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Recovery of Highly Concentrated Methane from Mine Ventilation and Degasification Emissions using a Separator at a Negative Pressure Gradient

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The article deals with the problems of recovery of methane from ventilation and degasification methane emissions from coal mines and its separation with concentration of up to 80%, suitable to use, for example, as fuel for internal combustion engines. Methane resources in coal beds in terms of reference fuel take the 3-4 position among fossil fuel resources in the world after coal, oil and natural gas. In 2013 global emissions of coal mine methane was approximately more than 50 bil. m^3 of methane per year. On the one hand, mine gas is similar to natural gas and has useful properties of a fuel; on the other hand, when released to the atmosphere it inflicts the ecological damage. The solutions proposed for ultimate recovery of coal dust and methane from low concentration methane dust air emissions into the atmosphere are relevant and timely. The design solutions developed for the gas treating equipment are based on the use of the Ranque effect for energy vortex swirling of gas streams at a negative pressure gradient including ventilation and degasification methane emissions from coal mines with subsequent maximum possible recovery of highly concentrated methane and mechanical impurities. Keywords: coal mine methane, ventilation, degasification, methane dust air emissions, resources, ecology, separator, vortex flow, rarefaction, increase in concentration, specific energy consumption.

Key words: Negative pressure gradient, Emissions, Methane, Recovery.

Methane resources in coal beds in terms of reference fuel according to the different estimates take the 3-4 position among fossil fuel resources in the world after coal, oil and natural gas. (Statistical Review of World Energy, 2010). In 2013 global emissions of coal mine methane was approximately more than 50 bil. m^3 of methane per year. China, the United States, the EU and Russia are the largest environmental "polluters" due to mine gas emissions. At that, the trend to increase coal mining predicts the increase in mine gas globally emitted up to 440 mln. t. in ÑÎ2 equivalent by 2020, mainly due to increased coal mining in China, Fig. 1. On the one hand, mine gas is similar to natural gas and has useful properties of a fuel, on the other hand, when released to the atmosphere it inflicts the ecological damage (World Energy Outlook, 2010; Global Anthropogenic Non-CO$_2$ Greenhouse Gas Emissions: 1990-2020, 2006; Elchaninov, 1995; Karaca, 2011; US Environmental protection Agency (EPA), Technological Series of the Coalbed Methane Outreach Program, 2009; Guidelines for the best practices in efficient degasification of sources of methane emissions and methane recovery from coal mines, 2010; Backhaus *et al.*, 2010).

Therefore, the solutions proposed for ultimate recovery of coal dust and methane from

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low concentration methane dust air emissions into the atmosphere are relevant and timely.

The main design solutions developed for the gas treating equipment are based on the use of the Ranque effect for intensive energy vortex swirling of gas streams, including ventilation and degasification methane emissions from coal mines, with subsequent maximum possible recovery of coal dust and highly concentrated methane to be used as fuel for internal combustion engines and for co-generation plants. Scientists and coal experts pay particular attention to solving the problem of coal mine methane which is due to the need to ensure methane safety in underground coal mining and passing the "gas barrier" in order to improve production efficiency. With the development of underground coal mining and increase in the depth of mining, the problem of coal mine methane enhanced, which includes the tasks for ensuring methane (gas) safety in coal recovery; degasification, capturing and recovery of coal mine methane; industrial (commercial) recovery of coal mine methane; reduced emissions of coal mine methane to the atmosphere. In 1994 the Research Institute of Comprehensive Exploitation of Mineral Resources of RAS submitted a proposal on the need for state support of researches performed in the country on methane recovery from high gas-bearing coal beds to the Research Council for the State Scientific and Technical Program (SSTP), coordinated by the Ministry of Higher Education, Science and Technology of the Russian Federation. In 1995-96, the decision to hold a tender on this problem was taken and two scientific and technical projects, included in the Nedra Rossii SSTP, were established:

Innovative Technologies of Methane Recovery from the Coal-Bearing Strata on the Fields of Productive Mines for Industrial Use and Improved Safety of Mining Operations (parent organization – Moscow State Mining University);

Techniques for Preliminary Methane Recovery (Extraction) from Coal Fields using Special Rock Massif Treatment Methods – Uglemetan (parent organization – Research Institute of Comprehensive Exploitation of Mineral Resources of RAS). The researches were further performed in 2002-2004 within the framework of a new project of the Ministry for Industry, Science and Technology of the Russian Federation "Development of Techniques for Recovery of Unconventional Hydrocarbons (coal bed methane, gas hydrate accumulations etc."). The results of researches and investigations performed on specified projects are well-known and are described in detail in a number of the above works (Kreinin, 2012; Tailakov, & Zastrelov, 2012). The causes for the lack of proper methane recovery in the Russian Federation and countries that produce most emissions, including the lack of technological tools for cost-effective production are shown in Table 1 (Karaca, 2011).

