KAPITEL 4 / *CHAPTER 4* [4]

JUSTIFICATION OF HYDRAULIC MINE AIR CONDITIONER FOR DEEP MINES

DOI: 10.30890/2709-2313.2023-18-03-017

Introduction

Coal in the energy sector of many countries of the world is an important natural resource. Due to the depletion of shallow coal deposits, most mines will reach development horizons of 2 thousand meters by 2030, where the temperature of the rocks will exceed 50^0C. In addition, intensive mechanization of coal mining leads to dusting of the mine air and an additional influx of heat, from which the air heats up above 400C. If the mine air is not cooled to a sanitary standard temperature of 26^0C and not cleaned of dust, this will lead to occupational diseases of miners.

Unfortunately, until now there is not enough scientific and technical developments to solve the problems of labor protection in deep mines in terms of the quality of mine air. The existing systems of centralized main ventilation of mines, due to the depth and length of mine workings, do not provide the necessary air quality in working faces. This requires the creation of efficient mobile mine air conditioning equipment for miners' workplaces. This is evidenced by the results of the analysis of information sources, both domestic and foreign resources on this research topic. Along with certain practical successes achieved in the fight against dust by water irrigation, the problem of effective air cooling in mine workings remains. In this regard, it becomes necessary to theoretically describe such a complex irrigation process, in which the mine air is simultaneously purified and cooled by water, i.e. its hydraulic conditioning. To do this, it is necessary to substantiate and develop devices for creating a complex process of dedusting and cooling mine air with water during their contact interaction.

Preliminary studies have shown that the problem of joint dedusting and cooling of mine air must be solved based on the use of hydraulic effects of pulsed wave flows with mass transfer thermodynamics between the components. It has been established that by using water with an initial temperature of 0^0C to 20^0C in special ejectors, it is possible to create a unit-capacity hydraulic air conditioner module, on the basis of which to develop a series of local air conditioners with the required thermal capacity. In this direction, a modular layout of a mine air conditioner is proposed for local areas of workplaces in deep coal mines, for example, faces, with a unit power of 10 kW, which requires justifying the parameters and schemes of the module of such an

---

[4] ***Authors:*** *Gogo Vladimir Beilovich, Chernykh Nadezhda Sergeevna*

air conditioner.

It is assumed that based on the study of the patterns of water fragmentation into drops in the air conditioner and the impact of drops on dusty warm air, the functional and parametric characteristics necessary to create a hydraulic air conditioner module will be obtained.

The urgency of the above has formed the scientific problem of substantiating the principle of operation of the hydraulic air conditioner module, as the basis for the design of a universal tool for improving the quality of mine air in terms of dust and temperature factors to ensure the requirements of labor protection for miners in deep mines.

4.1. Analysis of information sources and the scientific essence of the problem

Based on the analysis of scientific sources of information on this topic, it was concluded that the main means of mine air conditioning in mines are powerful (more than 100 kW) and expensive air conditioners. In [1], the emphasis is placed on the fact that the cooling of mine air due to the main ventilation of the mine leaves the issue of air conditioning in dead-end local zones of mine workings unresolved, where it is difficult to ensure the movement of ventilation flows. This is also the subject of work [2], which proposes to carry out aero logical control of ventilation in mine workings in order to ensure the required air quality. But it is difficult to do this because of the objective difficulties associated with a large long mine workings, in which the speed of air movement decreases. Therefore, in [3] for the normalization of the quality of mine mine air, district air conditioners are proposed. However, in this case, there are difficulties associated with their location in the limited space of workings. The air conditioners available at the mines have large dimensions and capacities, and the serial production of small dimensions with a power of up to 10 kW is not profitable for the manufacturer. An option to overcome these difficulties could be air conditioners built according to the schemes proposed in [4] and [5], but their proposals are difficult to implement in a mine due to the high operating pressure in air conditioners and the specific refrigerants used. A possible solution to the problem is proposed in the study [6], where schemes of low-pressure nozzle air sprinklers are recommended to normalize thermal conditions in underground workings. However, there are difficulties of such open air conditioning associated with humidification of the air in the working, broken rock masses and equipment. As a conclusion, work [7] emphasizes that the solution to the problem of air conditioning in mines depends on the conditions and type of installations used, as well as the cooling processes being implemented, which is especially important for local conditions.

