Global Journal of Pure and Applied Mathematics.
ISSN 0973-1768 Volume 12, Number 1 (2016), pp. 559-574

http://www.ripublication.com

The Technological and Design Solutions for Energy Vortex Gas Separation of the Ventilation and Degasification Emissions from Coal Mines using Gradient Separators CJSC COMPOMASH-TEK

Valery A. Moiseev,
Doctor of Science in Engg., Professor, CEO, CJSC COMPOMASH-TEK
3rd proezd Marjinoy Roshchi, 40, Moscow 127018, Russia.

Vladimir G. Piletskii,
Doctor of Science in Engg., Deputy CEO, CJSC COMPOMASH-TEK
3rd proezd Marjinoy Roshchi, 40, Moscow 127018, Russia.

Vladimir G. Andrienko,
Ph.D. In Engineering Science, Deputy CEO, CJSC COMPOMASH-TEK
3rd proezd Marjinoy Roshchi, 40, Moscow 127018, Russia.

Oleg V. Tailakov,
Prof. Dr. Ing., Chief Project Engineer, CJSC COMPOMASH-TEK
3rd proezd Marjinoy Roshchi, 40, Moscow 127018, Russia.

Andrey V. Chentsov,
Chief Structural Engineer, CJSC COMPOMASH-TEK
3rd proezd Marjinoy Roshchi, 40, Moscow 127018, Russia.

Abstract

The article deals with the problems of technological and design solutions for recovering methane from the ventilation and degasification methane emissions from coal mines. The current state of the underground coal mining is characterized by an increase in the depth of developments and by a deterioration of the natural and mining conditions. An increase in the gas content of mine workings is simultaneously observed due to the growth in the natural gas-bearing capacity of coal beds and adjacent strata reaching up to 25–30 m^3/t at the depths of 700–1000 m, which hinders the production of coal, increases its cost price, and affects the workplace safety of miners, while

bringing of methane to the surface leads to the negative environmental impacts. This methane is recovered to the surface both from a ventilation stream and through various methods of degasification; only a small part of it is utilized. There is a need to develop a new technology and equipment for the recovery of the highly concentrated methane from the ventilation and degasification methane emissions from coal mines, which significantly reduce the harmful methane and dust emissions into the atmosphere, for the possibility of its further application, for example, in the internal combustion engines.
The coal mine methane recovery has been earlier suggested through a number of ways:

- The adsorption and absorption methods using liquid hydrocarbon components.
- Obtaining the methane gas hydrates from the gas-air mixture with a lower content of methane therein.
- Separation through membranes and by other methods.

Despite the variety of methods for recovering the highly concentrated methane from the coal mine emissions, the energy vortex gas separation and the gas treatment of the methane-dust-air mixture are the most efficient according to the preliminary assessment and comparison of the specific energy consumption and capital investments. The simulation of the process of recovering the low concentrated methane and fine dust from the methane-air mixture, carried out in the Omsk State Technical University using the ANSYS software system, confirmed the possibility of separating the gas mixtures containing less than 0.5% of methane from the low concentrated methane and dust emissions from coal mines, and of recovering the methane in concentration of up to 80% with the fine coal dust treatment on the generated experimental samples of the energy vortex gas separation equipment.
The basic parameters and geometric characteristics of the gradient separators and dynamic filters were determined using the computational models, which allowed for the development of technological and design-layout solutions for technology modules comprising the generated experimental samples of the gas separation and gas treatment equipment for recovering the highly concentrated methane and mechanical impurities from the methane-dust-air mixtures.

Keywords: Coal Mine Methane, Methane Content, Degasification Methane, Ventilation Methane, Gradient Separatpr, Recovery of the Highly Concentrated Methane

Introduction

The current state of the underground coal mining with the increase in the depth of developments is characterized by a deterioration of the mining conditions — an increase in the gas content of mine workings due to the growth in the gas-bearing capacity of coal beds and adjacent strata reaching up to 25–30 m^3/t at the depths of 700–1000 m. The methane recovered to the mine workings hinders the production of coal, increases its cost price, and affects the workplace safety of miners, while bringing of methane to the surface leads to the negative environmental impacts. At coal mining, the methane is recovered to the surface from a ventilation stream and through various methods of degasification; only a small part of it is utilized. There is a need to develop a new technology and equipment for the recovery of the highly concentrated methane from the ventilation and degasification methane emissions from coal mines, which significantly reduce the harmful methane and dust emissions into the atmosphere, for the possibility of its further application, for example, in the internal combustion engines. The coal mine methane recovery can be carried out as follows:

- Through the adsorption and absorption methods using liquid hydrocarbon components.
- Obtaining the methane gas hydrates from the gas-air mixture with a lower content of methane therein.
- Separation through membranes and by other methods.

