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## Development of a new-generation vacuum pump for degassing units

**Abstract.** This article considers the problem of removing harmful or toxic gases from mine workings and industrial premises. Various designs of vacuum pumps are presented, and their performance is analysed. The disadvantages of existing vacuum pumps are identified, along with directions for the development of their designs. New technical solutions for vacuum pumps are offered. A new design for a rotary vacuum pump proposed by the authors is presented. Preliminary general assembly drawings of the pump in sectional view are provided for two extreme rotor positions, as well as two cross-sectional views corresponding to these two extreme rotor positions. A description of the construction of the rotary vacuum pump and its operation is provided. The advantages and capabilities of this rotary vacuum pump compared to the existing models are specified.

**Keywords:** pump, degassing unit, new technical solutions, mine degassing, industrial ventilation

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### Introduction.

In the mining, metallurgical and chemical industries, many technological processes involve the presence of harmful substances in the atmosphere of reaction chambers, premises, and workings, which impair the process technology or make it completely impossible. For example, in the mining industry, vacuum pumps are widely used in safety systems [1, 2]: to combat gas-dynamic phenomena [3, 4], ensure degassing of the coal-rock mass [5, 6], as well as to provide fire protection and maintain explosion safety [7, 8]. In the chemical industry, during the plasma-chemical conversion of coal into synthesis gas, air must be removed from the vessel containing the pulverized coal and replaced with hydrogen or steam. In the mining industry, during coal extraction, a significant amount of methane is released into the workings; this

must be removed or diluted with air to low concentrations to prevent the possibility of a methane-air mixture explosion [9, 10]. Removing methane, or diluting it with fresh air to acceptable levels (less than 3%), requires significant investment and substantially increases the cost of coal; therefore, vacuum pumps are used to remove methane; these are connected to a system of degassing wells linked by a degassing pipeline, and the methane is pumped to the surface where it is used as fuel. To address this challenge, high-performance vacuum pumps with high efficiency are required, which will reduce the overall costs of coal extraction and its production cost.

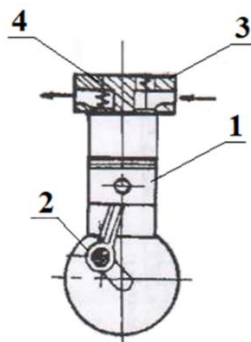
### Problem statement.

In the mining, metallurgical and chemical industries, the problem of effectively removing harmful

and explosive gases from production facilities and mine workings remains relevant. Existing vacuum pump designs are characterised by significant drawbacks, in particular increased friction and the presence of radial and axial clearances, which leads to gas leakage between zones of different pressure and results in reduced efficiency. This makes it impossible to create a deep vacuum, increases energy consumption and shortens the service life of the equipment. These drawbacks are particularly critical for degassing systems in coal mines, where the efficiency of methane extraction directly affects safety and the cost of coal production. Therefore, it is necessary to develop a new-generation vacuum pump with improved sealing, reduced friction and higher energy efficiency, capable of operating reliably under industrial conditions.

### Main material and results.

Rotary-piston vacuum pumps are well known, in particular those described in Patent US9080569B2, which consist of a housing with a cylindrical working chamber in which the piston performs a reciprocating motion by means of an eccentric or crank-and-rod mechanism [11]. As the chamber volume increases, gas is drawn in; as it decreases, the gas is compressed and discharged through the outlet valve into the gas pipeline. A piston vacuum pump (Fig. 1) comprises a housing in which pistons move reciprocally in both directions within cylindrical bores. As the pistons move and the volume of the cylinder bore increases, gas is extracted, for example, from boreholes. Conversely, as the pistons move and the volume of the cylinder bore decreases, the extracted gas is pressurised and fed into the mine gas pipeline for further use.



