Improving the efficiency of mine compressor units based on the improvement of their cooling system

Nabijon Abduazizov*,* Rustam *Juraev*[*], and *Dilshoda* Xatamova

Navoi State University of Mining and Technologies, Navoi, 210100, Uzbekistan

Abstract. Resource saving is one of the most important problems in the world, including for such an energy-intensive process as the operation of mining compressor units. In the mining industry, along with electrical energy, pneumatic energy or compressed air energy is widely used. Compressor units that generate this energy are the most energy-intensive equipment of the enterprise, the share of which in the balance of mining enterprises is 20-35%. The indicators of technological processes of mining enterprises depend on the level of perfection of compressor installations. Given the widespread use of compressed air, there is a need to reduce operating costs, based on the development of effective technical solutions in the production of compressed air in industrial enterprises The tasks associated with increasing the energy efficiency of the operation of compressor units have not been fully resolved.

1 Introduction

The share of electrical energy for the production of compressed air is about 20%, and in some cases reaches up to 90% of the total energy consumption for the production of a technological product. At metallurgical plants, about 5-10% of electricity is consumed for the production of compressed air, at machine-building enterprises up to 20%, and the mining industry consumes up to 30% [1].

The reduction in productivity and increase in the specific energy costs of mining compressor units is most affected by the cooling system of compressor units.

Improving the efficiency of reciprocating compressor units is possible on the basis of improving the cooling system. Since for reciprocating compressor units, energy losses due to undercooling are 20% [1].

The existing cooling system of compressor units has a number of significant drawbacks due to the peculiarities of their operation. The water used for cooling has a high salinity and various impurities, which impairs the operation of intermediate and end coolers.

An important factor affecting the operation of the cooling system of compressor units is climatic conditions. During the summer period, during the day, the air temperature reaches up to 40-45 ℃, which leads to an increase in the air temperature at the inlet to the compressor, as a result of which its performance decreases [2].

* Corresponding author: r.u.djuraev@yandex.ru

In addition, during the hot season, the operating cooling towers do not cool the circulating water to the required values, which also reduces the efficiency of the compressor unit as a whole.

2 Materials and methods

2.1 Investigation of the impact of compressed air-cooling quality on the efficiency of a compressor unit

One of the important factors affecting the efficient operation and performance of compressor units is air heating during the suction process. One of the important factors affecting the efficient operation and performance of compressor units is air heating during the suction process.

With an increase in intake air temperature, i.e. temperature of the beginning of compression, for 1 °C the work spent on compressing 1 kg of air increases by about 0.16%, and with an increase in intake air temperature by 6 °C - by 1%.

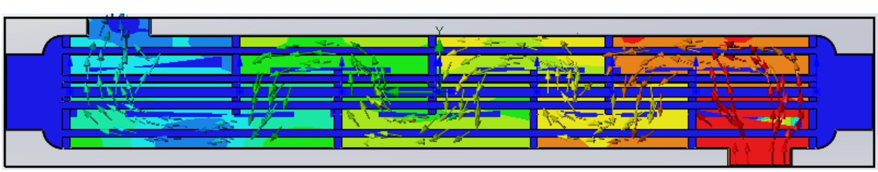
Another factor that negatively affects the efficient operation of compressors is the undercooling of air in the intercoolers of the piston compressor, increasing the temperature of the air leaving the intercooler of the piston compressor by every 6-8 °C leads to an excess consumption of electricity by 1% and a decrease in productivity by up to 5%.

The main cause of undercooling is poor-quality water, which causes scale deposits and contamination of the heat exchange surface of the coolers [3].

In order to determine the effect of the scale layer size on the efficiency of air cooling in the intermediate cooler of a reciprocating compressor, we conducted studies using the SOLIDWORKS FlowSimulation program.

The studies were carried out with compressed air temperatures tcom.air at the outlet of the cylinder 100°C, 110°C, 120°C, 130°C and 140°C. The cooling water temperature t1c.w. at the refrigerator inlet was 15°C, 20°C and 25°C, and the scale layer σnac gradually increased by 1 mm, from 1 mm to 5 mm.