Despite the variety of methods for recovering the highly concentrated methane from the coal mine emissions, the energy vortex gas separation and the gas treatment of the methane-dust-air mixture are the most efficient according to the preliminary assessment and comparison of the specific energy consumption and capital investments. The conducted analytical review of the scientific-technical regulatory and methodological literature and patent research involving the matter under consideration showed that the vortex gas separation and gas treatment are used in many industrial sectors including the preparation of the produced natural gas. The applied vortex apparatuses are mainly designed for the gases incoming under pressure. At the same time, the experience in the vortex separation of the flue gases in boilers and thermal power plants, gained by the CJSC COMPOMASH-TEK, is based on the rarefaction. This provides for the creation of vortex apparatuses of a slightly simplified construction — not under the pressure, but under the rarefaction, with less energy consumption. The "Krasnolimanskaya" Coal Company tried to apply the vortex apparatuses under the pressure for separating the methane-dust-air environments at the degasification of the coal mine emissions, but the efficiency factor did not exceed 50%, though it was anyway a success. However, in the world practice, the methane separation from the ventilation coal mine emissions is not carried out due to the low content of methane, which is 0.2–0.7%. In this regard, there arises a necessity of conducting research and simulating the processes of the energy vortex gas separation and gas treatment. Then, based on the identified distinctive features, formulated assumptions, and obtained dependencies, to use them for designing the energy vortex gas separation apparatuses.

A simple design of the vortex apparatus is characterized by the complex processes. The separation of the gas and dust flows in a gradient separator occurs due to its movement in the axial direction, which generates several vortex including countercurrent flows. The interaction of gas and dust flows defies a strict mathematical description. A sharp decrease in the tangential component of velocity is difficult to explain only by the wall friction of a gas and dust flow. Probably pulsing is one of the main causes of the kinetic energy dissipation. At the large gradients of velocity and pressure on the chamber's radius and length, the pulsing causes the increase in a gradient separator of the irreversibility of the processes of transferring kinetic energy from one layer to the others. On the one hand, the processes proceeding in a separation chamber differ from the most studied in the gas dynamics variants of turbulent flows with the enhanced role of pulsations. On the other hand, the value of these pulsations cannot be related to the time-averaged velocity through a simple dependence. Perhaps the description of this relationship will require using not one but several dependencies being true for the constrained areas of a separation camera, where the redistribution of the total energy in a vortex apparatus is caused by the following issues:

1. The kinetic energy flux directed from the periphery to the center.
2. The thermal energy flux, which occurs due to the implementation of the microcooling cycles by the turbulent moles as they move in the radial direction within the field of the high radial gradients of static pressure.
3. The variable specific heat as a function of pressure.

J. Ranck [Patent No. 743111 (France)] explained the vortex effect by the presence of the centrifugal force field, in which the internal gas particles compress the external ones [1], [2], [12], [14], after the second discovery of the vortex effect by R. Hilsch [1], [12], [13], who also believed that the defining role in the energy separation belongs to the friction forces between the gas layers. At the modern understanding of the vortex effect with its application for the separation of the coal mine methane and air emissions, the process is accompanied by a decrease in the enthalpy of the internal flow. To obtain the values in the temperature differences detected in experiments, the supersonic gas flow velocities in a separation chamber are needed. The fact of the supersonic flow existence was confirmed experimentally.

The hypothesis of convective heat transfer at the countercurrent interaction of vortices was suggested by J. S. Scheper in 1951 [16]. The vortex effect is explained by the presence of the thermal flux from the central to the peripheral gas layers.

The hypothesis of vortex interaction was suggested by A.P. Merkulov [6,7]. The main difference from the previous hypothesis is that the defining role in the transfer of energy from the axial to the peripheral layers is assigned to the radial turbulent pulsations of gas.

According to the authors [2], [3], [6], [7], [8], this hypothesis most fully reflects the specifics of the processes taking place in the separation chamber. Until now the scientists have failed to obtain a sufficiently reliable mathematical model of the gas separation processes despite the fact that a large number of highly qualified specialists are engaged in the study of the vortex effect. The first studies conducted by V.M. Brodianskii and A.V. Martynov [9], [10, in the early 60's demonstrated the efficiency of using a vortex tube for natural gas treatment and the capacity of the apparatus to separate gas-liquid mixtures.

These studies were further developed in the works by T.S. Alekseev, Iu.D. Raiskii, I.L. Leites et al. [4], [9], who specified the operation regularities of a vortex tube as of a gas-liquid mixture separator, and defined the conditions of the most efficient application of a vortex tube in the processes of treatment of the gas condensate mixtures.

A phase separation of the dust gas mixtures in a vortex apparatus is a typical example of the separation process of a fine phase. The role of the factors impeding the process of centrifugal separation is of great significance for such mixtures. The studies indicated the impact of the radial pulsations in a vortex gas flow on the effect of the fine component separation. The transfer of the dust particles in a separator's chamber is carried out under the action of the centrifugal forces and rarefaction, is characterized by the radial gradient of concentration of the diffusion flux that transfers dust to the near-axial areas of chamber.

The determination of the vortex swirling intensity using the gas-dynamic method for separating gas mixtures is based on imparting high velocity to the gas flow (up to the supersonic velocity) for generating high-velocity (static) temperature, which is obviously lower than the stagnation temperature at the apparatus inlet.

In the works [17], [18], this criterion was generalized for the case of tangential-blade, snail, and axial-tangential swirlers.

The detailed information on the determination of geometrical parameters of swirling for the different swirlers is given in the monographs [5], [4]. In many experimental studies, the degree of flow swirling was assessed just according to the slope angle of the swirling elements.

