IP} is the boiling temperature of refrigerant in the intra-pipe space, °C; i_X^{IN}, i_R, i_Y^{OUT} is the enthalpy, respectively, of the liquid cooling agent at the inlet, of reflux, and the ammonia vapor at the outlet, kJ/kg; F_X is the effective heat exchange surface, m^2; $n=526$ is the total quantity of heat-exchanging pipes; Φ_P, Φ_{IP} are, respectively, the heat flow from the side of the pipe and intra-pipe space, MW.

The developed algorithm, in contrast to those generally known, makes it possible to calculate the effective surface of heat exchange F_X at evaporator, under conditions of action of external perturbations, from the following formula:

$$F_X=\Phi/q. \quad (3)$$

The algorithm consists of two main cycles of convergence. The first cycle determines temperature Θ_{2CG} and estimates a calculation error δ_1 under condition $\Delta M_X^{IN}\ge0$, when the consumption of a cooling agent vapor and the reflux do not exceed the possible feed of a liquid cooling agent to the evaporator from ARU condenser. The second cycle relates to determining the temperature Θ_{2CG} and the effective heat exchange surface for the case $\Delta M_X^{IN}<0$, that is, under conditions of the existing constraint on the flow rate of a liquid cooling agent from ARU condenser. In this case, both cycles, provided the level is constant, ensure maintaining the overall balance of the evaporator in terms of consumption and energy.

5. Results of studying the influence of the consumption of reflux on efficiency of the process of heat exchange at evaporator

Mathematical modeling makes it possible to establish regularities in the influence of variable, both a vector of external perturbations $\boldsymbol{Z}(t)$ and a control vector $\mathbf{Y}(t)$, on the vector of state $\mathbf{X}(t)$ of the evaporator. Passing over to the space of the state variables, these vectors will take the following form:

$$\boldsymbol{X}(t)=\begin{bmatrix}\Theta_{2CG}(t)\\ H(t)\end{bmatrix};$$

$$\boldsymbol{Z}(t)=\begin{bmatrix}\Theta_{1CG}(t)\\ a_{NH_3}^{IN}(t)\\ \Theta_X^{IN}(t)\\ \xi_X^{IN}(t)\\ P_{IP}(t)\\ V_{CG}(t)\end{bmatrix};$$

$$\boldsymbol{Y}(t)=\begin{bmatrix}M_X^{IN}(t)\\ M_R(t)\end{bmatrix}. \qquad (4)$$

It should be noted that constraints in the research are predetermined by the range of change in the coordinates in the process of constructing a mathematical model of the evaporator. In this case, based on the results of building a new energy-efficient hardware-technological implementation of the unit for secondary condensation, the magnitude of temperature Θ_{1CG} is a constant at the level of 9.2 °C at the maximum thermal load for CG at the inlet [4].

Fig. 2 shows selected results of studying the control action related to the consumption of reflux M_R at different pressure P_{IP} on efficiency of the process of CG cooling at evaporator under the following constraints:

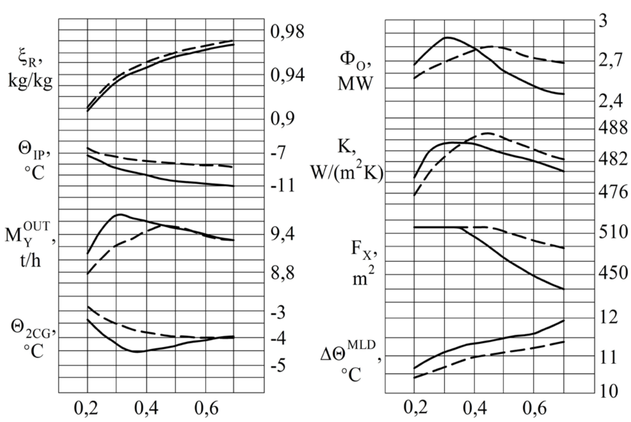
$V_{CG}=310798$ nm³/s; $a_{NH_3}^{IN}=0{,}103$ % by volume;

$a_{H_2}^{IN}=0{,}544$ % by volume; $a_{N_2}^{IN}=0{,}195$ % by volume;

$a_{CH_4}^{IN}=0{,}082$ % by volume; $a_{Ar}^{IN}=0{,}076$ % by volume;

$\Theta_{1CG}=9{,}2$ °C; $P_{CG}=23$ MPa; $M_X^{IN}=10$ t/h;

$\xi_X^{IN}=0{,}998$ kg/kg; $\Theta_X^{IN}=26$ °C.



