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Method development for determining the energy-efficient mode of air-cooling devices' operation

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Abstract: When ensuring the normative limit of the heat of the gas transmitted to the main gas pipelines by means of air cooling devices of the gas transmission compressor station, the modes of parallel operation of the fan motors of the air cooling device system are considered. At the same time, a comparison was made of methods for adapting air cooling devices to factors affecting energy-efficient operating modes. As a result, based on a mathematical model of the combustion operating mode through a gas-air cooling device, the possibility of regulating the engine speed and increasing the energy efficiency of the system, taking into account seasonal and temperature changes, is shown. The main parameters for saving energy sources are introduced into the technological processes of gas compression and cooling.

1. Introduction

As a result of the decrease in the world's reserves of raw materials and fuel and energy, as well as the increase in the demand for energy resources, the tasks of rational use of energy and raw materials are becoming more and more important. These problems are very relevant in the energy resources transmission industry, because the most energy-intensive processes and technologies of energy resources are concentrated here, which directly affects the cost of gas.

Air cooling devices (ACD) system is of great importance in ensuring the standard limit of gas temperature in gas transmission compressor stations (CS). At the same time, adaptation to the factors affecting the energy-efficient operation modes of air cooling devices is the basis for choosing the optimal mode. By adjusting the speed of air-conditioning devices through frequency control, ensuring optimal operation in accordance with the temperature of the months of the year provides an opportunity to reduce electricity consumption [1].

Currently, as a result of changing the usual strategy of increasing hydrocarbon production of Uzbekistan, the main problem is to save natural energy resources. It turns out that there is almost certainly a way to mitigate future energy shortages. These are methods of development and implementation of modern energy-saving technologies and high-tech equipment.

The main way to increase the energy efficiency of air-conditioning devices is to replace the non-adjustable electric drive with the adjustable electric drive. At the same time, it is necessary to coordinate the operating modes of air cooling devices with technological requirements and changes, to choose the operating modes after fully studying the degree of dependence of the factors affecting the operating mode.

The biggest factor influencing the energy efficiency of air cooling devices is the heat exchange process. Using a mathematical model of the heat exchange process, it is important to find the transfer functions of the object in terms of the volume flow of the cooling air and the temperature of the gas and air at the entrance of the device. At the same time, adapting frequency converters to operating modes is an issue that requires an efficient solution.

The working structure of the fans in the air cooling system is shown in Figure 1 below. The temperature of the gas entering the main gas pipelines is controlled by increasing or decreasing the number of fans with the indications received from the control temperature sensors.