In addition to the above obstacles, low concentration of methane and underdeveloped infrastructure (access to gas and/or electrical network) are serious reasons for low mine gas recovery.

In August 2003, the Government of the Russian Federation adopted the Energy Strategy of Russia for the period until 2020 in which, in particular, the following issues were addressed:

a) Development and implementation of new efficient environmentally friendly techniques for application of nonconventional resources of hydrocarbon raw materials, including coal bed methane;
b) Technical support of industrial recovery of coal mine methane;
c) Development of new techniques and equipment for efficient degasification of coal beds;
d) Implementation of new efficient environmentally friendly techniques for recovery, production, transformation, transportation and integrated use of fuel and energy resources (FER), which include coal bed methane.

Methane concentration in natural degasification is 0.2-0.7 %, and in closed mines and in active degasification of productive mines through the wells specially drilled on the surface can be 90 %. Degasification emissions containing more than 25% of methane (at that, the capacity of all mine-gas powered power plants is low – about 300 MW) undergo coal mine methane recovery. Ventilation emissions containing 0.3÷1.5% of methane, which release more than 70% of all coal mine methane, in low concentration are not completely used due to unprofitability of recovery (coal mine methane resources in the Russian

Federation amount to 40-65 billion m^3) (Koroleva, & Zakharova, 2011; Kostyuk, 2011). The example of problems of coal mine methane recovery is the Kemerovo Region. In 2013, methane emissions in the Kemerovo Region reached 735 thousand tons (in 2000 – 200 thousand tons) which is 50% of emissions from the enterprises in the region. Only 9 of 63 methane hazardous mines in Kuzbass are engaged in methane recovery. According to the analysis of scientific and technical literature and regulatory documents, the low level of methane recovery occurs due to low production rate and concentration, as well as fine coal duct pollution which results in abrasive wear of the equipment including vacuum pumps. To get methane concentration higher than 25% in degasification yield at mines, even those over classified in gas, the efficiency of degasification works must be improved, which will accordingly require high costs.

In this regard, methods and tools for increasing methane concentration in methane-air mixtures (MAM) of degasification and ventilation systems using diaphragm, separation, separation-diaphragm, vortex, adsorption and absorption methods are being developed. The experimental models of the plants for separation (upgrading) of MAM (Backhaus *et al.*, 2010; Bezpflug *et al.*, 2010) have been designed, produced and tested.

The purpose of this is to ensure efficient recovery of coal mine methane with concentration of 0.3-3.5%; 4.0-25%; 25-50% and more than 50% with the following applications:

a) 0.3-3.5% – to be burned in boiler furnaces and to obtain a working medium in external combustion chambers in order to generate heat and energy;
b) 4.0-25% – to be burned in furnaces and to be used in gas diesel engines and ICE;
c) 25-50% – to be used in power and chemical plants to produce energy and chemicals;
d) 50% and more – for household activities, chemical purposes and power industry.

With the concentration of methane captured is close to 100%, its supply for industrial use (gas pipeline sales) is the most attractive way to use methane. However, in addition to high concentration, gas must satisfy other strict requirements, such as the absence of impurities, water and dust. As a rule, this gas is recovered from preliminary degasification wells or by drilling into virgin coal beds where mine and ventilation gases are not mixed. Today only few countries sell mine gas in a gas pipeline.

In the United States, for example, where the price for natural gas is high, every year about 1.3 bcm of coal mine methane is supplied in a gas pipeline. In Europe, mine gas is used in a gas pipeline in the UK and the Czech Republic. In Germany – in container-type cogeneration plants.

However, major obstacles to such application in most countries is insufficient concentration of captured mine gas, inaccessibility of a gas pipeline in the immediate vicinity of a mine and/or low price of natural gas.