Therefore, the scientific essence of the problem being solved lies in a well-reasoned complex integration of the processes of cooling and purification of mine air in one hydraulic air conditioner. At the same time, it is necessary to resolve issues related to the justification of the scheme and layout of such an air conditioner for the local conditions of mines, which gives grounds for concretizing the problem, for which the solution will be directed only to the justification of a hydraulic air conditioner module with an energy capacity of up to 10 kW, autonomous in operation under the specific conditions of deep mines.

4.2. Purpose and tasks of the study

The purpose of the study is to substantiate the characteristics and layout of the hydraulic air conditioner module with an energy capacity of up to 10 kW, as the basis for the development of an integrated means of cooling and cleaning mine air in local areas of deep coal mines.

Achieving the goal required completing the following tasks: substantiate the mathematical model and conduct experimental studies of the hydraulic air conditioner module; to argue the features of the development of an autonomous hydraulic air conditioner of the required power on the basis of the proposed modules for the conditions of deep coal mines.

4.3. Research methods

The general research methodology is based on a systematic approach to the analysis of processes occurring in a hydraulic conditioner. The model of contact interaction of drops, dust and heat transfer in a flow during joint cleaning and cooling is analyzed analytically. A complex computer simulation of the processes under study was applied based on the principles of hydromechanics and thermodynamics. To clarify the theoretical dependencies, experimental studies were carried out on laboratory facilities using standard measuring equipment.

Processing of research data by methods of mathematical statistics and the theory of stochastic processes was carried out to generalize ideas about the laws of mine air cooling and dust trapping by water drops in the hydraulic air conditioner module.

4.4. Results of the study on the substantiation of the characteristics and layout of the hydraulic conditioner module

At the stage of preliminary studies to determine the conditions of air conditioning with drop water and the formation of a physical and mathematical model of the process, a study was made of the dynamics of a mixed flow of drops, dust and air. Based on changes in the structures of airborne dust flows obtained from high-speed video frames and processed by a computer program, the fractality of the mixture of drops, dust and air in the studied volume was determined.

To substantiate the mathematical model and subsequent analytical study of hydraulic air conditioning, computer processing of high-speed film frames of a dusty air-droplet flow with a temperature of 40C was carried out. This made it possible to substantiate its physical and mathematical model in the form of a fractal structure, which was traced in successive images. Such a composition of the mixture of droplets and dust in the air flow made it possible to mathematically describe the transitions of the states of the "warm air - droplets - dust" system into the "cooled air - droplets - dust" system. The transition is adequate to the process of hydraulic air conditioning, i.e. cooling and dust removal.

In the model compositions of fractals, random fluctuations in the flow were taken into account according to the “freeze frame”. The fractal structuring of the flow made it possible to obtain an analytical expression for determining the limiting mass of a water drop (M), which is capable of absorbing dust particles in this form:

$$M = m_0 \left(\sum_{i}^{N} 2^i k_S^{(N+2)-1} + (2^N - 1)(k_S^2 + 1) + 1 \right), \tag{1}$$

where k is the mass factor for the i-th merge step;

N is the number of steps (merges);

m_0 is the initial mass of a water drop.

The investigated fractal of the structure of the dust-droplet air flow is assumed to be binary, so one drop can capture only one or two dust particles without violating the fractal structure of the flow.

In the developed mathematical model of the capture of a dust grain by a drop, it was assumed that the penetration of a dust grain into a drop occurs with impulsive wave movement due to pressure fluctuations in the flow. In it, the own vibrations of drops and dust particles did not affect each other. At the same time, we believe that the processes of their merging depend on pressure fluctuations in the mixture along the flow length in the air conditioner chamber.

In describing the dynamics of interaction between a drop and a dust particle, the analytical relationship of the main parameters of the generalized flow component is used, which takes into account the frequencies of natural oscillations and the wave nature of their movements in space in the following form:

$$\frac{d^2x}{dt^2}+\gamma\frac{dx}{dt}=0; \tag{2}$$

$$\frac{d^2x}{dt^2}+\gamma\frac{dx}{dt}+\omega_0^2x=0, \tag{3}$$

where *x* is the coordinate of the movement of the component (dust and drops) along the *x* axis;

γ is the coefficient of proportionality, which is formed by the parameters of two bodies (dust and drops) and flow characteristics;

ω_0 is the natural cyclic oscillation frequency of the flow component.