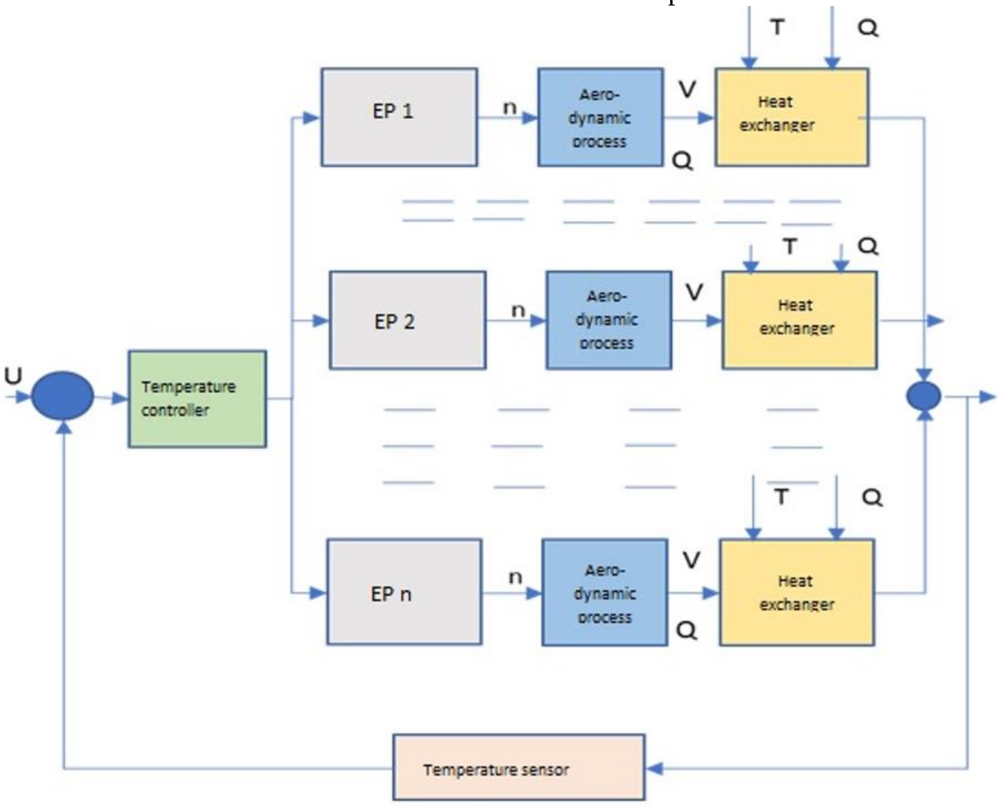

Figure 1. Parallel control system of ACD system [2]

Lowering the gas temperature allows you to increase the throughput of the pipeline and save fuel gas for the operation of gas pumping devices. Calculations carried out on air-cooling devices show that a decrease in the temperature of the transported gas by an average of 3°C increases the throughput of the cooling pipe by 1%. The process of cooling the transmitted gas increases the efficiency of the station and main gas pipelines [3].

2. Materials and methods

The algorithm for dividing the system of air conditioning devices into groups and achieving the possibility of controlling three groups at the same time using one frequency adjuster is presented in Figure 2 and in the formula (1) [4].

The group frequency control structure of fans of ACD system is described. This ensures that group 4 fan drives work in the high efficiency range.

One CS is installed for the remaining 3 groups. As a result of increased load, group 1 automatically switches to direct connection to the source. And group 2 is ensured to work in accordance with the load from low speed. And so the process continues. When the load approaches the maximum value, group 4 is removed from the optimal operation mode.

$$W_{ij} = \sum_{i=1}^{n} n_g \cdot P_{N.} \cdot cos\varphi \cdot \left(\frac{n_i}{n_{inom.}}\right)^3 \cdot t_i + \sum_{i=1}^{s} n_{gs} \cdot n_g \cdot P_{N.} \cdot cos\varphi \quad (1)$$

where, n_g- the number of fans in the group, n_{gs}- number of groups, P_N- fan motor power, t_i- fan operation time, n_i- motor speed, $n_{inom.}$- rated speed of the motor.

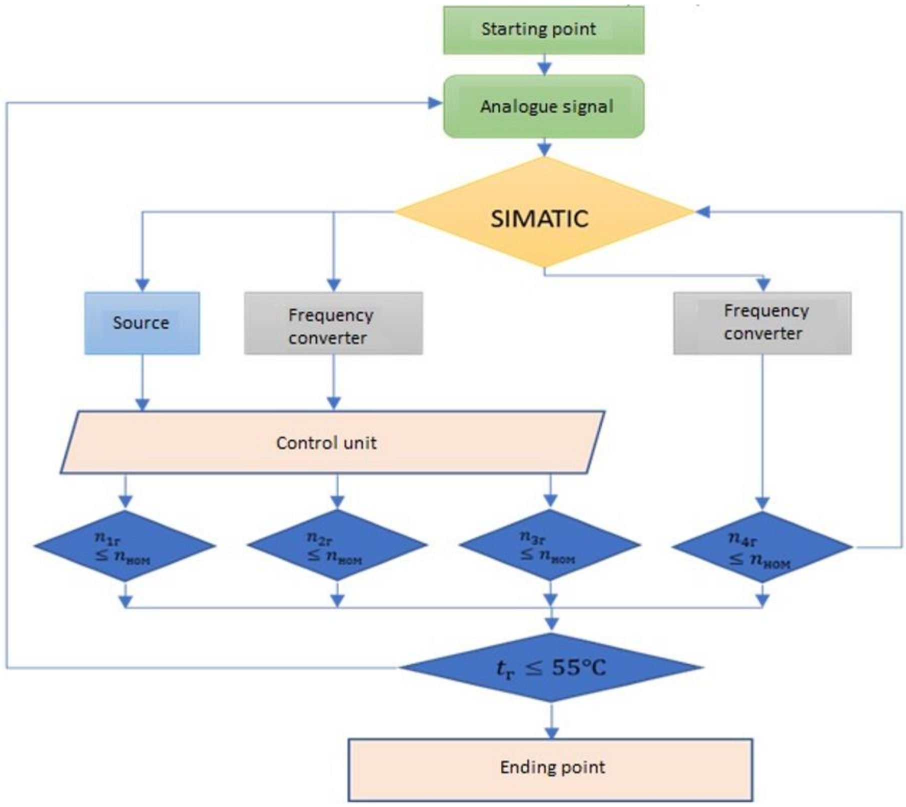

Figure 2. Management algorithm of ACDs

3. Results and Discussion

The variation of gas temperature up to ACD is presented in Figure 3.