The extraction works contain four sources of significant methane emissions [EPA-2009] (US Environmental protection Agency ÅÐÀ, Technological Series of the Coalbed Methane Outreach Program, 2009; Backhaus *et al.*, 2010):

a) open-pit mining;
b) underground mining (ventilation and degasification);
c) coal upgrading;
d) closed mines.

As a rule, the volume of methane emissions in open-pit mining is lower than that in underground mining due to a lower degree of coalification. In addition, emissions are released into the atmosphere; therefore, methane recovery for power generation is impossible.

Since methane of unsustained quality is recovered, since it depends on concentration, production rate, pressure and impurities – it cannot be directly used as an energy carrier or a basic resource for chemical and process plants (Backhaus, 2012; Ermolaev, & Cibaev, 2011; Antipov *et al.*, 2012; Kovetsky, & Kovetskaya, 2010; Kostyuk, 2011; Pavlov *et al.*, 2012; Parmuzin, 2011; Razgildeev, & Serov, 2010; Patskov *et al.*, 2010; Remezov, & Cherkashin, 2011; Tailakov, & Zastrelov, 2012; Tararin *et al.*, 2010; Travnikov, & Komina, 2010; Glushich *et al.*, 2012; Schwartz, & Brook, 2012).

The methods of methane recovery from ventilation emissions are not used in Russia, they are mainly used abroad, however, they are rather labor intensive and expensive.

To recover coal mine methane from degasification emissions absorption, cryogenic, diaphragm or combined methods are used, the main disadvantage of which is their high labor intensity, material and energy intensity with high consumption of reagents/sorbents, higher operating costs associated with large volumes of methane emissions to be recovered and processed. The following issues are complicated when addressed:

a) Recovery of highly concentrated methane of up to 80% from ventilation emissions from coal mines, in low methane content of 0.2-0.3%, which is not currently implemented in Russia and which causes environmental pollution and failure to use a fuel.

b) Removal of up to 90% of mechanical impurities from ventilation and degasification emissions from coal mines when recovering coal mine methane, which prevents abrasive wear of vacuum pumps, fittings, pipelines and equipment used for emitted methane recovery.

c) Obtaining of highly concentrated methane of up to 80% from degasification emissions including those with low methane concentration – less than 25%.

The assessment of the processes for mine gas treatment and recovery of highly concentrated methane from ventilation and degasification emissions based on performed predictive researches on recovery of methane-air mixtures using various methods is given in Table 2

Table 1.

Country	Basic constraints
China	Most mines are located far from gas pipelines Primitive degasification techniques, low yield Gas is mainly of low quality, i. e. methane concentration is less than 30 %
United States	In most states the capacity of gas pipelines is limited Relatively low electricity rates As a rule, a combined permit is issued for recovery of carbon-bearing minerals: for oil/ natural gas and coal
Russia	Competition with low-cost natural gas No technological tools for commercial production of coal bed methane Insufficient state support
Ukraine	Coal mine methane belongs to the state but the process of granting the right for production to mines and individuals is complicated Most coal enterprises are unprofitable Gas is mainly of low quality, i. e. methane concentration is less than 30 %
India	No techniques and technical knowledge The reserves have not been assessed, techniques have not been selected, project feasibility has not been developed No infrastructure for gas recovery

Table 2 .

Areas of research of high-concentration methane recovery processes	Gas source	Processing volumes per one unit, m^3/min	Methane output concentration	Energy consumption, kWh per tonne of methane at the output
Cryogenic	Degasification	10-15	50	403
Cryogenic with condensation	Ventilation air	10,000	90	1,103
Adsorption	Degasification	10-15	90	698
Diaphragm	Ventilation air	5,000	37.5	400-500
Gradient separator with a dynamic filter	Ventilation air	5,000	99.98	94
Gradient separator with a dynamic filter	Degasification	10-15	99.98	195