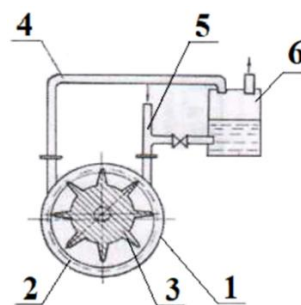
**Figure 1 - Piston vacuum pump:**  
1 - piston, 2 - crank-and-rod mechanism,  
3 - inlet valve, 4 - outlet valve

The drawbacks of conventional piston vacuum pumps include the need to install a check valve in the extraction line, which prevents the creation of pressure lower than that required to open the valve; this, in turn, reduces the gas flow rate from the well. Furthermore, piston pumps are quite complex, metal-intensive, expensive, and have limitations in terms of the rate and volume of gas removed per unit of time.

Liquid-ring vacuum pumps are also used, in particular those described in Patent US 20190063434A1, which consist of a sealed housing with a cylindrical working chamber in which a rotor

with vanes is eccentrically positioned [12]. A part of the housing volume is filled with water, which forms a liquid ring as the rotor rotates, thereby creating zones of gas rarefaction and compression, ensuring its evacuation and delivery.

A liquid-ring vacuum pump (Fig. 2) consists of a housing 1 hermetically sealed by covers on both sides, in which a vane wheel – the rotor 3 – rotates in a cylindrical bore. A part of the bore volume of the pump housing is filled with water, which, during the rotation of the rotor 3, acquires kinetic energy and is pressed against the walls of the bore in the form of a liquid ring 2. Due to gravity, the water layer at the lower part of the housing bore is thicker than in the upper part. This creates a water-free cavity near the wheel axis in the shape of a cylinder offset downward relative to the wheel axis. As they rotate within this cavity, the rotor blades 3 create a vacuum at the bottom and gas compression at the top. By connecting these sections of the liquid-ring vacuum pump cavities to the degassing pipeline 5 and the discharge pipe 4, we achieve the gas extraction from the coal seams.



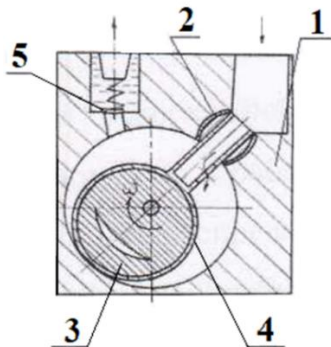
**Figure 2 – Liquid-ring vacuum pump:**  
1 - housing, 2 - liquid ring, 3 - rotor, 4 - discharge pipe,  
5 - degassing pipeline, 6 - water supply tank for the  
pump

The disadvantages of the liquid-ring vacuum pump [12] include low efficiency due to significant energy losses associated with creating and maintaining the liquid ring, as well as water and gas leakage into the gaps between the vanes and the housing; the need for a water tank to supply the pump; and low efficiency (approximately 0.5) due to significant energy losses caused by hydraulic losses in the liquid ring 2.

Single-stage plunger vacuum pumps are also available, in particular those described in Patent EP2873860A1, which consist of a housing with a cylindrical working chamber in which the plunger performs a reciprocating motion by means of a crank-and-rod mechanism [13]. As the volume of the working chamber increases, gas is drawn in, and as it decreases, the gas is compressed and discharged through the outlet valve.

A single-stage plunger vacuum pump (Fig. 3) consists of a housing 1, in the cylindrical bore of which an eccentric 3 slides along its surface together with a cylindrical plunger 4, which is positioned eccentrically relative to the central axis of symmetry of the cylindrical bore and through which gas enters from the vacuum zone. The plunger, together with the inlet pipe

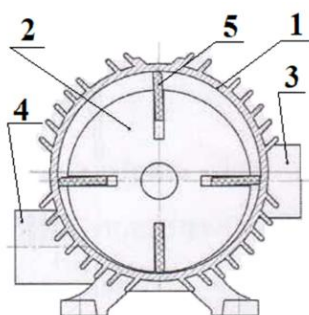
and rotary sleeve 2, divides the volume of the cylindrical bore in the housing into a vacuum chamber and a gas compression chamber; as it moves along the bore wall, it sequentially draws in and compresses the gas, forcing it through the outlet valve 5 into the gas pipeline