a *b*

Fig. 2. Dependence of efficiency indicators of the ARU evaporator operation on a change in pressure P_{IP} (——— P_{IP}=0.29 MPa; - - - - — P_{IP}=0.3 MPa) and the control action related to the consumption of reflux M_R: *a* — concentration of reflux ξ_R, boiling temperature of refrigerant in the intra-pipe space Θ_{IP}, consumption of the cooling agent vapor at the outlet from evaporator M_Y^{OUT}, temperature of *CG* cooling Θ_{2CG}; *b* — cooling capacity Φ_O, coefficient of heat transfer K, effective heat exchange surface F_X, average logarithmic temperature difference $\Delta\Theta^{MLD}$

Fig. 3–5 show results of studying the impact of control action related to the consumption of reflux M_R on the target indicators of operational efficiency of the evaporator, specifically the temperature of CG cooling Θ_{2CG} and the ARU cooling capacity ARU Φ_O under condition of change in the coordinates of perturbation vector and at the above-specified constraints. These include first of all such constraints as the concentration of cooling agent ξ_X^{IN}, the cooling agent consumption M_X^{IN}, which arrives from the condenser, and the concentration of ammonia in CG $a_{NH_3}^{IN}$ at the inlet from the evaporator.

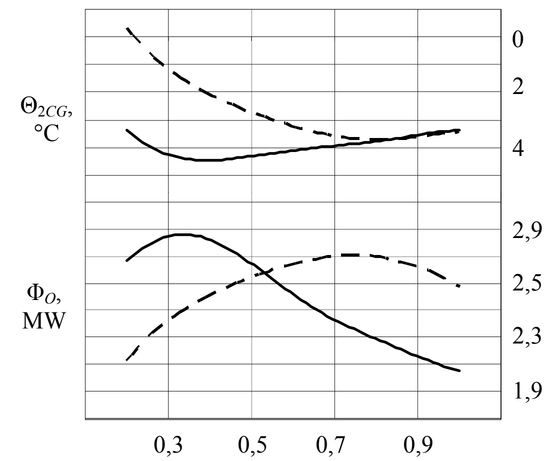


Fig. 3. Dependence of *CG* cooling temperature Θ_{2CG} and the ARU cooling capacity Φ_O on the control action related to the consumption of reflux M_R at different values of the refrigerant concentration ξ_X^{IN} at the inlet to the evaporator: ——— $\xi_X^{IN}=0{,}998$ kg/kg; - - - - — $\xi_X^{IN}=0{,}994$ kg/kg

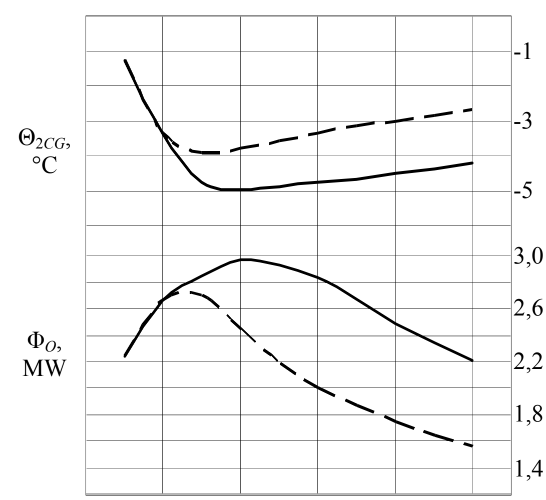


Fig. 4. Dependence of the CG cooling temperature Θ_{2CG} and the ARU cooling capacity Φ_O on the control action related to the consumption of reflux M_R at different values of the cooling agent consumption M_X^{IN} at the inlet to the evaporator: ——— $M_X^{IN}=10{,}5$ t/h; - - - - — $M_X^{IN}=9{,}5$ t/h

In this case, the values for these coordinates were chosen at the levels that are most typical for summer and winter operation seasons of the unit for secondary condensation, specifically ARU.