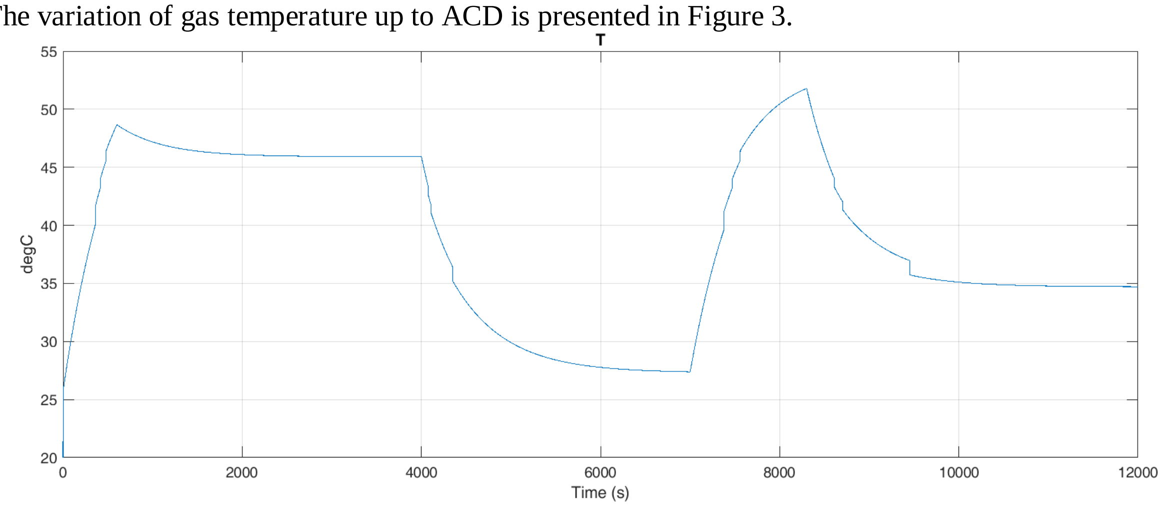

Figure 3. The temperature of the gas entering the ACD

The variation of the outlet temperature when the temperature of the gas entering the main gas pipelines is adjusted in the on-off operation mode relative to the inlet in Figure 3 is shown in the figure below (Figure 4).