**Figure 3 - Single-stage plunger vacuum pump:**  
 1 - housing, 2 - rotary sleeve, 3 - eccentric,  
 4 - plunger, 5 - outlet valve

The disadvantages of the single-stage plunger vacuum pump [13] include friction between the plunger and the surface of the cylindrical bore of the housing, which results in poor sealing between these surfaces, heats them up and promotes gas leakage from the high-pressure zone into the vacuum zone. This also requires greater energy consumption for the pump to operate, which, taken together, significantly reduces its efficiency.

There are known designs of rotary vane vacuum pumps, such as those described in Patent US 20140363319A1, which consist of a housing with a cylindrical chamber in which a rotor with radially movable vanes is arranged eccentrically [14]. The vanes divide the working volume into isolated chambers of variable volume, which ensures the successive suction and compression of gas followed by its discharge into the outlet channel.



**Figure 4 - Rotary vane vacuum pump:**  
 1 - housing, 2 - rotor, 3 - inlet nozzle, 4 - outlet nozzle,  
 5 - rotor vane

The rotary vane vacuum pump (Fig. 4) comprises a housing 1 in which within the bore a cylindrical rotor 2, positioned eccentrically relative to a cylindrical bore, rolls along its inner surface, an inlet 3 and an outlet 4 through which gas enters and is expelled from the pump. Radially arranged vanes 5 in the rotor are constantly pressed against the surface of the cylindrical bore by springs and divide the volume between the bore

and the rotor into isolated chambers. As the rotor rotates and rolls along the borehole surface, gas is successively admitted into and is displaced from the chambers isolated by plates. Once the gas has been discharged, a low-pressure zone is formed in the isolated chambers, into which gas is drawn, for example, from the wells.

The disadvantages of rotary vane vacuum pumps [14] include friction between the vanes and the surface of the cylindrical bore, as well as the end faces of the covers that enclose the cylindrical bore on both sides within the pump housing; furthermore, friction between the cylindrical rotor and these same surfaces results in the heating of the vanes, the rotor and the pump housing, an increase in the clearance between them, and an increase in the amount of gas flowing from the compression zone to the rarefaction zone. This increases the pump's energy consumption, reduces its efficiency, leads to rapid wear of its components, and increases the cost of the gas being extracted from the wells.

The drawbacks of the rotary vane vacuum pump with automatic vacuum breaking [15] include limitations typical of this class, such as the constant sliding friction between the vanes, the rotor and the housing, which results in heating and wear. Over time, the radial and axial clearances increase, causing internal gas leakage and a reduction in vacuum depth and efficiency. Sealing largely depends on mechanical contacts and the oil film, which degrade during operation, limiting service life and requiring regular maintenance.

Therefore, the main drawbacks of vacuum pumps are the clearances between the components and friction, which increases gas leakage from the high-pressure area to the low-pressure zone, preventing the creation of a deep vacuum, as well as increasing the energy consumption required to create a vacuum and reducing the service life of the vacuum pumps.

In this study, the investigation of vacuum pump operation was conducted in several directions simultaneously. First, the direction of development for these pumps was identified. The results showed that rotary vane vacuum pumps performed best compared to other types. Thus, the gas removal rate can range from 0.0003 to 0.8 m<sup>3</sup>/s, with residual pressure in the vacuum chambers ranging from 2 kPa to 0.5 kPa. The rotor vanes can be arranged either radially or tangentially on the rotor. These pumps do not have an inlet check valve; they are smaller and lighter than other vacuum pump designs while offering the same flow rate, and they also have a high mechanical efficiency of 0.8–0.85.

However, they also have significant drawbacks: a short service life before the rotor vanes need replacing due to heat generated by friction against the pump housing, which leads to an increase in both radial and axial clearances and gas leakage between the high- and low-pressure chambers.