Figure 1 shows some of the test results from the SOLIDWORKS FlowSimulation software.



$t_1 = 120°C; t_{1cw} = 20°C; \sigma_{nac} = 5\ mm$

Fig. 1. Test results obtained in the SOLIDWORKS FlowSimulation software to determine the effect of scale layer size on cooling efficiency.

Based on the results of studies to determine the effect of the size of the scale layer on the cooling efficiency, the dependences of the change in the temperature of the compressed air at the outlet of the intermediate cooler on the thickness of the scale layer at different temperatures of the cooling water were obtained.

Below in Figure 2 shows a graphical dependence of the change in the temperature of compressed air at the outlet of the intermediate cooler $t_{com.air}$ at an air temperature at the inlet t_{air}=120°C on the thickness of the scale layer σ at cooling water temperatures $t_{1c.w.}$ 15°C, 20°C and 25°C.

An increase in the thickness of the scale layer σ for every 1 mm leads to an increase in the temperature of the cooled air $t_{c.air}$ at the outlet of the refrigerator by an average of 5%.

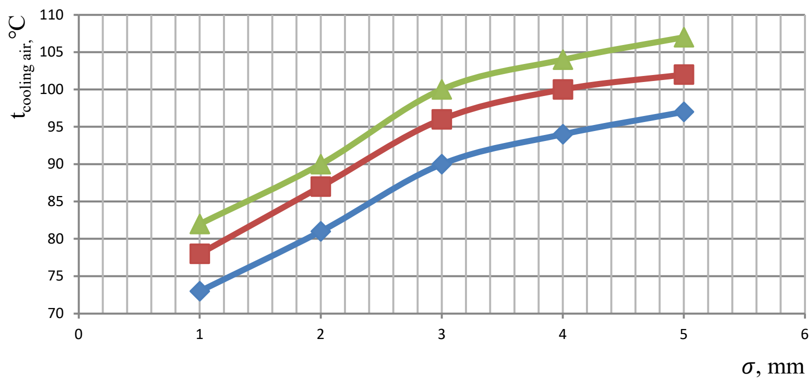


Fig. 2. Dependence of the temperature change of the compressed air at the outlet of the intermediate cooler $t_{c.air}$ at the air temperature at the inlet $t_{c.air}$ = 120℃ on the thickness of the scale layer σ at different temperatures of the cooling water $t_{c.w}$.

Since the atmospheric temperature reaches high values in the summer period, the efficiency of the cooling towers is much reduced; on hot days of the year, the cooling towers cannot cool the cooling circulating water to the set values. Thus, the efficiency of the compressor unit as a whole decrease, since the compressed air at elevated temperatures expands in volume and reduces the useful performance [4].

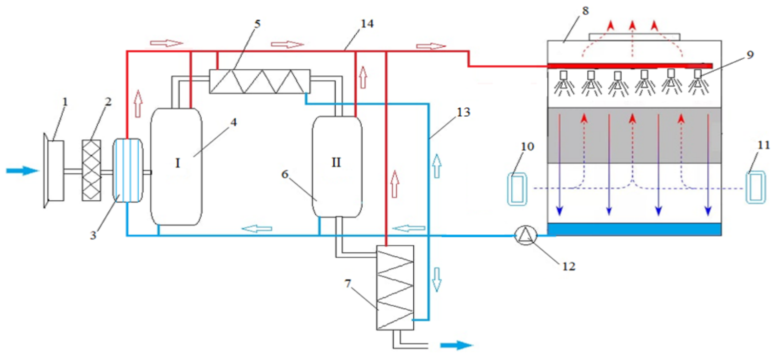
A study of the operation of cooling tower coolers shows that the main reason for the decrease in cooling efficiency is the poor performance of water spray (spray) devices.

2.2 Development of an effective technical solution for cooling the air sucked in by the compressor

It is obvious that a decrease in the temperature of the intake air leads to an increase in the weight capacity of the compressor, if it does not limit the drive power [5].