1. There are dozens of theoretical works that reveal the physical nature of the vortex effect and provide options for its analytical solutions. The majority of the works [15], [19], [20], [21], [22], [23] are based on the hypothesis of transformation of a free vortex occurring in the inlet section of a vortex tube into a forced vortex.
2. The intensity of swirling is characterized by the integral swirl parameter [11], [24], [25], which is the ration of flow of an axial component of the moment of momentum to the flow of an axial component of momentum in the swirler outlet, and to the radius of this outlet

$$F = \frac{M}{K r_{out}}, \tag{1}$$

Where the value $M = 2\pi\int_0^{r_{out}} \rho V_z V_\varphi r^2 dr$ is the flow of an axial component of the moment of momentum through the cross section of the radius r_{out}, and the value $K = 2\pi\int_0^{r_{out}} \rho V_z^2 r dr$ – is the flow of an axial component of pulse through the same section.

$$F = \frac{\pi G r_{out}}{Q}, \tag{2}$$

If to take the average velocity in the inlet channel of a swirl device as a velocity scale, then the rate and circulation of flow can be presented as follows $Q = \pi r_{in}^2 V_{in}$,
$G = \varphi \alpha_{in} V_{in}$.

$$F = \frac{\varphi \alpha_{in} r_{out}}{r_{in}^2}, \qquad (3)$$

Creating a model of the two-phase turbulent swirled dust and gas flow is a prerequisite for the development of methods for calculating the vortex apparatuses for gas separation and gas treatment of different technological applications, and for the reduction of the costly experimental studies. Currently, in connection with the computer technology development, there is a progress to the calculation of vortex apparatuses for gas separation and gas treatment.

In the created gradient separators under certain conditions (at a negative pressure gradient), a swirled flow is generated, in which the energy vortex gas separation of a methane-dust-air stream into its components with the efficiency of up to 100% occurs. This is confirmed by the simulations and calculations in different modes of efflux and concentrations of the components performed in the Omsk State Technical University using the ANSYS software package.

A series of calculations was carried out in order to obtain the optimum characteristics of the processes of the methane-dust-air mixture separation. The methane and mechanical impurities emitted from the ventilation and degasification emissions of coal mines are selected as the main criterion.

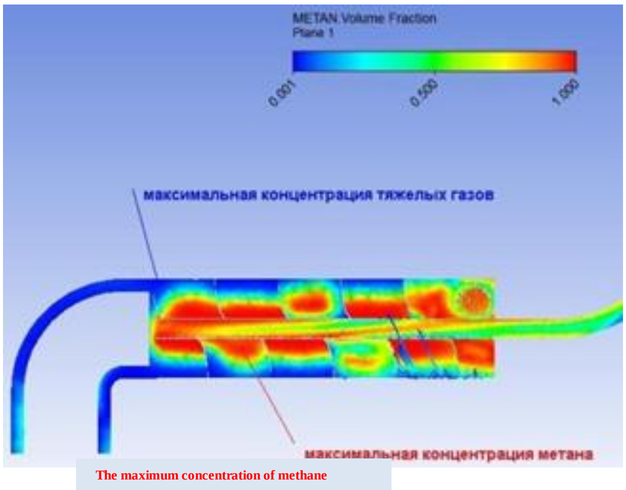


Figure 1: The scheme of separation of methane with mechanical impurities in the transverse and longitudinal sections of a gradient separator

As seen in Figure 1, the central bundle is a mixture of methane with mechanical impurities and condensate. At the periphery, the air is shown, which is heavier in density with respect to methane.

Figure 2 shows the scheme of the estimated outlet sections of the heavy air and lighter gas components of methane. The calculated dependencies are given as applied to the first stage separator. The computational models for the second and third stage separators are similar.