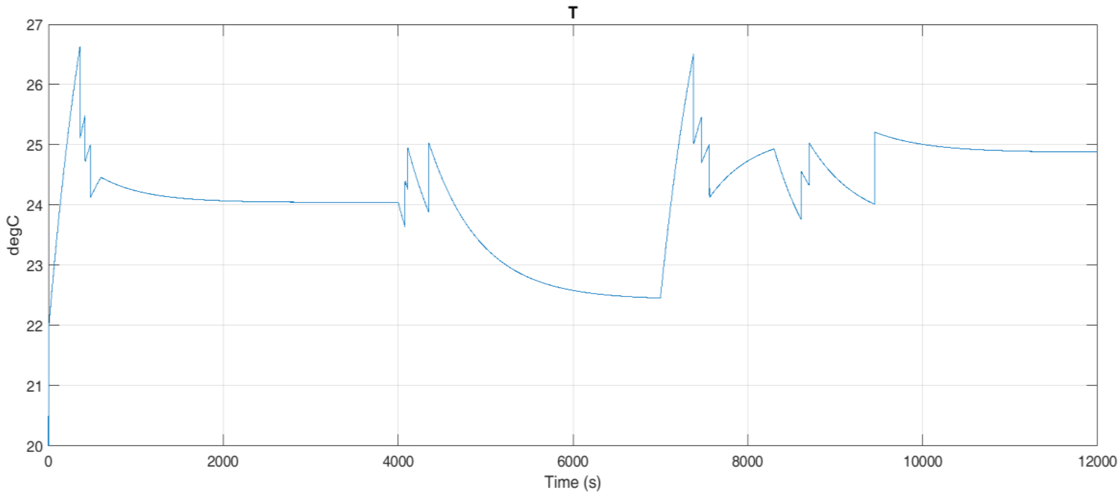

Figure 4. The temperature of the gas at the outlet of the ACD

Reducing the temperature of the gas transferred from the compressor station and stabilizing it reduces the intensity of corrosion processes of main gas pipelines. The uneven temperature of the gas entering the gas pipelines leads to an increase in the corrosion processes of the pipelines and, accordingly, to a shortening of the service life of the pipeline. In the case of no gas cooling, the gas temperature fluctuations are close to the outside air temperature fluctuations. Therefore, it is necessary not only to cool the gas after compression, but also to ensure that its temperature stabilizes with the required accuracy. In order to maintain temperature stability, it is necessary to adapt to changes in gas transfer and external temperature of the seasons. The change of the seasonal electricity consumption of the air conditioning system over the past years is presented in Figure 5.

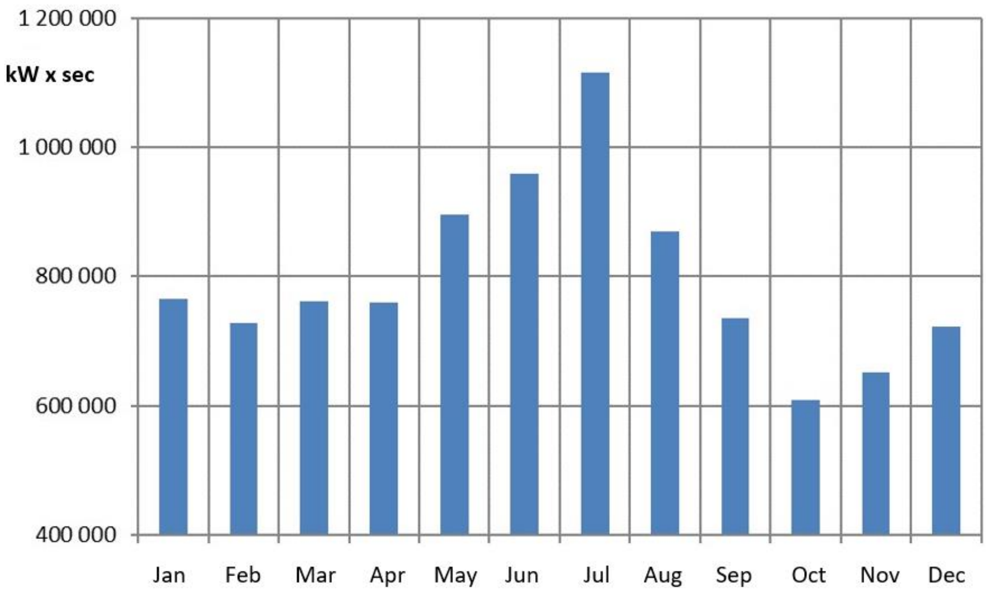

Figure 5. ACD electricity consumption

The gas cools the finned tube wall of the heat exchanger, which is cooled by a stream of cold air. In the mathematical description of heat transfer processes, the system of nonlinear Foure equations is often used and considered as a heat exchanger object with distributed parameters [5]. Nevertheless, since the ACD control system is equipped with a sensor that measures the average gas temperature at the outlet of the heater, it is important to know the temperature distribution along the radius and length of the pipe for the synthesis of the system. This conclusion allows us to consider the process of heat transfer in ACD as an object with concentrated parameters and use the laws of conservation of energy and heat balance in deriving transfer functions. Heat and mass transfer processes occurring in the heat exchanger are described by a system of nonlinear equations (2) [5].