The air intake temperature of the compressor can be lowered in simple and cheap heat exchangers using cold water from a cooling tower, in which case an intake air cooler is installed before the compressor between the filter and the first compressor stage. The installation of coolers at the suction in front of the compressor creates additional hydraulic resistance to the movement of the intake air, which in turn leads to an increase in the energy costs of the unit's drive. In our proposed design of the cooler, the distance between the tubes through which the cooling water circulates is chosen in such a way that the created hydraulic resistance will not be significant [6].

Figure 3 shows a schematic view of an open-loop cooling system for a two-stage reciprocating compressor with a heat exchanger for artificially cooling the intake air.



1 - air intake, 2 - filter, 3 - air cooler before the compressor, 4 - first stage of the compressor, 5 - intermediate cooler, 6 - second stage of the compressor, 7 – aftercooler
8 - cooling tower, 9 - water spray, 10 and 11 - fans, 12 - pump, 13 - chilled water pipeline, 14 - heated water pipeline

Fig. 3. Scheme of an open-loop cooling system of a two-stage reciprocating compressor with a heat exchanger for artificial cooling of the intake air.

In the SOLIDWORKS FlowSimulation program, we studied the magnitude of the temperature decrease when artificially cooling the air drawn in by the compressor on the heat exchanger using cold water received from the cooling tower.

The studies were carried out for air temperatures at the cooler inlet t_l with the value of 25 °C, 30 °C, 35 °C, 40 °C, 45 °C and with cooling water temperatures received from the cooling tower $t_{c.w.}$ 5 °C, 10 °C, 15 °C, 20 °C and 25 °C.

Based on the results obtained using the SOLIDWORKS FlowSimulation program, a graphical dependence of the change in air temperature $t_{1c.a.}$ at the outlet of the cooler on the temperature of the cooling water $t_{1c.w}$, shown in Figure 4.

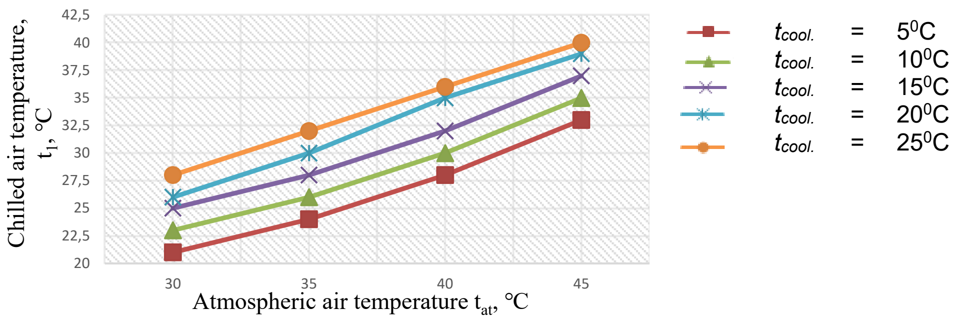


Fig. 4. Graphical dependence of the change in air temperature t_2 at the outlet of the cooler on the temperature of the cooling water t_c.

3 Results

The results of these studies show that the use of an intake air cooler before the compressor can reduce the temperature of the air entering the compressor cylinder by up to 10°C, depending on the temperature of the cooling water.

As a result of the regression analysis carried out on the basis of the experimental data shown in Figure 4, the dependence of the temperature of the cooled air when installing an artificial cooling device before it is supplied to the compressor on the ambient temperature was obtained:

$$t_{c.a.} = 0{,}8\, t_{at.} - a, \tag{1}$$

where a- is the change in temperature, °C.

The established regression dependence can be used to determine the temperature of artificially cooled air, before it is supplied to the first stage of the compressor, depending on the temperature of the cooling water $t_{c.w.}$ and on the ambient temperature t_a.