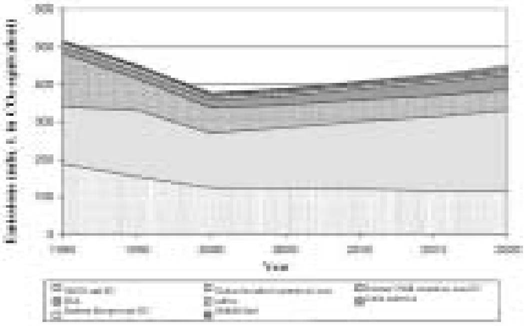
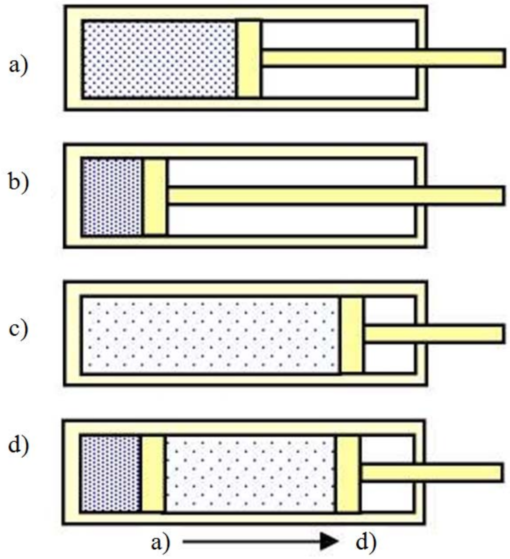


Fig. 1. Change in the amount of mine gas emitted in the world



a) normal state; b) compressed state; c) rarefied state; d) complex-rarefied state.

Fig. 2. Model of gas mixture states

(Backhaus, 2012; Koroleva, & Zakharova, 2011; Kostyuk, 2011; Kreinin, 2012; Mischenko *et al.*, 2011; Report of JSC "GIAP", 1994).

As Table 2 shows, the most efficient method for treatment of mine gases and recovery of highly concentrated methane from them is the solution using a set of equipment consisting of two gradient separators and a dynamic filter. At that, the performance significantly exceeds the existing methods. When methane is recovered from methane dust air mixtures, degasification is halved in power consumption and methane concentration is doubled; when methane is recovered from MAM, ventilation air is 2-5 times less in power consumption and improved in methane output. There are no analogues of a gradient separator with a dynamic filter in methane concentration recovery in Russia and abroad.

Gradient separators and typical dynamic filter units are the main devices which implement the processes of energy vortex gas separation for recovery of highly concentrated methane and mechanical impurities from ventilation and degasification emissions from mines.

The gas dynamic flow, generated in a gradient separator, is called intensively swirling with negatively strained intermolecular bonds of the state of a methane dust air flow in a gradient separator. There are four gas states:

1) Normal state (P= 0);
2) Compressed state (P > 0);
3) Rarefied state (P < 0);
4) Compressed and rarefied state (0 < P < 0).

These four gas states are shown in Figure 2. Position *a* of a piston corresponds to a normal gas state (P = 0); position *b* – to a compressed gas state (P > 0); position *c* – to a rarefied gas state (Đ

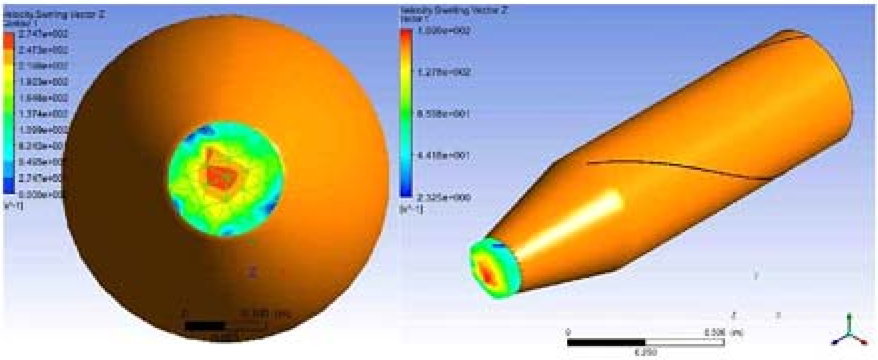


Fig. 3. Model of generation of stable energy vortex gas separation in a gradient separator