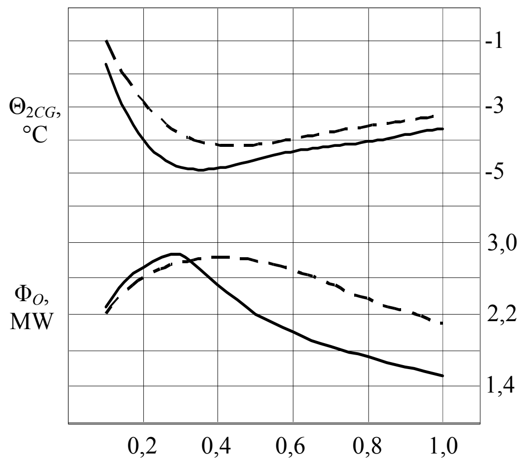


Fig. 5. Dependence of the CG cooling temperature Θ_{2CG} and the ARU cooling capacity Φ_O on the control action related to the consumption of reflux M_R at different values of the concentration of ammonia in CG $a_{NH_3}^{IN}$ at the inlet to the evaporator: ——— – $a_{NH_3}^{IN} = 9$ % by volume; - - - - – $a_{NH_3}^{IN} = 11$ % by volume

6. Discussion of results of studying the control action related to the consumption of reflux on efficiency of the ARU evaporator performance

The dependences shown in Fig. 2 that were constructed based on the results of research in terms of cooling capacity $_O$ and CG cooling temperature Θ_{2CG} are of extreme character due to the control action related to the consumption of reflux M_R. This is predetermined, in turn, by the extreme dependence of the cooling agent vapor consumption M_Y^{OUT}, which increases at the expense of reducing the temperature of a liquid cooling agent boiling temperature Θ_{IP}. The latter contributes to a decrease in the CG cooling temperature and an increase in cooling capacity.

Thus, for example, an increase in the consumption of M_R from 0.2 t/h to 0.35 t/h at a constant boiling pressure $P_{IP} = 0{,}29$ MPa leads to that the mean concentration of a boiling cooling agent ξ_R increases from 0.9071 kg/kg to 0.9408 kg/kg. That in turn leads to a decrease in the boiling temperature of the cooling agent Θ_{IP} from −8.24 °C to −9.71 °C. Given this, there is an increase in the average temperature difference $\Delta\Theta^{MLD}$ from 10.68 °C to 11.24 °C and in the consumption of a cooling agent M_Y^{OUT}, which vaporizes, from 9.08 t/h to maximum 9.65 m/h. Under these circumstances, temperature Θ_{2CG} decreases from −3.36 °C to minimum −4.5 °C, while cooling capacity Φ_O increases from 2.66 MW to maximum 2.84 MW. Heat transfer coefficient K increases and reaches a maximum value of 485.5 W/(m^{2}K). That indicates, as known from [11], reaching the critical limit of the bubbling boiling mode of the cooling agent. At the same time, lowering the temperature Θ_{2CG} by 1.14 °C through the control action related to the consumption of reflux enables the reduction of natural gas consumption by 350 thousand nm^3/year.

A further increase in control action M_R, for example, to 0.5 t/h, leads to the increased concentration of ξ_R, reduced temperature Θ_{IP} and increased temperature difference $\Delta\Theta^{MLD}$, respectively, to 0.9562 kg/kg, −10.1 °C, and 11.32 °C. That reduces the effective heat exchange surface from 520 m^2 to 481.27 m^2, indicating the establishment of the transitional boiling regime of the cooling agent. Such a regime is characterized by that the large steam cavities form at the surface. As a result, "dry" plots appear at the surface that seem to rule out part of the surface from heat exchange. Under such circumstances, the supply of heat directly to vapor occurs less intensively. This causes a decrease in the consumption of vapor M_Y^{OUT} to 9.52 t/h, a heat transfer coefficient K to 482.5 W/(m^{2}K) and the cooling capacity Φ_O to 2.63 MW. In this case, the temperature of CG cooling Θ_{2CG} will rise to −4.25 °C, that is, by 0.25 °C, and the consumption of natural gas will grow by almost 77 thousand nm^3/year.

An increase in pressure is most often caused by an increase in the temperature of water that cools the absorber. According to Fig. 2, an increase in pressure P_{IP} from 0.29 MPa to 0.3 MPa requires an increase in the magnitude of the consumption M_R from 0.35 t/h to 0.45 t/h for establishing the critical limit of the bubble boiling mode of the cooling agent. In this case, due to an increase in the temperature difference $\Delta\Theta^{MLD}$ from 10.83 °C to critical 11.01 °C, the cooling capacity will increase from 2.73 MW to maximum 2.79 MW, and the temperature of CG cooling Θ_{2CG} will drop from −3.7 °C to minimum −3.98 °C. The result of such a control action related to the consumption, the yearly consumption of natural gas could be reduced by 88 thousand nm^3/year.