The actual specific work of multi-stage compression when using a device for artificial cooling of the air sucked in by the compressor is recommended to be determined by the formula:

$$L_c = \frac{k}{k-1} R(0{,}8\, t_a - a) \sum \left\{ (1 + \frac{\Delta T}{0{,}8\, t_{a.} - a}) \left[(\frac{P_k}{P_n - \Delta P_2})^{\frac{1}{\delta_1}} - 1 \right] \right\} \tag{2}$$

where k - the adiabatic exponent; R - is the gas constant of air; ΔT - air undercooling to the ambient temperature T_o in the apparatus before the second stage, *°C; P_k, P_n* - initial and final pressure in the second stage; ΔP_2 - pressure loss in the apparatus before the second stage;

$$\delta_1 = \frac{k\eta_{pol\,1}}{k-1}, \tag{3}$$

where $\eta_{pol\,1}$ - is the polytropic efficiency of the first section.

The indicator work of multi-stage compression when using a device for artificial cooling of the air sucked in by the compressor is determined by the formula:

$$\sum L_{ind} = \frac{P_1^{in} V_{on}}{\lambda_{\text{т}}} \frac{k}{k-1} \left[\varepsilon_1^{\frac{k-1}{k}} + \frac{T_{out}^1}{0{,}8\, t_{a.} - a} \left(\varepsilon_2^{\frac{k-1}{k}} - 1 \right) - 1 \right] \tag{4}$$

where P_1^{in} - air pressure at the suction before the first stage of compression, MPa; T_{out} - temperature at the outlet of the intercooler, °C; ε - pressure ratio of the first section; V_{vs} - intake air volume, m^3.

The isothermal efficiency of the compressor unit, taking into account the temperature of artificially cooled air, is recommended to be determined by the formula:

$$\eta_{iz} = \frac{L_{iz}}{L_c} = \frac{0{,}8\, t_{a.} - a}{t_{a.}} ln\pi_{\text{к}} \left[\frac{\psi_{\text{к}} k}{(k-1) \sum_1^n \left(\frac{\pi_1}{1-r_1}^{1/\delta_1} - 1 \right)} \right]^{-1} \tag{5}$$

where $\psi_{\text{к}}$ - the coefficient of reduced cooling losses, ψ_l=1.01÷1.12; $\pi_l=P_k/P_n$ is the ratio of stage pressures along the inlet and outlet sections; $r_l=\Delta P/P_n$ – relative pressure losses.

It should be emphasized, taking into account expression (1), that the decrease in temperature at the suction is significantly reduced by artificial cooling.

As a result, the air temperature at the end of the suction cylinder decreases, which leads to an increase in the actual performance of the compressor unit, which is recommended to be determined by the formula:

$$Q_p = V_{\text{p}}' \cdot \frac{P_1'}{P_1} \cdot \frac{0{,}8\, t_{atm.} - a}{T_1'}, \quad m^3/_h \tag{6}$$

where V_{p}' - the volume of air sucked in, m^3/h; P_1 and T_1 are the pressure and absolute air temperature in front of the compressor, respectively; P_1' and T_1' are, respectively, the pressure and absolute temperature of the air in the cylinder during suction.

One of the reasons for the decrease in the productivity of the compressor unit is the heating factor $\lambda_{\text{т}}$, the exact value of which has not been established due to the difficulty in determining the exact temperature T_1 at the beginning of suction.

Dependence (1) obtained by us as a result of experimental studies allows specifying the value of $\lambda_{\text{т}}$.

In order to form the necessary dispersity and spray angle, a design of a cascade nozzle has been developed. Guide fungi are installed on the nozzles, which ensure the swirling movement of water droplets and their effective crushing.

Figure 5 shows a general view of the developed nozzle design.

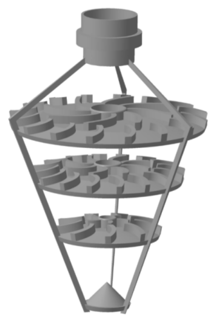


Fig. 5. General view of the developed design of the cascade nozzle.

The developed nozzle design was studied in the SOLIDWORKS Flow Simulation program. Figure 6 shows the results of studies obtained in the program for determining the speed and temperature of droplets at the outlet of the nozzle.