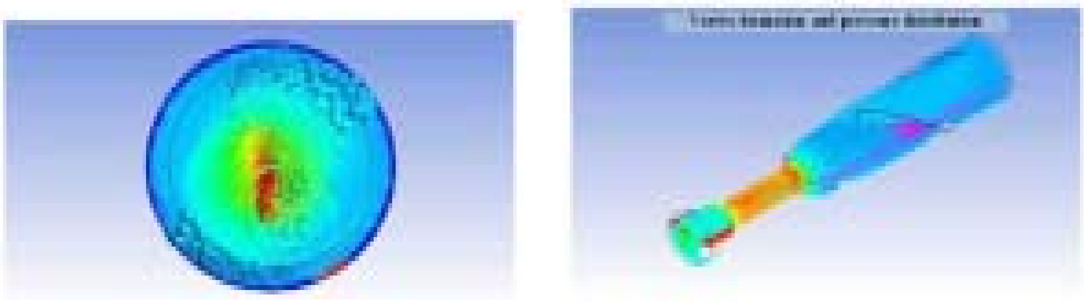


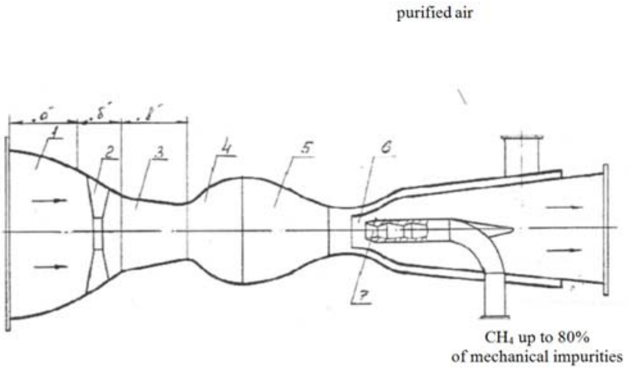
Fig. 4. Model of pressure distribution in a cross section of a swirling flow of mine gases

Fig. 5. Model of assessing the effect of a gas flow with high rarefaction on a swirling dust and gas flow

< 0). If we start to move the piston from position *a* to position η, at the time of its moving a gas is at a negative pressure gradient (position *d* in the Figure). The higher the piston movement velocity is, i.e. $\left(-\frac{dP}{dt}\right)$, the higher the value of a negative pressure gradient in a gas is.

When recovering highly concentrated methane and mechanical impurities from ventilation and degasification emissions from mines, a methane dust air flow goes to a gradient separator. The inlet nozzle of a gradient separator is connected to the existing main vent duct or degasification pipeline by an exhaust duct.

The methane dust air flow goes to the gradient separator through the inlet nozzle, where it will be intensively swirled due to fixed swirlers and special duct geometry. The number of revolutions of a flow will be up to 200 rev/sec in



1 – confusor; 2 – bladed swirler; 3 – confusor; 4 – swirl nozzle; 5 – paraboloidal confusor; 6 – nozzle; 7 – receiver of a flow of highly concentrated methane with mechanical impurities and their bypass.

Fig. 6. Diagram of a gradient separator for intensive swirling of a methane dust air flow and extraction of highly concentrated methane and mechanical impurities from it, including fine coal dust

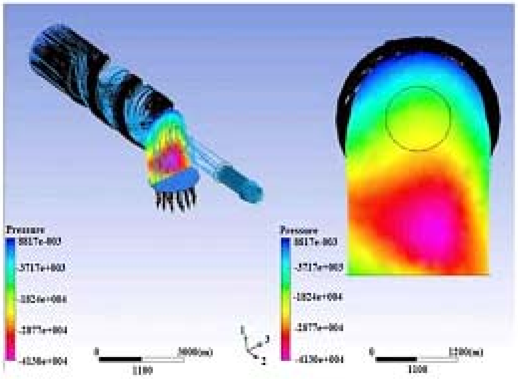


Fig. 7. Model of temperature distribution in a cross section of a swirling methane dust air flow

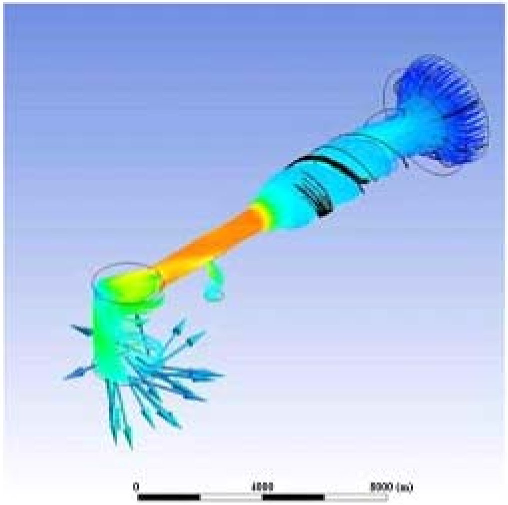


Fig. 8. Model of distribution of methane and mechanical impurities in a swirling methane dust air flow in a gradient separator and dynamic filter

the separator throat (experimental and calculated data received under the ANSYS program), which ensures generation of stable energy vortex gas separation and reduced pressure in the center of a swirling flow (Fig. 3, 4).