In view of this, new technical solutions have been developed to address each of these disadvantages. Thus, instead of rotor vanes, a cylindrical rotor with an

elastic material (such as rubber) on its surface has been proposed; this rotor has a diameter smaller than the inner diameter of the housing, is positioned eccentrically relative to it, and rolls on bearings along the inner cylindrical surface of the housing. This ensures tight sealing between the housing and the rotor, minimal rolling friction, and complete absence of radial clearances and gas leakage in the radial direction. To create separate high- and low-pressure chambers, a locking roller is pressed against the rotor by springs; together with the rotor's rotation, it rolls around its own axis, rising and falling with the rotor, and ensures the complete absence of radial clearances and gas flow in the radial direction between the rotor and the locking roller. To lubricate the rotor surface and prevent radial gas flow, a reservoir containing liquid lubricant is located in the lower part of the pump housing; the locking roller is periodically fully submerged in this lubricant, but it always remains immersed to a depth of one-third of its diameter. This prevents radial gas flow beneath the locking roller and ensures lubrication of the rotor surface and the inner surface of the housing cylinder.

These new technical solutions ensure, on the one hand, minimal friction between the pump housing and the rotor and, on the other hand, complete sealing between the rotor and the housing in the radial direction.

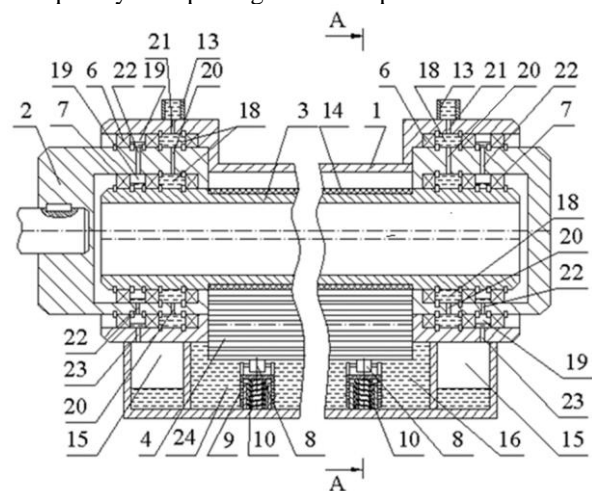
As is well known, the most difficult task is to create a seal between a stationary part and a rotating part. This problem is typically solved by using stuffing box seals, but these have significant drawbacks. This is how they work when pressed against a rotating shaft, but during operation they wear out and their contact pressure against the shaft decreases, which leads to gas leaks; therefore, in this case, it is better to use a liquid as the sealing medium. Indeed, the lubricating fluid fills even the smallest clearances, continuously occupies the entire space between the components, and forms a continuous barrier preventing gas leakage.

To prevent gas leakage between the end faces of the rotor and the housing, a new technical solution has been proposed – a liquid seal between the bearing rows, which involves the following: the cavities between the bearing rows, equipped with sealing washers, are completely filled with liquid lubricant that fills all clearances, while its which is constantly maintained by a supply from the lubricant reservoir through channels in the pump housing and rotor.

There is some leakage of liquid lubricant from the insulating chambers between the bearings, both towards the bore of the housing and towards the pump end faces. The lubricant flowing towards the bore of the housing comes into contact with the flexible surface of the rotor and lubricates it, improving contact with the cylindrical surface of the housing. The lubricant which flows towards the pump end faces enters the oil drainage chambers formed by a further row of bearings and, through the outlet channels in the housing and rotor, lubricant leakage flows into the lubricant collection chambers at the bottom of the pump, which

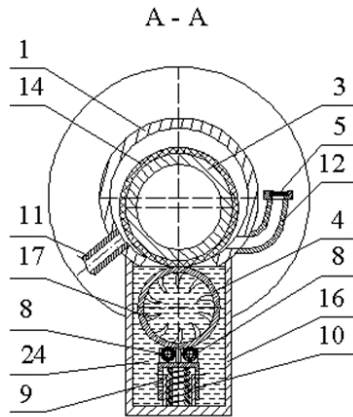
ensures the collection of lubricant leakage from the bearing assemblies and their reuse.