The solution to equation (3) is the expression:

$$x(t)=x_0e^{-\varepsilon t}\left(\frac{1}{\omega}(1+\varepsilon)\sin\omega t+\cos\omega t\right). \tag{4}$$

An analysis of equation (4) makes it possible to determine that with weak oscillations of the flow particles, the exponential exponent *(εt)* can be considered constant during one cycle of oscillations.

Under this assumption, the second term in equation (4) can be ignored, and then the total energy of the component is:

$$E(t)=E_0e^{-\gamma t}, \tag{5}$$

where *E(t)* is the total energy of the component in the wave process (the sum of the kinetic and potential energies of the drop and dust) for a given moment of time;

E_0 is the initial energy of the component.

Therefore, the total energy of the component in the wave process will be:

$$E(t)=\frac{m}{2}\left[\left(\frac{dx}{dt}\right)^2+\omega_0^2x^2\right], \tag{6}$$

where *m* is the mass of the flow component (droplets and dust).

The initial energy of the flux component is given by:

$$E_0=\frac{m}{4}(\omega^2+\omega_0^2)(c_1^2+c_2^2), \tag{7}$$

where *ω* is the cyclic oscillation frequency of the flow component; c_1 and c_2 are constants.

Given that *ω = 2πν*, then the oscillation frequency of the component will be equal to:

$$v = v_0 e^{\frac{-\gamma d_0}{V}}, \tag{8}$$

where d_0 is the diameter of the component before collision with other components; V is the linear velocity of the component (equal to the flow velocity).

The fractal distribution of the components along the flow is shown in fig. 1.

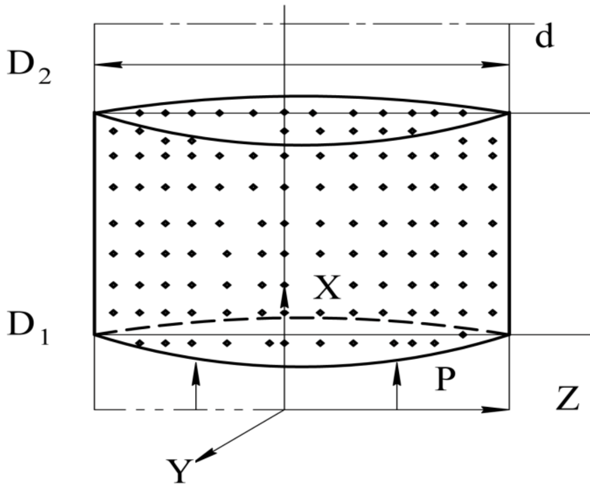

Figure 1– Scheme of the fractal volumetric distribution of flow components with a two-dimensional wave disturbance

We accept the condition that first a two-dimensional wave disturbance is created in the flow in the form of a pressure pulse P in the flow.

Boundary conditions of perturbation in the studied flow volume:

$$\tilde{o}(t_0) = \tilde{o}_0; \qquad P_0 = P(t_0, x_0),$$

where t_0 is the time of the pulse counting start along the coordinate (x); P0 is the initial pressure.

We accept that the flow is ideal and in Lagrangian variables it is characterized by a system of equations in a reduced form:

$$\frac{\partial P_{\text{æ}}}{\partial t} = \frac{C_{\text{æ}}\,\rho_{\text{æ}}\,T_{\text{æ}}}{1-\alpha_{\tilde{A}}}\left[\frac{3\alpha_{\tilde{A}}}{\alpha_{\text{æ}}}w + \left(\frac{\alpha_{\tilde{A}}}{J} + \frac{\rho_{\text{æ}}}{J^2\rho_{\text{æ}\,0}}\right)\frac{\partial J}{\partial t}\right]; \tag{9}$$

$$w_A = \frac{P_{\tilde{A}} - P_{\text{æ}}}{T_{\text{æ}}\,\rho_{\text{æ}}\,C_{\text{æ}}\sqrt[3]{\alpha_{\tilde{A}}}}w_R; \tag{10}$$

$$\frac{\partial w_R}{\partial t} = \frac{1}{a}\left(\frac{P_{\tilde{A}} - P_{\text{æ}}}{\rho_{\text{æ}}} - 1{,}5\alpha_{\tilde{A}}w_R^2 - 4v_{\text{æ}}\frac{w_R}{\alpha_{\text{æ}}}\right), \tag{11}$$

where ρ is the density of the flow mixture; P_A is the pressure in the flow; ω is the radial velocity of drops; J is the Jacobean of the transition from Lagrangian to Euler variables; C is the specific heat capacity of the liquid; a is the average radius of the phase region; α is the relative volumetric content of phases; g is the liquid index; G is the gas index.