With such intense swirling the appropriate structure of a methane dust air flow will be formed with molecular weight separation and high negative pressure gradient by channel section will be formed (Fig. 3,4). Thus, dust and methane component will concentrate in the axial, central part of the whole flow, and the air flow purified from mechanical impurities and coal mine methane will go to the peripheral part. The gas dynamic flow, which is generated in a gradient separator affected by rarefaction, is called intensively swirling with negatively strained intermolecular bonds – ISNP-flow.

If the velocity dust and gas flow adjoins the other gas flow with a higher underpressure, the other gas flow is a “pump” which is used to extract the isolated and separated portion of a dust and gas mixture.

Taking into account the calculated nature of generation of a swirling methane dust air flow in the above models (Fig. 3, 4, 5) the diagram of a gradient separator has been made. The flow which is the mixture of gases in mechanical impurities is supplied into the inlet confusor I containing two sections *a* and *b* of the same profile, where the flow is accelerated. The gas flow in the section *b* receives an additional impulse for swirling by bladed swirler 2.

The gas dynamic flow generated in a gradient separator, which has a number of properties similar to those of vortex flows, will ensure efficient recovery of coal mine methane with ÑÍ_4 concentration of up to 80% and mechanical impurities from ventilation and degasification methane dust air emissions:

1) The thermal motion of molecules of a methane gas mixture is intensified and the Ranque effect occurs, i.e. the effect of temperature redistribution across a cross section of a separator, while the temperature falls in the center it increases at the periphery, which can result in reduced moisture of a methane component separated when using excess heat;
2) The suspended particles conveyed by the flow are concentrated in a central part of a separatorà in the form of a dust “cord”, which is caused by inflow of mechanical impurities into the rarefied core of the swirling gas flow, the following condition is observed: the smaller is the size of coal dust particles, the closer they are to the center.
3) Gas components due to different molecular weight are distributed in the section of a swirling channel – with a smaller molecular weight – (high-concentrated methane) in the intense rarefaction zone in the center, purified air with higher molecular weight – in the peripheral zone.

4) High-concentrated methane with mechanical impurities withdrawn from the receiver goes to a dynamic filter for final sedimentation of mechanical impurities and recovery of highly concentrated methane.

When using the Ranque effect with generation of vortex flows under pressure, the diameters of existing structures with vortex tubes do not reach the size of up to 1 meter, since the energy separation effect does not increase in this case. Having conducted the researches of a gradient separator with negative pressure gradient it was experimentally proven that when the diameter of a gradient separator is increased, the energy separation effect is increased as well, including gas flow through a cross section, this means that performance of the flow treatment plant will increase to up to 200,000 m^3/h.

CONCLUSIONS

Methane concentration in ventilation emissions from coal mines in natural degasification can amount to 0.2-0.7%, and in closed mines and in active degasification of productive mines through the wells specially drilled can be 90%. Methane concentration in degasification emissions mainly make up from 25 to 45%. The methods of methane recovery from ventilation emissions are not used in Russia, they are mainly used abroad, however, they are rather labor intensive and expensive.

To recover coal mine methane from degasification emissions absorption, cryogenic, diaphragm or combined methods are used, the main disadvantage of which is their high labor intensity, material and energy intensity with high consumption of reagents/sorbents, higher operating costs associated with large volumes of methane emissions to be recovered and processed.

The performed comparative assessment of existing methods of recovery of highly concentrated methane from mine ventilation and degasification emissions and the suggested method has shown a potential advantage of intensive swirling vortex of methane dust air flows at a negative pressure gradient.

The scheme is suggested for more efficient implementation of the vortex Ranque effect, for energy vortex gas separation and recovery of highly concentrated methane from ventilation and degasification emissions from coal mines, where the main device is a separator with a negative pressure gradient.

Having conducted the researches of a gradient separator with negative pressure gradient it was experimentally proven that when the diameter of a gradient separator is increased, the energy separation effect is increased as well, including gas flow through a cross section, this means that performance of the flow treatment plant will increase to up to 200,000 m^3/h, which significantly expands the area of practical application of the suggested technique and equipment for gas separation and treatment.

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