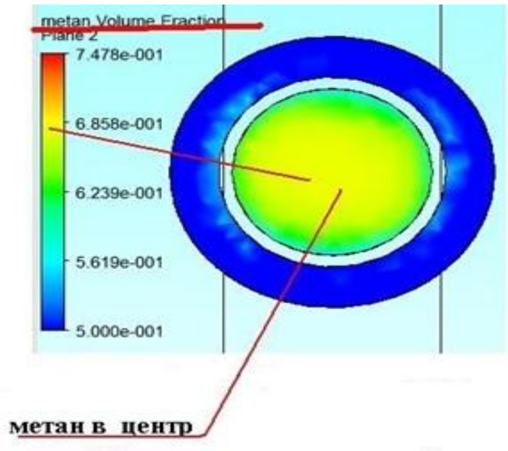


Figure 2: The schemes of the calculated outlet sections of methane

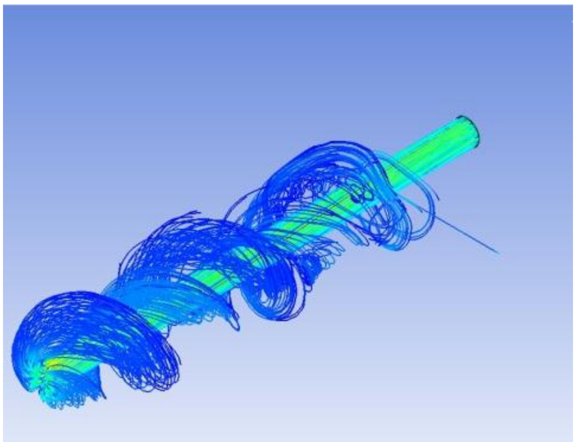


Figure 3: The model of the air efflux speed lines

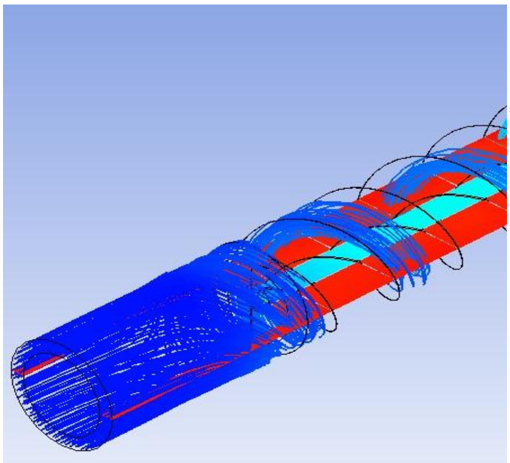


Figure 4: The model of the air efflux speed lines

Figures 3 and 4 show the models of the methane and air speed lines. As seen from the analysis of models obtained through the numerical simulation, the structure of the swirled flow of a methane-dust-air mixture is separated into two flows — a central one consisting of methane, mechanical impurities, and condensate, i.e. a near-axial flow, and a peripheral one consisting of heavy components — air.

Figure 5 shows the spatial configuration of the central near-axial flow structure, and Figure 6 shows a scheme of swirling in the structure of a moving peripheral flow in a gradient separator.

The conducted studies of the nature of motion of the obtained structures of a methane-dust-air mixture revealed the following features:

- A near-axial flow is swirled around its figure axis and moves along it in the shape of a cord.
- A peripheral flow is swirled around its figure axis, located in the "center" of the structure, in the shape of a spiral, moves along the axis of a gradient separator, with the presence of the radial turbulently swirled air volumes.

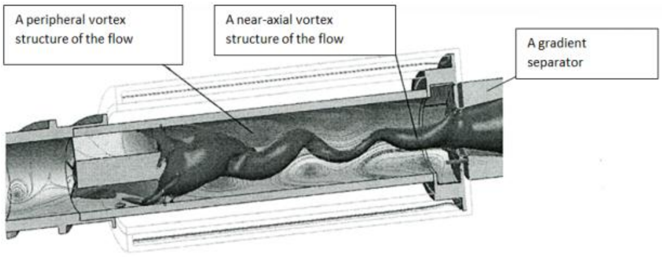


Figure 5: A spatial configuration of the central structure of the flow of a methane-dust-air mixture (near-axial) and of the peripheral vortex structure of the flow obtained due to the numerical simulation of a gradient separator

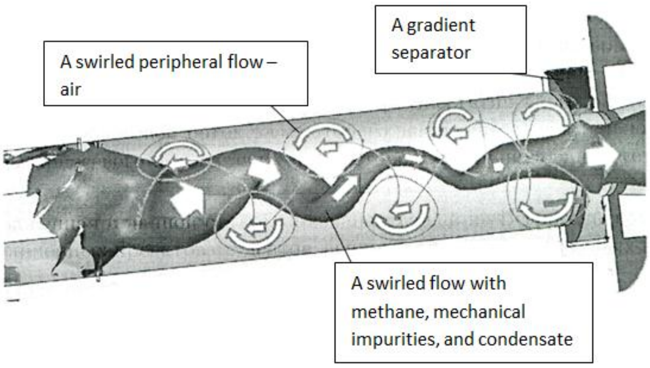


Figure 6: A scheme of swirling of a methane-dust-air mixture in the structure of a flow moving in a gradient separator

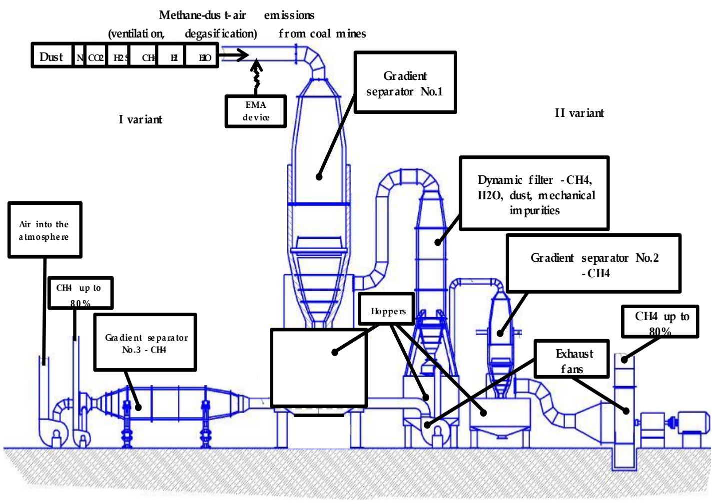
When creating certain conditions on rarefaction and efflux velocities as well as at certain geometry of a gradient separator, an increase in the concentration of methane is possible during the process of separation of a methane-dust-air mixture of the coal mine emissions.