The solution of heat transfer equations gives an analytical dependence for finding the final air (gas) temperature at the outlet of the air conditioner in the following form:

$$T_{\Gamma} = T_0 - \frac{1}{C_p}\left\{\frac{V_{\Gamma}^2}{2} + \frac{\varepsilon}{1-\varepsilon}\int_0^{\infty}[CT(m) - CT_0 + \frac{V^2(m)}{2}]g(m)dm\right\}. \qquad (12)$$

The system of equations (9-12) and the equation is solved by numerical methods in software implementation, for example, MathCAD, and gives an illustration of the effects of non-linearity of parameters, in particular, the evolution of a pressure wave impulse in a flow in the following form:

$$P(t,x) = P_0 - P^* \exp(-\varepsilon), \qquad (13)$$

where P_0 is the initial pressure (in the initial section); $P*$ is the amplitude of the pressure pulse; - indicator of the duration of the impulse, equal to:

$$\varepsilon = \left(t - 0{,}5t^*\right)t_0^{-1}, \qquad (14)$$

where t is coordinate time; $t*$ is the duration of the current pulse; t_0 is the characteristic duration of the initial pulse.

The equations (2 - 8) of the pulse-wave state of drops and dust particles in the air flow reflect the condition that the instantaneous effective radii of drops in the process of their action on particles - dust particles should change according to the accepted dependence:

$$R_k(t) = R_{k0} + \Delta_k f(t); \qquad \Delta_k (R_{k0})^{-1} << 1, \qquad (15)$$

where $R_k\ (t)$ is the instantaneous droplet radius; R_{k0} is the unperturbed radius of the drop; Δ_k is the drop fluctuation amplitude in the effective volume of the flow component; $f(t)$ is the droplet pulsation function, which depends on time.

Of interest for research is the system of equations for the pulse-wave motion of a drop with a trapped dust grain relative to the flow axis, taking into account the pulsation amplitudes, therefore, with an accuracy of the second order of smallness, we can write the system of equations:

$$\begin{cases} \dfrac{dV_k}{dt} = 2(\dot{V}_{\tilde{A}} - g) - \dot{V}_k[\dfrac{9\eta}{R_{k0}^2\rho_{æ}}(1 - \dfrac{2\Delta_k}{R_{k0}} + \dfrac{3\Delta_k}{R_{k0}^2}) + \dfrac{3}{R_{k0}}\Delta_k(1 - \dfrac{\Delta_k}{R_{k0}})], \\ \ddot{\Delta}_k + \omega_k^2\Delta_k = \chi_k(\Delta_k, \dot{\Delta}_k, V_k \ldots), \end{cases} \qquad (16)$$

where V_k is the rate of translational motion of the drop; V_G - gas-air flow velocity; g is the acceleration of gravity; $\rho_{æ}$ is the liquid density of the drop; η is the dynamic coefficient of fluid viscosity; ω_k is the cyclic frequency of pressure fluctuations in the flow.

It is natural that during the pulse-wave motion of the flow components, regions arise in it, in which drops and dust particles also move opposite to the direction of the main movement. This is an important effect for trapping dust particles with droplets and cooling the air in the air conditioner, as this increases the frequency of collisions between droplets and dust particles, as well as the time that droplets act on warm air to cool it. On this basis, it is legitimate to accept that, using (16), we obtain the cyclic pulsation frequency:

$$\omega = \left\{ \left(R_{\acute{A}\hat{I}}^2 - R_{MO}^2\right)^{-1} \left[3Ag(n_{\acute{A}} - n_M) + \frac{2\sigma[R_{MO}(3n_{\acute{A}} - 1) + R_{\acute{A}\hat{I}}(1 - 3n_M)]}{\rho_{æ} R_{\acute{A}\hat{I}} R_{MO}} \right] \right\}^{1/2}. \quad (17)$$

,

where ω is the cyclic frequency of pulsations in the flow; $R_{\acute{A}\hat{I}}$,$R_{\acute{I}\hat{I}}$ are the initial radii of large and small drops; n_A, n_M are, respectively, the relative amounts of large and small drops; A is a parameter depending on the particle coordinate; σ is the coefficient of surface tension of the droplet liquid.