The concentration of a liquid cooling agent at the inlet to the evaporator ξ_X^{IN}, given the seasonal fluctuations in the temperature of air that cools the ARU condenser, also varies quite widely. It follows from Fig. 3 that the extreme (minimum) temperature value Θ_{2CG} as a result of increasing the concentration ξ_X^{IN} from 0.994 kg/kg to 0.998 kg/kg reduces from −3.8 °C to −4.5 °C at a constant pressure $P_{IP} = 0{,}29$ MPa. At the same time, there is a shift in the direction of reducing the magnitude of the control action related to the consumption of reflux from 0.8 t/h to 0.35 t/h, at which the minimum values for Θ_{2CG} are provided. Under such a condition, the cooling capacity increases from 2.69 MW to 2.84 MW and the annual consumption of natural gas could be reduced by 215 thousand nm^3.

At a constant heat supply to the generator-rectifier and the seasonal fluctuations of condensation pressure, there is a change in the consumption of a cooling agent vapor that arrives to the condenser, and a liquid cooling agent to the evaporator. The result of such changes in the consumption M_X^{IN}, for example, from 9.5 t/h to 10.5 t/h (Fig. 4) is also a shift in the required control action related to the consumption of reflux from 0.3 t/h to 0.4 t/h, at which the minimum temperature values Θ_{2CG} are achieved, namely at the level of −3.9 °C and – 4.98 °C. At the same time, the maximum cooling capacity Φ_O is reached, respectively, 2.71 MW and 2.96 MW. Given such a control action related to the consumption of reflux, a reduction by 332 thousand nm^3 in the yearly consumption of natural gas is achieved.

The result of the application of *CG* air cooling at the stage of primary condensation is the significant decrease in the concentration of ammonia in CG $a_{NH_3}^{IN}$, which predetermines a change in the thermal load of the evaporator. According to the derived dependences (Fig. 5), a decrease in the concentration $a_{NH_3}^{IN}$, from 11 % by volume to 9 % by volume leads to a shift in an extremum towards decreasing the control action related to the consumption of reflux, that is, from 0.4 t/h to 0.3 t/h.

Under such a condition, we observe extremes of temperature Θ_{2CG} respectively, at the level of −4.22 °C and −4.98 °C;

the cooling capacity reaches maximum values of 2.8 MW and 2.85 MW. In this case, the annual consumption of natural gas could be reduced by 234 thousand nm^3.

The research we conducted proved the essential impact of the consumption of reflux for such powerful ARU on the CG cooling efficiency, and, therefore, on the energy efficiency of production. In this case, the application of control action related to the consumption of reflux in the range from 0.2 t/h to 0.8 t/h ensures a reduction in the annual natural gas consumption by 500 thousand nm^3 on average.

The established extreme character of the CG cooling temperature dependence Θ_{2CG} on control action related to the consumption of reflux and the displacement of an extremum under conditions of changing the values for the coordinates of perturbation vector $\mathbf{Z}(t)$ confirms the need to build a system of optimal software control over temperature mode of CG cooling. The main element of such a system must be a subsystem of optimization for calculating the magnitude of the coordinate of control action related to the consumption of reflux, which determines the optimal state vector $\mathbf{X}(t)$ of the evaporator.

An analysis of the above process of computation testifies to the possibility of solving a multidimensional optimization problem using a gradient-free method of the step type applying the algorithms for a one-dimensional search for an extremum. Gradient-free methods, as known from [12], in terms of a character, are most suitable for the optimization of existing industrial systems.

Given the sensitivity of the object to a change in the consumption of reflux, the most appropriate is to use a scanning method in the space of only one variable. Such a method ensures, by applying a small search step, that an extremum would not be omitted [13]. Given this, with respect to the derived dependences, we accepted a search step for the consumption of reflux at the level of 0.02 t/h. At the same time, the algorithm's flowchart shown in Fig. 1 was complemented with the third cycle of search for a global extremum.

The resulting algorithmic tools for minimizing the temperature Θ_{2CG} of CG cooling makes it possible to employ it in the optimization subsystem. This subsystem is the main component in the general technical structure for the automated system of optimal program control over the ARU evaporator. In the future, we plan to build an information-control subsystem, based on the real-time database and hardware-software tools for collecting and processing current information about the state of a technological object.