Based on the obtained results of the theoretical studies, on the performed simulation of the processes of energy vortex gas separation of the dust-gas streams with the extraction of gas components and dust with condensate, the choice of models is substantiated together with their interpretation for the energy vortex separation of the methane-dust-air emissions from coal mines with the recovery of the highly concentrated methane and mechanical impurities; a technological layout scheme is developed for the technological module of gas separation and gas treatment with the recovery of the highly concentrated methane and mechanical impurities with condensate, which is shown in Figure 7.

To increase the concentration of the emitted methane and the degree of its air and suspended solids treatment, the technological modules will probably require different configuration. For example, Figure 8 shows a technological scheme comprising two variants of configuration of the technological modules.

The first variant includes one technological module with the connection of a gradient separator No. 3. This variant may provide for the methane recovery on the condition of low dust content in the incoming flows, for example, during the process of degasification of the abandoned coal mines.

The second variant includes three serially connected modules, which allows for the high concentration of methane and excludes the presence of mechanical impurities. The issue of stages of the energy vortex gas separation and gas treatment should be addressed directly when binding to the specific targets taking into account the conditions and methods of disposal of the emitted methane and the separated mechanical impurities.



I variant for the technological module application (gradient separator No.1) with an additional gradient separator No.3;
II variant for the technological modules application includes the gradient separators No.No. 1, 2 with hoppers and dynamic filter.

Figure 7: A technological scheme comprising technological modules of a single-system or a triple-system energy vortex gas separation of the ventilation and degasification emissions from coal mines with the recovery of the highly concentrated methane, mechanical impurities, and coal dust.

Figure 8 shows a technological scheme of the highly concentrated methane recovery from the ventilation and degasification emissions (Patent No. 2406826 "A Method for Underground Coal Mining", CJSC "Uglemetan Service"). The technological scheme of CJSC "Uglemetan Service" includes two technological modules of CJSC COMPOMASH-TEK.
The first module provides for the first stage of gas separation and gas treatment, which significantly reduces the previously occurred abrasive wear of the vacuum pumps 8 and 9, and increases the concentration of methane in the methane-air flow channeled through the vacuum pumps to the second technological module comprising a gradient separator 15 and a dynamic filter with a hopper 17. The highly concentrated methane obtained at the output is applicable, including as a motor fuel, both in the form of a compressed and liquefied gas, as well as the raw material for the petrochemical processing. Depending on the content of mechanical impurities in coal dust (with or without enrichment), it can be also applied for the preparation of coal-water slurries (CWS), briquettes.

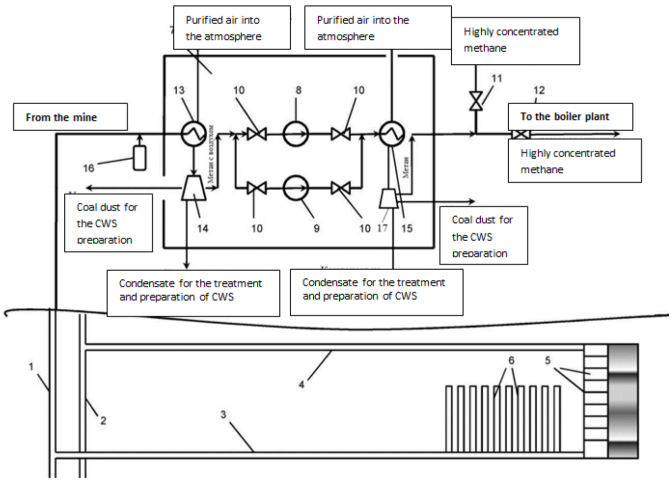


Figure 8: A technological scheme for the highly concentrated methane recovery from the ventilation and degasification emissions from coal mines. 1 – downcast shaft; 2 – ventilation shaft; 3 – haulage roadway; 4 – ventilation roadway; 5 – powered support sections; 6 – drilled degasification wellbores; 7 – pump station with vacuum pumps 8 and 9, gradient separators 13 and 15, dynamic filters 14 and 17, and shutters 10; 11 – a shutter of the flare for the discharge of air with the low concentration of methane; 12 – a shutter for the supply of emitted methane to a boiler plant; 16 – an electromagnetic action device (EMA)

An approximate calculation of the technical and geometric characteristics of gradient separators based on the initial data on the incoming methane-dust-air flow:

1. Volumetric flow rate of a methane-dust-air mixture – up to 20,000 nm^3/h;
2. Temperature – up to 25 ^oC;
3. Dust content – up to 50 mg/m^3;
4. Dust fineness – 0-180 microns;

5. Density of a methane-dust-air mixture $\rho_o = 0.824$ kg/nm^3
6. At the temperature of 25 ºC and at the average rarefaction of 50 mmAq $\rho_t = 0.631$ kg/m^3

The physical flow rate of a methane-air mixture equals to:

$$G_{V_t} = G_V \frac{\rho_o}{\rho_t} = \frac{0.824}{0.631} \cdot 20{,}000 = 26{,}117.5 \text{ nm}^3/\text{h}$$

The estimated velocity of a methane-air mixture a the separator inlet

$$G_z = \frac{G_{V_t}}{3{,}000 \cdot F} = \frac{26{,}117.5}{3{,}000 \cdot 0.16} = 45.3 \text{ m/s}$$

Based on the conditions for preserving the structure of the swirled gas flow, the diameter of the incoming section must be at least 800 mm.