$$\left.\begin{array}{c} G_g \cdot \rho_g \cdot \mathrm{C}_h \cdot \left(\mathrm{T}_{ch.g.} - \mathrm{T}_{k.g.}\right) + m_g \cdot \mathrm{C}_g \cdot \dfrac{dT_g}{dt} + \alpha_g \cdot F_{ich} \cdot \left(\mathrm{T}_g - \mathrm{T}_{tr}\right) = 0 \\ m_{tr} \cdot \mathrm{C}_{tr} \cdot \dfrac{dT_{tr}}{dt} - \alpha_g \cdot F_{ich} \cdot \left(\mathrm{T}_g - \mathrm{T}_{tr}\right) + \alpha_h \cdot F_{nar} \cdot (\mathrm{T}_{tr} - \mathrm{T}_h) = 0 \\ G_h \cdot \rho_h \cdot \mathrm{C}_h \cdot (\mathrm{T}_h - \mathrm{T}_{k.h.}) = \alpha_h \cdot F_{nar} \cdot (\mathrm{T}_{tr} - \mathrm{T}_h) \end{array}\right\} \tag{2}$$

where, G_g and G_h- gas and air flow rate; ρ_g and ρ_h- density of gas and air; C_g and C_h- specific heat capacity of gas and air; m_g and m_{tr}- gas and pipe mass; α_g and α_h- coefficient of heat transfer from gas and air to the wall of heat exchange pipes; F_{ich} and F_{nar}- internal and external heat exchange surfaces; T_g and T_h– average temperature at the outlet of gas and air cooling devices; $\mathrm{T}_{g.k.}$ and $\mathrm{T}_{h.k.}$- average values of gas and air temperature at the inlet of the air cooler; T_{tr}- average temperature of the heat exchange pipe; t- working time [6, 7].

The first and third equations in the expression reflect the law of conservation of gas and air heat fluxes, respectively. The second equation is the equation for the heat balance between the air supplied to the pipe and the exhaust gas accumulated in the heat exchanger material.

The main parameters affecting the efficiency of the ACD are the air flow G_h, the average gas and air temperature T_g and T_h at the outlet of the heat exchanger. The gas and air temperatures at the ACD inlet are $\mathrm{T}_{g.k.}$ and $\mathrm{T}_{h.k.}$, and the gas flow rate at the ACD inlet is G_g.

The first equation in expression 1 shows that the ACD heat exchange process has the property of nonlinearity. The main variables that cause nonlinearity are G_h and T_h, G_g and T_g parameters that cause nonlinearity. In order to bring the nonlinear quantities into a linear form in the implementation of the ACD control system, it is possible to take the heat exchange coefficient as a constant indicator as a result of determining a certain point in the coordinates of the heat exchanger, bringing the quantities G_g, G_{h0}, T_{h0} and $\mathrm{T}_{h.k0}$ into a linear form.

Then, passing to the equations in expression (2), separating the main nonlinearities into a series of Taylor equations and restricting to the first decomposition conditions, we get a system of linear equations describing the dynamics of the heat exchange process in the air cooling device (Eq. 3):

$$\left.\begin{array}{c} (G_g \cdot \rho_g \cdot \mathrm{C}_h + \alpha_g \cdot F_{ich}) \cdot \Delta\mathrm{T}_g - G_g \cdot \rho_g \cdot \mathrm{C}_g \cdot \Delta\mathrm{T}_{g.k.} + m_h \cdot \mathrm{C}_h \cdot \frac{dT_g}{dt} - \alpha_g \cdot F_{ich} \cdot \Delta\mathrm{T}_{tr} = 0 \\ m_{tr} \cdot \mathrm{C}_{tr} \cdot \frac{d\Delta T_{tr}}{dt} - \alpha_g \cdot F_{ich} \cdot \Delta\mathrm{T}_{ich} + \alpha_g \cdot F_{ich} \cdot \Delta\mathrm{T}_g + \alpha_h \cdot F_{tash} \cdot \Delta\mathrm{T}_{tr} - \alpha_h \cdot F_{tash} \cdot \Delta\mathrm{T}_{tr} = 0 \\ \Delta G_h \cdot \rho_h \cdot \mathrm{C}_h \cdot (\mathrm{T}_{k.h.} - \mathrm{T}_{k.h0}) + (G_{h0} \cdot \rho_h \cdot \mathrm{C}_h + \alpha_h \cdot F_{nar}) \cdot \Delta\mathrm{T}_h - G_{h0} \cdot \rho_h \cdot \mathrm{C}_h \cdot \Delta\mathrm{T}_{k.h0} = \alpha_h \cdot F_{nar} \cdot \Delta\mathrm{T}_{tr} \end{array}\right\} \tag{3}$$