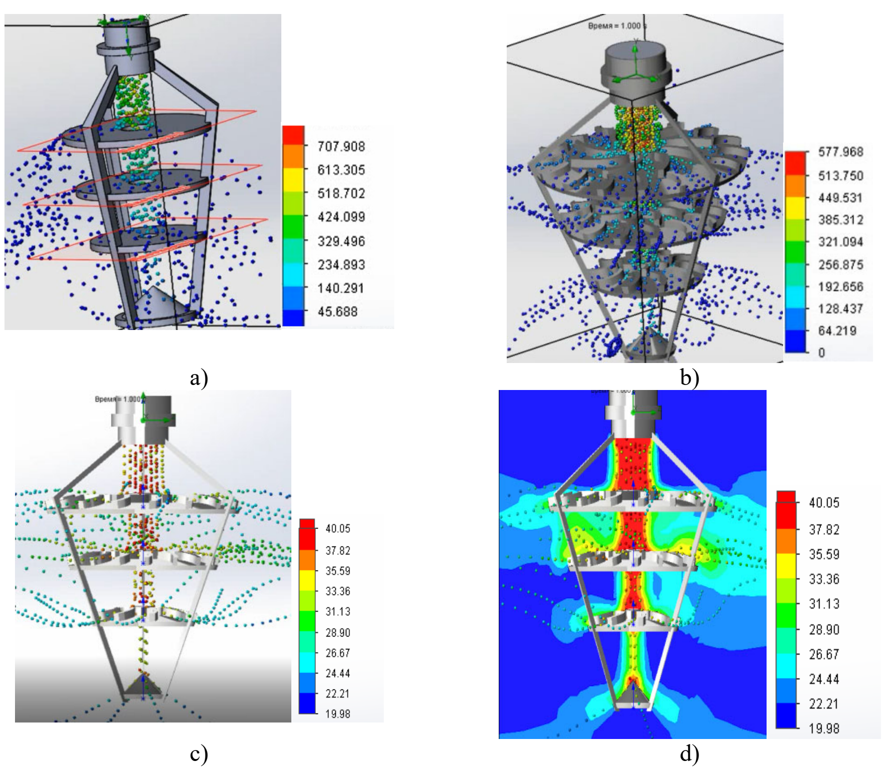


Fig. 6. The results of the study to determine the speed in the conventional (a) and in the developed design of the cascade nozzle (b), and the results of studies of the droplet temperature at the outlet of the developed nozzle (c and d).

The results of the studies performed, shown in Figure 6, show that the spray rate of drops at the outlet of a conventional cascade nozzle is 45.6 m/s. The droplet spray rate at the outlet of our developed cascade nozzle design is 64.2 m/s, thus, the proposed nozzle design helps to increase the spray rate of water droplets by 18.6 m/s (40%), which leads to effective water cooling.

The prevention of scale formation is possible due to the electromagnetic treatment of the circulating cooling water.

We have developed an installation for electromagnetic treatment of circulating water in laboratory conditions.

In order to determine the effectiveness of the developed plant for electromagnetic treatment of circulating water, we conducted experimental tests.

The main objective of the experimental work was to establish the dependence of the formation of a layer of scale on the surface of a metal pipe on the temperature of the circulating water, with and without the use of a device for electromagnetic water treatment.

Based on the results of experimental work, the dependence of the thickness of scale formation on the duration of operation of the intermediate and aftercoolers of the reciprocating compressor was established at different temperatures of the cooling water with an average hardness of 20 °J (Ca-12 mg/l; Mg-8 mg/l) (Figure 7 and Figure 8).

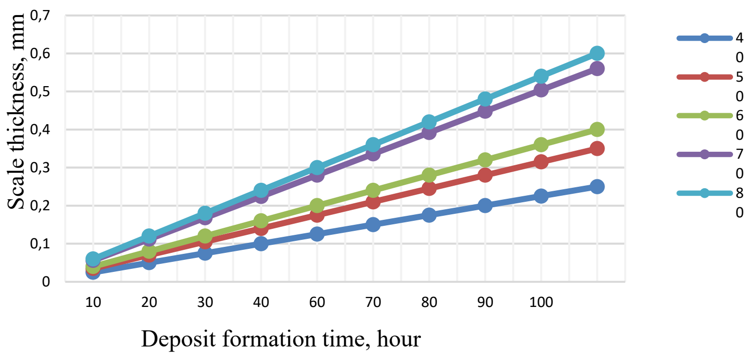


Fig. 7. Graphical dependence of the scale thickness on the operating time of coolers without the use of a device for electromagnetic water treatment at various temperatures of the cooling water.