7. Conclusions

1. Based on the results of mathematical modelling, we established the dependence of efficiency indicators of the processes of heat exchange at evaporator on a change in the control action related to the consumption of reflux and the coordinates of the external perturbation vector. Among these indicators, we should highlight such of them as thermal fluxes, cooling capacity, the temperature of CG cooling coefficients, temperature head, and heat transfer coefficients. We established a pattern of the extreme character of dependence of cooling capacity, temperature of CG cooling on the consumption of reflux, an increase in which leads to an increase int the temperature head of evaporator. Reaching the maximum cooling capacity, and thus the minimum cooling temperature of CG at a certain temperature head, is predetermined by the critical mode of bubble boiling of a cooling agent. A further increase in the temperature head with a growing consumption of reflux contributes to the establishment of the transitional regime of boiling. Such a mode is characterized by the appearance at the heated surface of "dry" plots, which leads to a decrease in the efficiency of the heat exchange surface and cooling capacity and to an increase in the temperature of CG cooling. We built dependences of the CG cooling temperature on the control action related to the consumption of reflux, which characterize the displacement of an extremum under conditions of changing the values for the coordinates of the perturbation vector.

2. We have defined the efficiency indicators of ammonia production, namely the consumption of natural gas under conditions of change in the control action related to the consumption of reflux and coordinates of the perturbation vector. It is established that the underestimation of the control action related to the consumption of reflux for such a large-ton production significantly affects the temperature of CG, and therefore the energy efficiency of production. It is shown that given the existing constraints and stabilization of reflux consumption, for example, at the level of 0.35 t/h, decreasing the concentration of a refrigerant at the inlet to the evaporator from 0.998 kg/kg to 0.994 kg/kg, would provide for an increase in the temperature of CG from the evaporator by 2.5 °C, and therefore an increase in the annual consumption of natural gas by 768 thousand nm^3. At the same time, increasing the control action related to the consumption of reflux to 0.8 t/h could decrease the temperature of CG from the evaporator only by 0.7 °C, which provides for a reduction in the annual consumption of natural gas by 553 thousand nm^3.

3. We have developed the algorithmic tools for minimizing the temperature of CG cooling and for numerical estimation of the optimal state vector. The use of a given algorithm contributes to solving the optimization problem by a gradient-free technique of the step type applying the methods of one-dimensional search for an extremum. Employing a given algorithm ensures the construction of subsystem for an optimal software control over low-temperature evaporators at absorption-refrigeration plants in a unit for secondary condensation in ammonia production.

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EXPERIMENTAL STUDY INTO OPTIMAL INTER-DEPENDENCE OF ENERGY-TIME COSTS FOR EMPTYING A DRY DOCK

P. Khristo
Specialist, Senior Lecturer
Department of Electromechanic systems with a computer control
Odessa National Polytechnic University
Shevchenka ave., 1, Odessa, Ukraine, 65044
E-mail: Pavel.John.Khristo@gmail.com

Оцінений вплив дискретних властивостей мікропроцесорної системи управління на основі Arduino Due на точність фізичної моделі докової насосної станції шляхом моделювання в MATLAB. При цьому враховувалися такі чинники, як період комутації ШІП, крок квантування по рівню і за часом АЦП і ЦАП мікропроцесора, час виконання програмного циклу, шум молодших розрядів АЦП, шум і інерційність датчика струму, а також відхилення параметрів ємнісних фільтрів, включених в канали зворотного зв'язку по напрузі, від номінальних значень, навантаження перетворювача і перепад напруги на клемах акумуляторної батареї.

За результатами розрахунків стало ясно, що цим впливом можна знехтувати і дані, зібрані за допомогою фізичної моделі докової насосної станції, є достовірними. Шляхом фізичного моделювання отримана експериментальна залежність між витратами енергії-часу на спорожнення камери сухого дока, яка підтверджує можливість значної економії енергії, коли процес оптимізується за відповідним критерієм. Це стало можливо завдяки багатократному чисельному рішенню крайової задачі безпосередньо на фізичній моделі. Знята характеристика свідчить про те, що при малих значеннях тривалості процесу спорожнення камери економія енергії, яка досягається за рахунок оптимального управління електроприводом насоса, відносно невелика в порівнянні з варіантом нерегульованого електроприводу. Проте при затягуванні процесу вона може досягати значень на рівні 13 %. Також звертає на себе увагу той факт, що починаючи з деякого значення часу спорожнення камери сухого дока, енергія вже практично не міняється, що робить раціональним введення неробочої паузи в закон оптимального управління об'єктом.

Таким чином, підтверджена можливість і доцільність оптимізації процесу спорожнення камер сухих (наповнення – наливних) доків за критерієм енергоспоживання дослідним шляхом

Ключові слова: Arduino Due, U4814, наливний, сухий док, насос, електропривод, оптимальне управління

1. Introduction

At shipbuilding and ship dock enterprises, which have dry or liquid dock-chambers, ensuring the optimal performance of main pumps of the dock pumping station is quite an urgent issue today. A key feature of working modes of pumping stations serving dry docks is a continuous and significant change in the level of fluid in the process of