When differentiating operations are replaced by the symbol $p = \frac{d}{dt}$, the expression (2) becomes the following operator (Eq. 4):

$$\left.\begin{array}{c} (m_g \cdot \mathrm{C}_h \cdot p + G_g \cdot \rho_g \cdot \mathrm{C}_g + \alpha_g \cdot F_{ich}) \cdot \Delta\mathrm{T}_g - G_g \cdot \rho_g \cdot \mathrm{C}_g \cdot \Delta\mathrm{T}_{g.k.} - \alpha_g \cdot F_{ich} \cdot \Delta\mathrm{T}_{tr} = 0 \\ (m_{tr} \cdot \mathrm{C}_{tr} \cdot p - \alpha_g \cdot F_{ich}) \cdot \Delta\mathrm{T}_{tr} + \alpha_g \cdot F_{ich} \cdot \Delta\mathrm{T}_g + \alpha_h \cdot F_{tash} \cdot \Delta\mathrm{T}_{tr} - \alpha_h \cdot F_{tash} \cdot \Delta\mathrm{T}_{tr} = 0 \\ \Delta G_h \cdot \rho_h \cdot \mathrm{C}_h \cdot (\mathrm{T}_{h0} - \mathrm{T}_{k.h0}) + (G_{h0} \cdot \rho_h \cdot \mathrm{C}_h + \alpha_h \cdot F_{nar}) \cdot \Delta\mathrm{T}_h - G_{h0} \cdot \rho_h \cdot \mathrm{C}_h \cdot \Delta\mathrm{T}_{k.h0} = \alpha_h \cdot F_{nar} \cdot \Delta\mathrm{T}_{tr} \end{array}\right\} \tag{4}$$

The obtained equations allow to find the transfer functions in relation to the effects of control and operation of the heat exchange process. When viewed as $\Delta\mathrm{T}_{k.h} = 0$ and $\Delta\mathrm{T}_{k.g} = 0$, equation (4) can be described as in expression (5):

$$\left.\begin{array}{c} (m_g \cdot \mathrm{C}_h \cdot p + G_h \cdot \rho_g \cdot \mathrm{C}_g + \alpha_g \cdot F_{ich}) \cdot \Delta\mathrm{T}_g - \alpha_g \cdot F_{ich} \cdot \Delta\mathrm{T}_{ich} = 0 \\ (m_{ich} \cdot \mathrm{C}_{ich} \cdot p - \alpha_g \cdot F_{ich}) \cdot \Delta\mathrm{T}_{ich} + \alpha_g \cdot F_{ich} \cdot \Delta\mathrm{T}_g + \alpha_h \cdot F_{tash} \cdot \Delta\mathrm{T}_{tr} - \alpha_h \cdot F_{tash} \cdot \Delta\mathrm{T}_{tr} = 0 \\ \Delta G_h \cdot \rho_h \cdot \mathrm{C}_h \cdot (\mathrm{T}_{h0} - \mathrm{T}_{k.h0}) + (G_{h0} \cdot \rho_h \cdot \mathrm{C}_h + \alpha_h \cdot F_{nar}) \cdot \Delta\mathrm{T}_h = \alpha_h \cdot F_{nar} \cdot \Delta\mathrm{T}_{tr} \end{array}\right\} \tag{5}$$

In expression (4), we find the section for Loplace transformations and $T_g(p) = L\{\Delta T_g\}$, $G_h(p) = L\{\Delta G_h\}$, the transfer function with respect to the control operation of the reciprocal exchange process (Eq. 6):

$$W_y(p) = \frac{T_g(p)}{G_h(p)} = \frac{k_G}{a_0 \cdot p^2 + a_1 \cdot p + 1} \tag{6}$$

The value of the parameters used in the calculation of the transfer function of the air cooling device is given below (Eq. 7, 8 and 9):

$$k_G = \frac{\frac{\alpha_g \cdot F_{ich} \cdot \alpha_h \cdot F_{tash} \cdot \rho_h \cdot C_h}{\rho_h \cdot C_h \cdot G_g + \alpha_h \cdot F_{tash}}(T_{ch.ho} - T_{k.ho})}{(G_g \cdot \rho_g \cdot C_g + \alpha_g \cdot F_{ich})\left(\alpha_g \cdot F_{ich} + \alpha_h \cdot F_{tash} - \frac{\alpha_h^2 \cdot F_{tash}^2}{G_{ho} \cdot \rho_h \cdot C_h + \alpha_h \cdot F_{tash}}\right) - \alpha_g^2 \cdot F_{ich}^2} \tag{7}$$