The elastic properties of a dusty droplet-air flow provide the necessary pressure pulsations, and, accordingly, the process of introducing dust particles into drops. Pressure pulsations in the flow are created by specially designed water-air multi-chamber ejectors.

Therefore, the analytical part of the study, built on fractal models obtained from experimental photographic materials, allows us to state that for dust particles and droplets in the air flow, it is possible to create frequency pressure fluctuations that increase the efficiency of the introduction of dust particles into droplets, i.e. hydrodedusting process. At the same time, it is also assumed that air cooling will improve due to an increase in the time of the pulse-wave movement of droplets in the volume of the air conditioner.

To verify these statements, experimental studies were carried out, the generalization of the results of which makes it possible to substantiate the parameters and design of the required hydraulic conditioner module for the required conditions of the mine.

Experimental studies were carried out on installations having natural dimensions in order to reduce scale effects and in modes corresponding to real operating conditions. The experiments were carried out in the hydromechanics laboratory of DonNTU (Pokrovsk). The diagram of the laboratory experimental setup is shown in fig. 2.

On the scheme of the experimental setup, it is indicated: 1 – electron-optical camera (EOC), 2 – electron-optical converter of the image intensifier tube; 3-digital high resolution CCD camera (1280x1024); 4-pulse flash lamp (IL); 5—photo trigger device, 6—consisting of a laser (L) and a photo sensor (PD); computer (PC), 7 - gate and 8 - program modules.

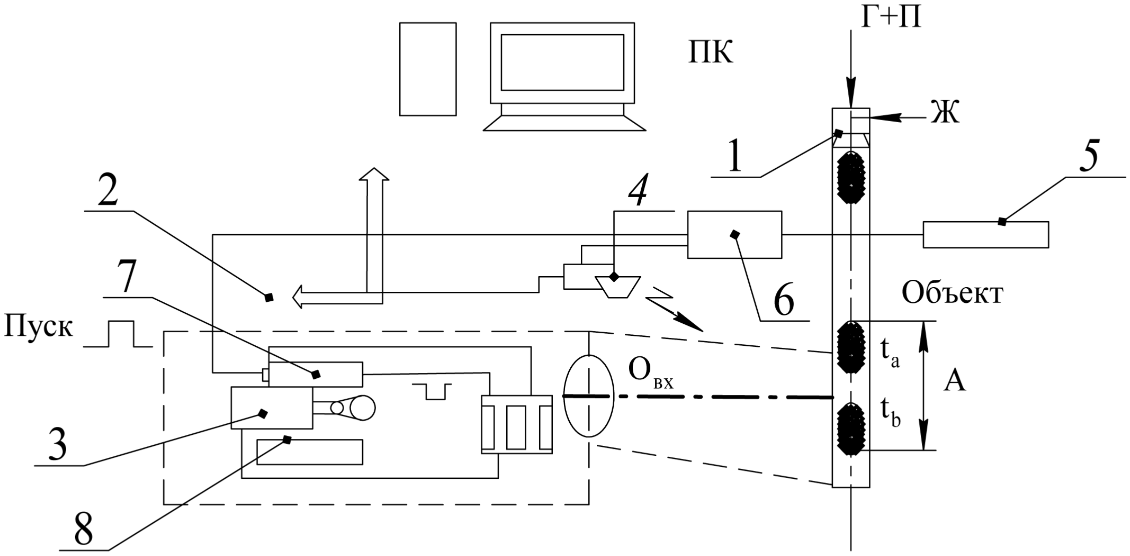

Figure 2 - Scheme of the experimental setup

In order to refine the model of the fractal structure of a dusty air-droplet flow, ultra-high-speed video recording of the processes of interaction between liquid drops and solid dust particles in the flow was used. On the basis of computer processing of frames obtained by the VS-FAST camera and an electronic optical complex, fractal models of the structure of a dusty air-droplet flow have been developed.