As mentioned above, one of the problems with vacuum pumps is the clearance between the rotor faces, which rotate both about their own axis and in a circular motion relative to the pump housing or end faces. In our case, the locking roller rotates about its own axis and moves linearly relative to the housing. This problem is difficult to resolve completely using the known methods for sealing moving parts; therefore, the authors proposed a new technical solution. In this case, it is also expedient to use a liquid that will continuously fill the clearance between the end faces of the locking roller and the pump housing and end caps; however, this liquid must rise and fall together with the locking roller. For this purpose, the roller is designed as a hollow cylinder containing semi-circular rotor vanes inside. As the locking roller is in constant contact with the rotor and rotates under the action of the rotor's rotation, and as at least one-third of the roller's diameter is always immersed in the liquid lubricant, the roller vanes scoop up the liquid lubricant and transport it to the top of the roller. The liquid lubricant gradually flows into the end clearances between the ends of the locking roller and the housing and pump sleeves, filling these clearances and thus creating a hermetic seal. As these clearances are minimal, and given the time taken for the roller to rise and fall, the amount of lubricant entering the roller as it is immersed and raised is sufficient to keep the end clearances of the roller constantly filled. Furthermore, the roller is always immersed in lubricant to at least one-third of its diameter. Immersion to a depth of one-third of the diameter allows the lower vane of the roller and the space between the surrounding vanes to be fully immersed, filling this space with liquid lubricant and subsequently transporting it to the top of the roller.



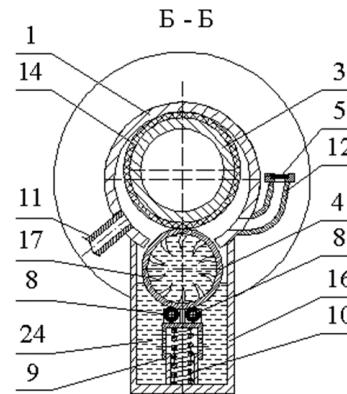
**Figure 5 – Overall view of a rotary vacuum pump in longitudinal section with the rotor in the upper position: housing 1, sleeve 2, rotor 3, locking roller, 4, housing bearings 6, rotor bearings 7, housing bearings 8, cup 9, spring 10, reservoir 13, elastic coating 14, lubricant collection chamber 15, roller sealing chamber 16, sealing chambers 18, lubricant drainage chambers 19, channels 20 inlet channel 21, drain channels 22, outlet channel 23, liquid lubricant 24**

Based on new technical solutions to the problems associated with vacuum pumps, the authors have developed a new design for a rotary vacuum pump, as shown in Figs. 5–8.

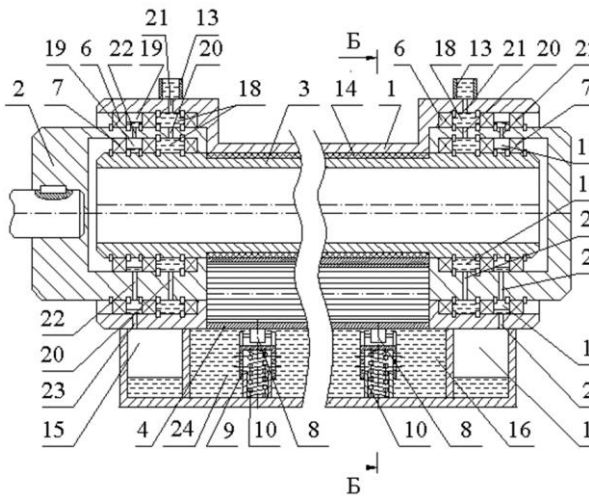


**Figure 6 - Cross-sectional view A–A of the rotary vacuum pump: housing 1, rotor 3, locking roller 4, check valve 5, roller bearings 8, cup 9, spring 10, inlet nozzle 11, outlet nozzle 12, elastic coating 14, roller sealing chamber 16, rotor vanes 17**

surface of the housing 1 while simultaneously rotating about its own axis. At the same time, the locking roller 4 also starts rotating about its axis, being pressed against the rotor 3 by spring 10 via cup 9 and roller bearings 8 (Figs. 5, 6).