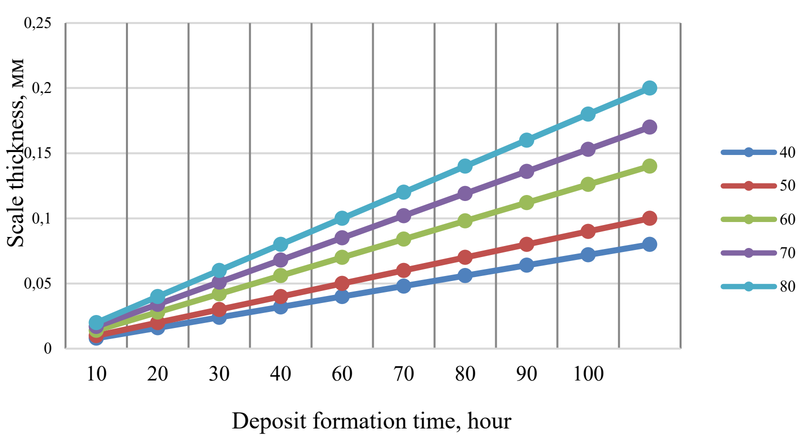
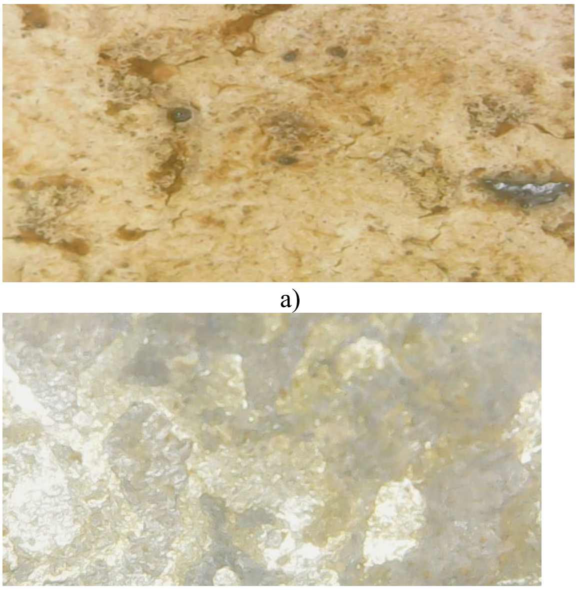


Fig. 8. Graphic dependence of the scale thickness on the operating timeof coolers using a device for electromagnetic water treatment at different temperatures of the cooling water.

From the graphs shown in Figure 7 and Figure 8, it is observed that the electromagnetic treatment of circulating water helps to reduce the formation of scale on metal surfaces by an average of 70-80%.

Figure 9 shows a microscopic photograph of the metal pipe wall after the completion of the experimental work. An analysis of the microscopic photographs taken shows that the use of electromagnetic treatment reduces the formation of a layer of scale on the walls of a metal pipe.



a)

b)

a) operation of the pipe without the use of a device for electromagnetic water treatment, b) with the use of a device for electromagnetic water treatment

Fig. 9. Microscopic photograph of the wall of a metal pipe.

As it can be seen, the scale layer on the wall of the metal pipe, shown in Figure 9a, is much thicker than the layer shown in Figure 9b.

Thus, the use of a device for electromagnetic water treatment helps to reduce the formation of scale on the surfaces of heat exchangers.

In cooling towers, part of the cooling water is lost due to droplet entrainment and evaporation, water losses are compensated by make-up (additional) water. In some cases, the total loss of water in cooling towers is 20-30% per day.

During the operation of the circulating system, due to the evaporation of part of the water, there is a gradual increase in the concentration of salts dissolved in water, as well as due to the constant addition of make-up water.