In the experiments, quartz dust (10–20) µm was used, sprayed in an air stream, which was affected by water drops (100–200) µm, formed by water dispersion by an ejector located in a transparent tube. Successive frames of the flow confirmed the accepted model for studying its structure in the form of fractals with binary systems of drops and dust particles in the air.

It has been experimentally confirmed that the creation of a pulse-wave motion of a dusty air-drop mixture in a fixed volume makes it possible to increase the efficiency of the process of collecting dust by drops on fig. 3.

Figure 3 shows the experimental dependences of the propagation of pressure pulses in the investigated volume of the air flow along its length, which make it possible to substantiate the required length of the hydraulic conditioner module.

To create a pulse-wave motion of a dusty air-droplet flow and adjust the calculated parameters, a multi-chamber ejector was developed and tested [8, 9], with which experiments were carried out to create a pulse-wave hydrodynamic dedusting and air cooling, and which is the basis of the air conditioner module.

The gaps between the cylindrical chambers of the ejector and the opening angles of diffusers and confusers formed by them were experimentally determined for working water pressures (0.5–2) MPa.

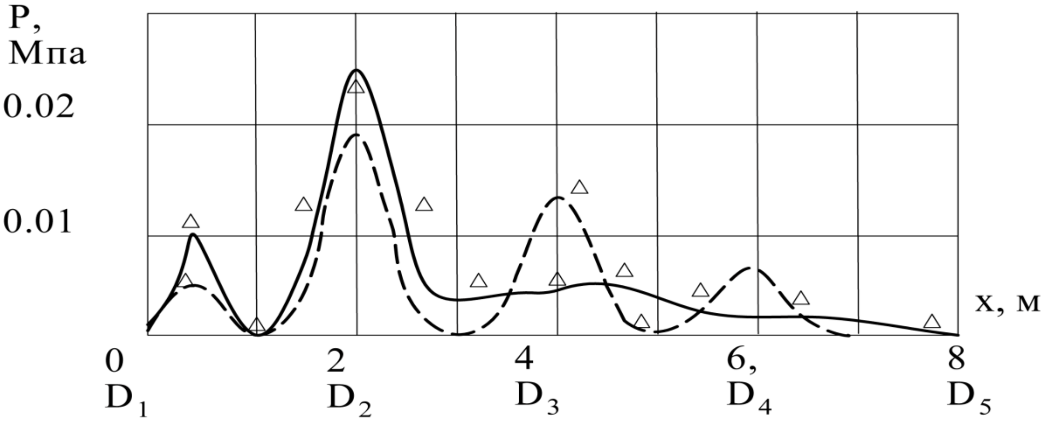

Figure 3 – Graphical interpretation of the propagation of a pressure pulse in the working volume of the flow along the length: D1, D2, - pressure sensors

It is also experimentally determined that the gaps between the cylindrical chambers constitute a decreasing arithmetic progression. It has been established that the gaps between the chambers less than 5 mm and more than 9 mm are not effective, since they do not create pulse-wave flow movements at a given pressure.

It is experimentally obtained that the dust suppression efficiency is 98.8%, and the air temperature decreased from 32°C to 25°C at the initial working water temperature of 20°C. This provides regulatory requirements for the required quality of mine air [10].

4.5. Justification of the design of the hydraulic conditioner module

Analytical and experimental studies make it possible to justify the design of a hydraulic mine air conditioner based on a module with multi-chamber water ejectors (Fig. 4).

Figure 5 shows a diagram of the design of the mine air hydraulic conditioner module, which operates as follows: water is supplied under pressure through pipe 1, and air is supplied through channel 2 for cooling and dust removal. The diagram shows: 3 - multi-chamber ejector; 4 - air outlet pipe; 5 – air outlet channel; 6 - pipe for separating water drops.