The calculations performed at the Omsk State Technical University using the ANSYS software system provided the basic dimensions and parameters of a gradient separator No.1:

- The maximum internal diameter – 900 mm;
- Total length – 5,964 mm;
- Wight (without racks) – 2,500 kg.

The gradient separators No. 2 and dynamic filter are calculated similarly.

The simulation of the dust intake processes was carried out using the ANSYS CFX software system in the Omsk State Technical University. Figure 9 shows some simulation results:

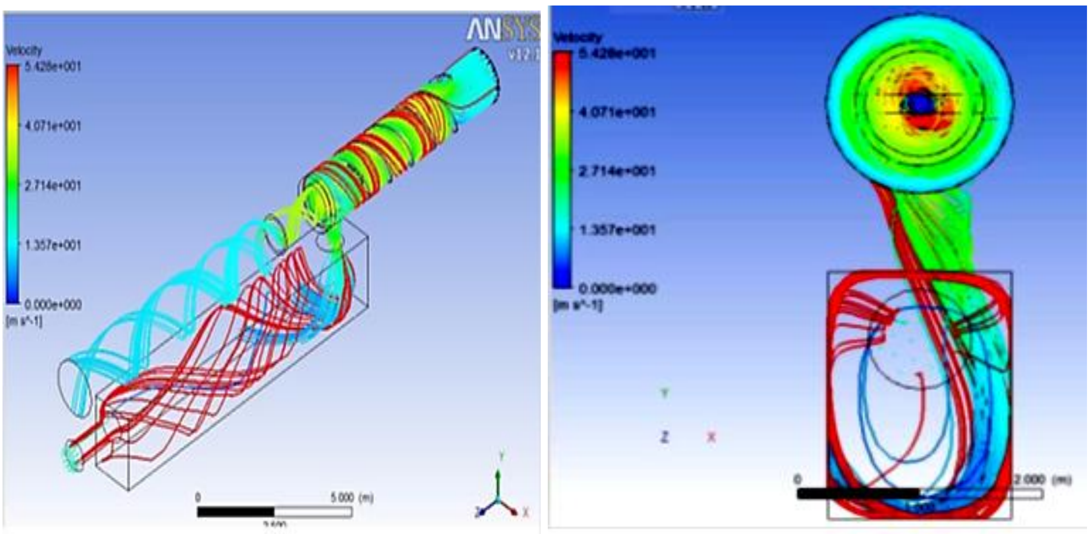


Figure 9: A scheme of the dust intake simulation (ANSYS)

The studies showed that according to the efficiency of gas purification from the dispersed particles, the dynamic filter outperforms the bag filters and electrostatic precipitators as well as the wet scrubbers.

A methane-dust-air mixture through the inlet connection (A) enters the dynamic filter, then (B) moves along the aero supply channel, and exits the spin nozzle. At this section, a methane-dust-air mixture is in the negative stress condition. Then the gas mixture jets turn back (C), pass through the incoming jets, i.e. essentially pass through the filter formed from the moving layers of air, which is in the negative stress condition. When the gas stream is moving along the volume of the rotary chamber, it contacts with the precipitation lattice in that volume, in which the gas is relatively immobile. The particles of the high speed stream move into this volume and precipitate into the hopper. But not all the particles are precipitated. A part thereof moves to the apparatus outlet, and here, under the influence of an incoming jet, they are redirected to the rotary chamber of a dynamic filter. This is an aerodynamic trap — the particles have a possibility to enter the rotary chamber of an apparatus, but cannot exit it, and at the end completely precipitate in the hopper. Therefore, the particles will be able to enter a channel, but will not be able to exit it.

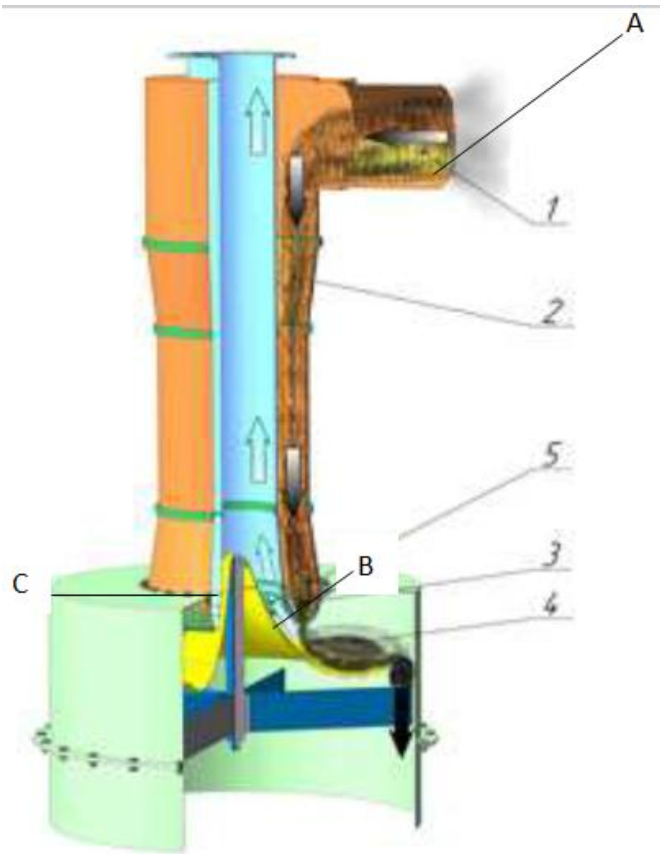


Figure 10: Dynamic filter arrangement

A dynamic filter includes: 1 – an inlet connection for a methane-dust-air mixture; 2 – aero supply channel for the mixture; 3 – spin nozzle; 4 – rotary chamber; 5 – outlet channel for pure methane.