$$a_0 = \frac{m_g \cdot C_g \cdot m_{tr} \cdot C_{tr}}{(G_g \cdot \rho_g \cdot C_g + \alpha_g \cdot F_{ich})\left(\alpha_g \cdot F_{ich} + \alpha_h \cdot F_{tash} - \frac{\alpha_h^2 \cdot F_{tash}^2}{G_{h_0} \cdot \rho_h \cdot C_h + \alpha_h \cdot F_{tash}}\right) - \alpha_h^2 \cdot F_{ich}^2} \tag{8}$$

$$a_1 = \frac{m_g \cdot C_g\left(\alpha_g \cdot F_{ich} + \alpha_h \cdot F_{tash} - \frac{\alpha_h^2 \cdot F_{tash}^2}{G_{ho} \cdot \rho_h \cdot C_h + \alpha_h \cdot F_{tash}}\right) + m_{tr} \cdot C_{tr}(G_g \cdot \rho_g \cdot C_g + \alpha_g \cdot F_{ich})}{(G_g \cdot \rho_g \cdot C_g + \alpha_g \cdot F_{ich})\left(\alpha_g \cdot F_{ich} + \alpha_h \cdot F_{tash} - \frac{\alpha_h^2 \cdot F_{tash}^2}{G_{h_0} \cdot \rho_h \cdot C_h + \alpha_h \cdot F_{tash}}\right) - \alpha_h^2 \cdot F_{ich}^2} \tag{9}$$

The equation represents the coefficients of the transfer function, the generalized solution of the dynamic indicators of the cooling device is calculated. The analysis showed that, taking into account the range of parameters, it can be described in the following form.
By using the transmission functions of the ACD workflow control system, system sensing can be realized. When determining the transfer function coefficients, ACD is calculated taking into account the following parameters:

$G_g = 2{,}3366\,\frac{m^3}{s}$ - volume of gas transfer;
G_h=48,6 $\frac{m^3}{s}$ - volume of air transfer;
$\rho_g = 0{,}7158\ kg/m^3$ – gas density;
$\rho_h = 1{,}2754\ kg/m^3$ - air density;
$C_h = 1{,}007\ kJ/(kg \cdot K)$ - specific heat capacity of air;
$C_g = 1{,}7\ kJ/(kg \cdot K)$ - specific heat capacity of gas;
$m_g = 16{,}04\ g/mol$- mass of the gas;
$m_h = 28{,}98\ g/mol$- mass of air;
$\alpha_g = 6{,}5\ W/(M \cdot K)$- thermal conductivity of gas;
$\alpha_h = 11\ W/(M \cdot K)$- thermal conductivity of gas;
$F_{tash} = 83{,}6\,m^2$ - outer surface of the heat exchanger;
$F_{ich} = 4{,}2\,m^2$ - internal surface of the heat exchanger;
$T_{k.g.} = 62{,}5$ °C - inlet gas temperature;
$T_{k.g.} = 35$ °C - inlet air temperature;
$T_{ch.g.} = 52{,}5$ °C - outlet gas temperature;
$T_{ch.h.} = 48$ °C - outlet air temperature;
$m_g = 16{,}04\ g/mol$- mass of the gas;
$m_{tr} = 1215\ kg -$ mass of the tube;
F_{tash}=83,6 m^2 - outer surface of the heat exchanger;
F_{ich}=4,2 m^2 - inner surface of the heat exchanger.

Using the above values, the following calculation function is generated (Eq. 10):

$$W_y(p) = \frac{0{,}261}{9{,}75 \cdot p^2 + 841{,}679 \cdot p - 1}. \tag{10}$$

High accuracy results are obtained when electricity consumption is calculated using the calculation function. It is possible to achieve up to 35% savings in electric energy when choosing the optimal seasonal operating range through the calculation function, taking into account the heat exchange process in the cooling device.

4. Conclusions

In conclusion, the analysis of the mode of operation of the air drive by the fan showed that the most electricity consumption in gas-fired gas transmission compressor stations corresponds to ACDs (up to 75%), and that the use of the on-off system does not give a high result in adjusting the required temperature. As a result of the introduction of frequency adjusters to air-cooling devices, the stability of the gas outlet temperature is ensured. ACD has determined that it is possible to increase the efficiency of electricity by up to 35% of the seasonal indicators of electricity consumption.

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