One of the optimal solutions to prevent the formation of scale on the surfaces of heat exchangers of compressor units is, initially, the use of filtered water as circulating water. But at the same time, there is a need for constant filtration, added make-up water.

In order to effectively filter the added make-up water to the cooling system, we have developed a device for softening the make-up water of the cooling system of compressor units. The basis of the make-up water softener is a filter containing filter material.

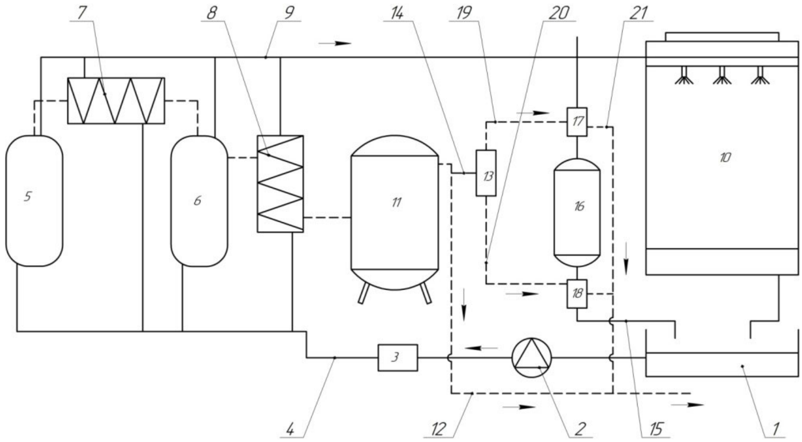
A bentonite-coal sorbent made from local raw materials was used as a filter material, which can be repeatedly regenerated up to 7-8 times. After regeneration, the carbon sorbent does not lose its original properties.

In the process of experimental testing of the developed filter, it was revealed that the efficiency of water purification is higher at high temperatures of filtered water. When the water temperature is 50-55°C passing through the filter, the purification efficiency reaches 90-92%.

Therefore, at the inlet to the filter, the water is heated in the water heater and at the outlet of the filter, the water is cooled back, a heat exchanger is used as a heater and cooler.

Heating and cooling of make-up water requires significant energy costs, in order to reduce energy losses, heating and cooling of water is carried out by a vortex tube. The principle of operation of a vortex tube is based on the effect of vortex temperature separation of air.

Figure 10 shows a general view of the cooling system of compressor units when a make-up water softener is installed in it.



1 - sump, 2 - pump, 3 - electromagnetic water treatment apparatus, 4 - cooling water pipeline, 5 - first compressor stage, 6 - second compressor stage, 7 - intermediate cooler, 8 - aftercooler, 9 - heated water pipeline, 10 - cooling tower, 11 - compressor receiver, 12 - pipeline for supplying compressed air to the consumer, 13 - vortex tube, 14 - pipeline, 15 - make-up water pipeline, 16 - filter, 17 - water heater, 18 - water cooler, 19 - pipeline hot air flow, 20 - cold air flow pipeline, 21 – pipeline

Fig. 10. General schematic view of the cooling system of compressor units after installation of a make-up water softener.

In order to determine the effectiveness of the developed device for softening the make-up water of the cooling systems of compressor units, experimental tests were carried out.

Based on the results of experimental studies of the developed make-up water softening device, the dependence of the decrease in the total hardness of the softened water on its temperature has been established.

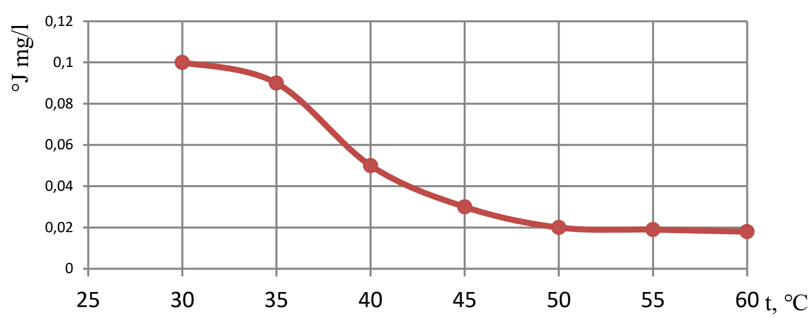


Fig. 11. Graph of the dependence of the change in the total hardness of softened water °J on its temperature *t*.