**Figure 8 - Cross-sectional view B–B of the rotary vacuum pump: housing 1, rotor 3, locking roller 4, check valve 5, roller bearings 8, cup 9, spring 10, inlet nozzle 11, outlet nozzle 12, elastic coating 14, roller sealing chamber 16, rotor vanes 17**



**Figure 7 – Overall view of a rotary vacuum pump in longitudinal section with the rotor in the lower position: housing 1, sleeve 2, rotor 3, locking roller 4, housing bearings 6, rotor bearings 7, housing bearings 8, cup 9, spring 10, reservoir 13, elastic coating 14, lubricant collection chamber 15, roller sealing chamber 16, sealing chambers 18, lubricant drainage chambers 19, channels 20 inlet channel 21, drain channels 22, outlet channel 23, liquid lubricant 24**

The rotary vacuum pump operates as follows. Liquid lubricant 24 from the reservoir 13, through channel 21 and channels 20, is supplied to the sealing chambers 18 as well as to the roller sealing chamber 16. The inlet nozzle 11 is hermetically connected to the mine degassing pipeline on the side of the wells in the coal seams, while the outlet nozzle 12 is connected to the mine degassing pipeline on the side of its outlet from the mine to the surface. The pump drive is then switched on, which starts rotating the sleeve 2, connected to the housing 1 via the housing bearings 6. The rotor 3, which is connected to the sleeve 2 by means of rotor bearings 7, begins to roll along the inner

The gas compressed by the moving rotor 3 cannot pass between the rotor 3 and the locking roller 4, since the roller is pressed against the elastic coating 14 of the rotor 3. The compressed gas cannot pass beneath the locking roller 4 as well, because its lower part along its entire length is continuously immersed in the liquid lubricant 24 below its level in the roller sealing chamber 16. The gas is therefore displaced by the rotor 3 into the outlet nozzle 12 and further through the check valve 5 into the degassing pipeline, toward its outlet from the mine to the surface (Figs. 6, 8). Gas leakage between the end face of the sleeve 2 and the housing 1, and further through the housing bearings 6, as well as between the radial surface of the rotor 3 and the rotor bearings 7, is also impossible, since all these bearings are equipped with sealing rings on both sides (one of the available bearing designs). In addition, gas flow is blocked by sealing chambers 18 located between the bearings, which are completely filled with liquid lubricant 24. During vacuum pump operation, minor leakage of liquid lubricant 24 from the sealing chambers 18 is possible; therefore, lubricant drainage chambers 19 are arranged behind them, into which the leaking lubricant 24 flows and is subsequently drained through channels 22 and 23 into the lubricant collection chamber 15. On the other side of the sleeve 2, the liquid lubricant 24 is largely retained by the rubber elastic coating 14 of the rotor 3, and then flows down along the walls of the sleeve 2 and the housing 1 into the roller sealing chamber 16. To have the sealing chambers 18 remain completely filled with liquid lubricant 24, a reservoir 13 is mounted on the surface of the housing 1 and is hermetically connected to it. The reservoir is filled with liquid lubricant 24, which is supplied through channels 21 and 20 to replenish the lubricant in the sealing chambers 18. Excess liquid lubricant