Based on the models and calculations, the design and layout solutions of the experimental samples were developed for the equipment intended for the effective gas separation and gas treatment of the methane-dust-air mixtures of the ventilation and degasification emissions from the coal mines with the recovery of highly concentrated methane and mechanical impurities with coal dust, Figure 1.

A technological module comprises a gradient separator; a dynamic filter with a storage hopper; two exhaust fans, which create a negative pressure gradient in the apparatuses for the passing energy vortex methane-dust-air stream; a set of connecting flue pipes.

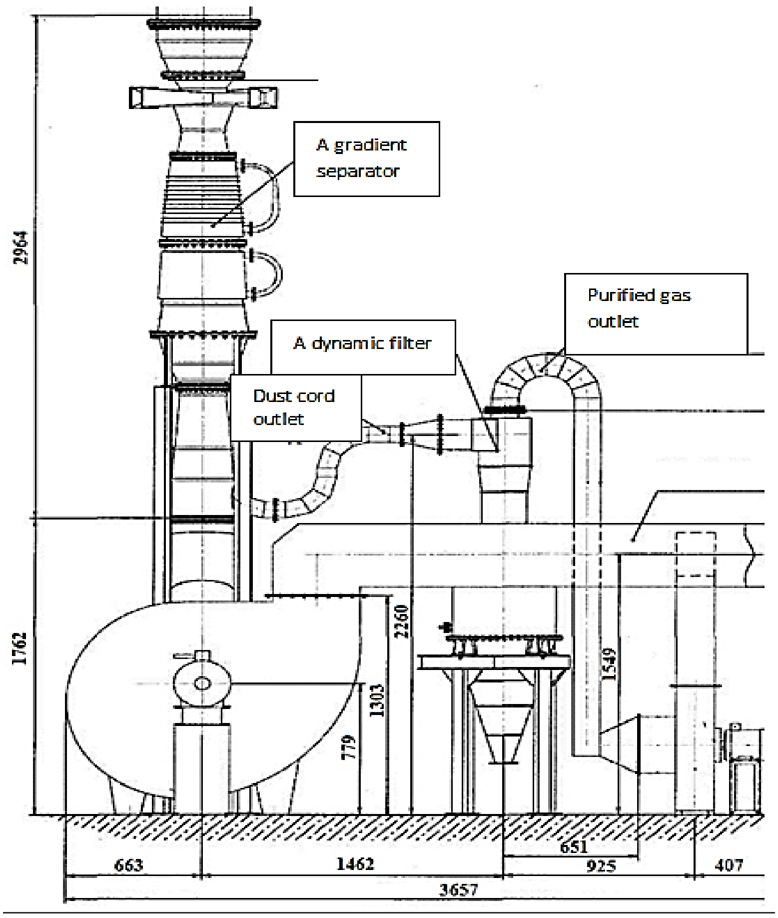


Figure 11: The design-layout solutions for a technological module of the experimental samples of the equipment intended for the energy vortex gas separation and gas treatment of the methane-dust-air emissions from coal mines with the recovery of the highly concentrated methane and и mechanical impurities.

Conclusions

The processes proceeding in the vortex tube chambers of the gradient separators differ from the most studied in gas dynamics variants of the turbulent flows with their enhanced role of the following issues:

- The pulsation occurred at the high velocities of the swirled flows and rarefaction according to the radius of gas flows, due to which the near-axial gas layers are cooled, and the peripheral – are heated.
- The thermal energy fluxes resulting due to the microcooling cycles of turbulent moles during their movement in the vortex tube chambers of the gradient separators in the radial direction.
- The cooling in the vortex tube chambers of the gradient separators of the central gas flow and the concentration of its components.
- the shapes of the nozzle flow path, its flow section, device profiles intended for the swirling and outlet of flows from the vortex tube chambers of the gradient separators.

Despite the variety of methods for recovering the highly concentrated methane from the coal mine emissions, the energy vortex gas separation and the gas treatment of the methane-dust-air mixture at the negative pressure gradient are the most efficient according to the preliminary assessment and comparison of the specific energy consumption and capital investments, which defines the simplicity of the technological and design solutions of the created experimental samples of a gradient separator and dynamic filter.

Based on the conducted studies and performed simulation of the processes of the energy vortex gas separation and gas treatment, the choice of the estimated models was substantiated for the efficient gas separation and gas treatment of a methane-dust-air mixture with the recovery of the highly concentrated methane and mechanical impurities from the ventilation and degasification emissions from the coal mines.