Figure 11 shows the dependence of the decrease in the total hardness of softened water °J on its temperature t.

The results of experimental studies, shown graphically in Figure 11, show that the highest efficiency of water softening is achieved at water temperatures of 50-60 °C.

When softening water with a total hardness of 0.21°J mg/l and a temperature of 30 °C, at the outlet of the filter, the total hardness of softened water was 0.1°J mg/l. As the water temperature increased, a decrease in hardness was observed, and when the water temperature increased to 50 °C, the total hardness of the water at the outlet of the make-up water softener decreased to 0.02°F mg/l. The efficiency of water purification in the device was 92-93%.

4 Conclusion

On the basis of the research conducted on the topic of the article, the following conclusions are obtained, which have theoretical and practical significance:

- the dependence of the change in the temperature of the compressed air at the outlet of the intermediate cooler of the multistage compressor on the thickness of the scale layer and the temperature of the cooling water has been established, which makes it possible to determine the decrease in the efficiency of cooling the air entering the next stage of the compressor;
- a device has been developed for cooling the air sucked in by the compressor, which makes it possible to increase the efficiency and productivity of the compressor without increasing the drive power;
- a mathematical model of the working processes of a reciprocating compressor with the use of a device for cooling the intake air is proposed, which makes it possible to determine the efficiency and actual performance of the installation;
- a device for electromagnetic treatment of circulating water has been developed, which makes it possible to reduce the intensity of scale formation on the surfaces of the intermediate and aftercooler of the reciprocating compressor air by 80%;
- a new design of the water spray nozzle of the cooling tower is proposed, which allows to increase the rate of spraying of water drops by 40% due to the effect of secondary crushing of the drop, as a result of which the efficiency of water cooling is achieved;
- the empirical dependence of the change in the thickness of the layer of deposits on the surfaces of intermediate and aftercoolers from the time of operation at various water temperatures with and without the use of a device for electromagnetic water treatment has been established;
- a device for softening the make-up water of the cooling system of compressor units has been developed, which makes it possible to reduce the formation of scale on the heat exchange surfaces of the intermediate and aftercoolers of the compressor;
- the experimental dependence of the change in the total hardness of water on its temperature in the developed device for softening the circulating water of the cooling system of compressor units was established, the efficiency of water purification in the developed device is achieved at water temperatures above 50 °C, while the total hardness is reduced by 93%;
- the use of a vortex tube, the principle of operation of which is based on the effect of vortex temperature separation of air for heating and cooling make-up water in a device for softening make-up water of the cooling system of compressor units, makes it possible to reduce energy costs for heating and cooling water.

As a result of the introduction of an electromagnetic water treatment device, a device for softening the make-up water of the cooling system of compressor units and a device for cooling the air sucked in by the compressor, an economic effect of 20,000,000 (twenty million) soums was obtained for the operation of one 2VM10-63/10 compressor per year.

References

1. A.G. Stapel, Klepzig Fachderichte **3,** 145-146 (1972)
2. D.N. Khatamova, N.A. Abduazizov, R.U. Juraev, Innovative technologies **1**, 55-77 (2021)
3. R.U. Juraev, M.V. Merkulov, V.A. Kosyanov, A.M. Limitovsky, Mining Journal **12**, 71-73 (2020)
4. M.V. Merkulov, R.U. Djuraev, O.B. Leontyeva, G.Y. Makarova, Y.B. Tarasova, IJETER **8**, 4383-4389 (2020)
5. R.U. Juraev, B.Kh. Shomurodov, D.N. Khatamova, Yu.F. Tagirova, *Modernization of the cooling system for reciprocating compressor units,* Proceedings of the IX International Scientific and Technical Conference on the topic «Achievements, problems and modern trends in the development of the mining and metallurgical complex», Navoi (2017)
6. D.N. Khatamova, N.A. Abduazizov, R.U. Juraev, Mining Bulletin of Uzbekistan **4**, 91-94 (2021)