flowing out of the lubricant collection chamber 15 is collected and returned to the reservoir 13 (Figs. 5, 7). During rotation of the rotor 3, the locking roller 4 also rotates and moves translationally following the rotor 3 up and down, while its end faces slide along the end surfaces of the sleeve 2 and the housing 1. Since there is a clearance between the locking roller 4 and these components, gas leakage may occur in this zone. To seal this gap, the locking roller 4 is designed as a hollow cylinder with open ends, inside which semicircular vanes are arranged along its entire length. In the lower position, the locking roller is completely immersed in the liquid lubricant 24, which fills its entire internal volume. As the rotor moves to the upper position, the roller rises together with it, and liquid lubricant 24 flows out from its ends, filling the end clearance between the locking roller 4 and the sleeve 2 and housing 1. The semicircular rotor vanes 17 of the locking roller 4, rotating together with the roller, lift the liquid lubricant 24 to the top of the roller, where it is discharged into the end clearance between the locking roller 4, the sleeve 2, and the housing 1. This ensures that the entire clearance is filled with lubricant when the locking roller is in its upper position. In the upper position of the locking roller 4, its lower part remains submerged to one-third of its diameter below the level of the liquid lubricant in the roller sealing chamber 16. Therefore, the liquid lubricant 24 is continuously lifted by the rotor vanes 17 to the upper part of the locking roller 4 and, continuously flowing out, ensures sealing of the clearance.

As the rotor 3 rolls along the inner wall of the housing 1, it moves downward, displacing the gas through the outlet nozzle 12 and the check (flap) valve 5 into the degassing pipeline from the mine to the surface. At the same time, a low-pressure region is formed on the opposite side of the rotor, and gas from the wells in the coal seams begins to flow in through the degassing pipeline. After the rotor 3 passes its lowest position (Figs. 7, 8), it begins to compress the gas that has entered from the wells and filled the volume between the rotor 3 and the inner wall of the housing 1, and the cycle is repeated.

## Interpretation of results and their approval.

The obtained results indicate that the proposed design of the rotary vacuum pump ensures a significant reduction in energy losses and gas leakage between chambers of different pressures due to the absence of sliding friction and the use of liquid sealing in radial and axial clearances. The application of an elastic rotor, a locking roller, and a lubricating fluid as a universal sealing medium makes it possible to increase the efficiency, improve the stability of vacuum generation, and extend the service life of the pump compared to the known analogues. Taken together, the results obtained provide grounds for considering the proposed technical solutions to be well-founded and promising for practical implementation in degassing systems of the mining and related industries.

## Conclusions.

The new design of the rotary vacuum pump proposed by the authors, therefore, has the following advantages over existing vacuum pumps:

- absolute sealing between moving and both moving and stationary components, achieved by filling all clearances with lubricating fluid, which prevents gas leakage between high- and low-pressure chambers as well as air ingress into the pump from the surrounding environment;
- slight friction between the rotor and the housing, as well as between the rotor and the locking roller, in the form of rolling friction on a lubricated surface. In other pump assemblies, only rolling friction occurs in lubricated bearings;
- there are no parts or materials subject to rapid wear, as the only friction involved is rolling friction on a lubricated surface under low load;
- a wide operating range with the ability to adjust the rotor speed and its performance, and to create a deep vacuum;
- simple design and a long service life.

The specified advantages of the proposed rotary vacuum pump make it possible to reduce costs associated with gas extraction from coal seams, gas fields, or with vacuum generation in mine workings and technological processes.

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## Створення вакуумного насосу нового покоління для дегазаційних установок

**Анотація.** В статті розглянута проблема видалення шкідливих або отруйних газів з шахтних виробок та виробничих приміщень. Показані різні конструкції вакуумних насосів та проведений аналіз їх роботи. Визначені недоліки відомих вакуумних насосів та напрямки розвитку їх конструкцій. Показані нові технічні рішення вакуумних насосів. Приведена нова конструкція роторного вакуумного насосу запропонована авторами. Дані ескізи креслення загального виду насосу у розрізі у двох крайніх положеннях ротору, а також два поперечних перерізу у двох крайніх положеннях ротору. Приведений опис складу роторного вакуумного насосу та його роботи. Вказані переваги та можливості даного роторного вакуумного насосу у порівнянні з відомими.

Ключові слова: насос, дегазаційна установка, нові технічні рішення, дегазація шахт, промислова вентиляція.

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