The specific features and conditions of the energy vortex gas separating dust-gas flows occurrence in the gradient separators were determined, the simulation was carried out as applied to the gas separation and gas treatment of the methane-dust-air mixture of the ventilation and degasification emissions from the coal mines necessary for the development of the technological and design solutions for the creation of the experimental samples of the equipment for gas separation and gas treatment.

Using the computational models, the basic parameters and geometrical characteristics of the gradient separators and dynamic filters were determined, which allowed developing the technological and design-layout solutions on the technological modules comprising the created experimental samples of the gas separation and gas treatment equipment for the recovery of the highly concentrated methane and mechanical impurities from the methane-dust-air mixtures.

Acknowledgments

This article presents the results of work performed under the Agreement on Granting a Subsidy No. 14.579.21.0080 of November 28, 2014 (a unique identifier of applied researches and advanced experiments (project) RFMEF157914X0080) with financial support from the Ministry of Education and Science of the Russian Federation.

References

[1] Zholondkovskii, O.N. (1985). *Attention – Air*. Moscow: Nedra, "Moskovskii rabochii" publication.

[2] Piralishvili, Sh.A., Poliaev, V.M., & Sergeev, M.N. (2000). *Vortex Effects. Experiment, Theory, Technical Solutions*. Moscow: UNPTs. Energomas.

[3] Suslov, A.D., Ivanov, S.V., Murashkin, A.V., & Chizhikov, Iu.V. (n.d.). *Vortex Apparatuses*. Moscow: Mashinostroenie.

[4] Alekseev, V.P., & Martynovskii, V.S. (1956). The Effect of the Vortex Temperature Separation of the Superheated Vapors and the Experimental Verification of the Hilsch-Fulton Hypothesis. *Proceedings of USSR Academy of Sciences, 1*.

[5] Alekseev, V.P., & Martynovskii, V.S. (1956). The Study of the Effect of the Vortex Temperature Separation of Gases and Vapors. *The Journal of technical Physics, 10*(26).

[6] Merkulov, A.P. (1969). *The Vortex Effect and its Technical Application*. Moscow: Mashinostroenie.

[7] Merkulov, A.P., & Piralishvili, Sh.A. (1969). *The Study of the Vortex Tube with the Additional Flow. Some Research Questions of Heat Transfer and Heat Engines. Issue 37*. Kuibyshev: KuAI.

[8] Merkulov, A.P., Piralishvili, Sh.A., & Mikhailov, V.G. (1973). *An Analysis of the Distribution of the Circumferential Moments of Momentum in the Vortex Tubes. Some Research Questions of Heat Transfer and Heat Engines. Issue 56*. Kuibyshev: KuAI.

[9] Borodianskii, V.M., & Leites, I.L. (1962). *The Dependence of the Ranque Effect on the Properties of Real Gases*. IFZh.

[10] Martynov, A.V., & Borodianskii, V.M. (1967). *The Study of the Parameters of a Vortex Flow inside a Ranque-Hilsch's Tube. Vol. 12*. IFZh.

[11] Gupta, A., Lilli, D., & Sanred, N. (1987). *Swirled Flows*. Moscow: Mir.

[12] Kuznetsov, V.N., Kuznetsov, V.I., & Barsukov, S.N. (1983). *The Ranque's Vortex Effect*. Irkutsk.

[13] Chizhov Iu.V. (1997). On the Ranque Effect Values Dependence on the Physical Nature of a Working Body. *Energetika, 1*.

[14] Shankina, A.A., & Piralishvili, Sh.A. (2010). The Similarity in the Vortex Tubes of Rank-Hilsch. *Thermal Processes in Technique, 2*(4).

[15] Fulton, C.D. (1950). *Ranque's Tube, Refrigerating Engineering*.

[16] Zhidkov, M.A., Leites, N.P., & Maginuev, B.G. (1974). The Natural Gas Desulfurization by the Low-Temperature Sorption of Condensable Hydrocarbons. *Gas Industry, 6*.

[17] The Vortex Effect and its Technological Applications. (1981). *The Proceedings of the III All-Union Scientific and Technical Conference, Kuibyshev, KuAI.*

[18] Mikheev, M.L. (1947). *The Basics of Heat Transfer*. Gosenergoizdat.

[19] Takahama, H. (1965). Studies of Vortex Tube. *Bulletin of JSME, 31*.

[20] Khalatov, A.A. (1989). *Theory and Practice of Swirled Flows*. Kiev: Naukova Dumka.
[21] Vulis, L.A., & Kostritsa, A.A. (1962). The Elementary Theory of the Ranque Effect. *Teploenergetika, 10.*
[22] Gordzovskii, G.L., & Kuznetsov, Iu.E. (1954). To the Theory of a Vortex Tube. *Proceedings of USSR Academy of Sciences, OTN, 10.*
[23] Dubinskii, M.G. (1955). The Flow of Rotating Gas Streams in the Annular Channels. *Proceedings of USSR Academy of Sciences, OTN, 11*.
[24] Sazhin, V.S., & Gudin, L.I. (1995). *Vortex Dust Collectors*. Moscow: Chimia.
[25] Khalatov, A.A. (1999). *The Theory and Practice of the Swirled Flows.* Kiev: Naukova Dumka.