The hydraulic air conditioner must be specially designed for the specific conditions of the local zone of a coal mine, for example, in the case of shearer destruction of rocks, in the sections of ventilation drifts adjacent to long walls, it is possible to arrange several consecutive modules of air conditioners. In haulage workings, at rock mass loading points, in the areas of operation of tippers and interfaces, parallel arrangement of modules is possible. In workings with slopes,

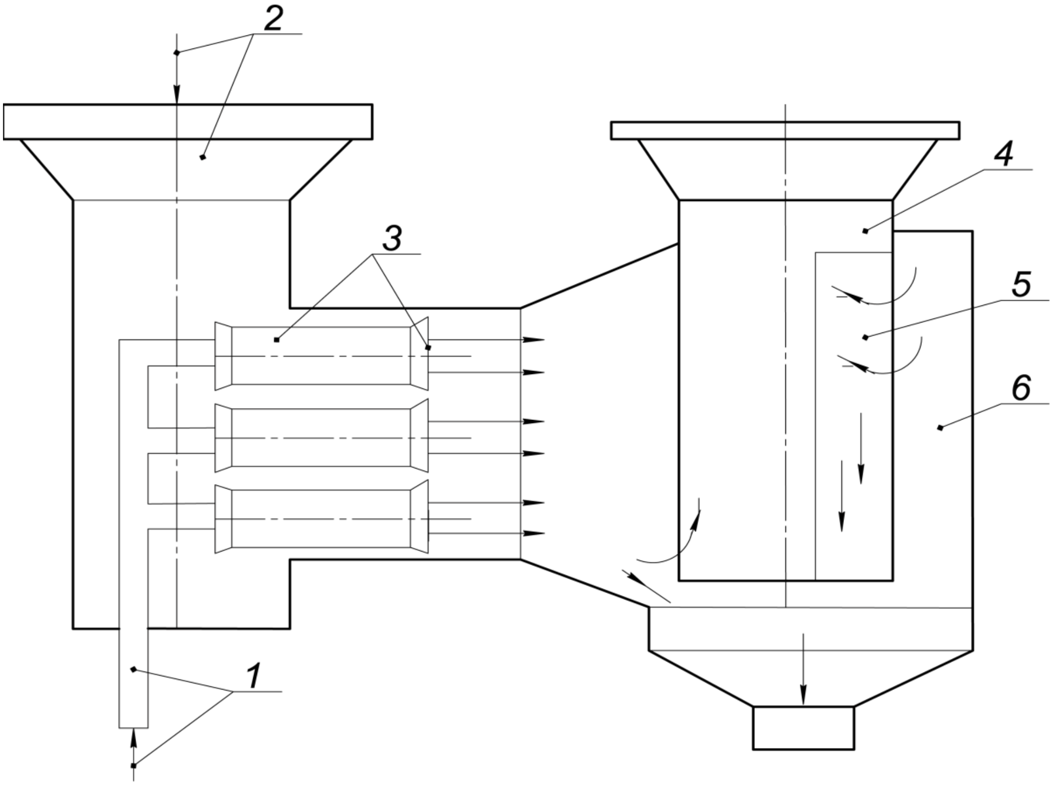

Figure 4 - Scheme of the hydraulic conditioner module

bremsbergs, sections of development workings, conveyors, as well as in the processes of moving sections of mechanized fastening, the modules can be portable and mounted on mobile platforms.

The peculiarity of the proposed method of mine air hydraulic conditioning is that the refrigerant and purifier is water, which can be connected to the mine fire system. The tests carried out have shown the advantage of hydraulic mine air conditioning, which is more efficient than existing means. The proposed air conditioning method can be used at initial water temperatures ranging from 1°C to 20°C and air temperatures not exceeding 45°C.

The development of this study on the development of a hydraulic mine air conditioner in the future is possible in the study of serial and parallel operation of air conditioner modules. In addition, it seems promising to develop special designs of portable and autonomous installations for local working areas in deep mines with the possible use of ice, especially in winter.

Conclusions

1. A substantiated mathematical model of the fractal structure of the flow of a mixture of air and water drops made it possible to determine the limiting mass of a drop, which is necessary for calculating the flow parts of a hydraulic air conditioner.

2. The occurrence of wave effects that increase the conditioning occurs when pressure pulses are created in the flow of a mixture of air and drops. The pressure pulse amplitudes increase by a factor of 2 at distances of 0.25 of the chamber length from the beginning of the disturbance. The efficiency of air conditioning with wave effects is on average 20% higher than with no pulsation.

3. The basis for the development of a 10 kW hydraulic air conditioner module for deep mines is a multi-chamber ejector, in which the necessary pulsation frequency is created, which makes it possible to obtain an emulsion of water and air in the air conditioner for effective cooling and purification of mine air.