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MATHEMATICAL MODEL OF THE REVERSE WATER POST-PURIFICATION AT MINING ENTERPRISES WHEN USING ELECTROMAGNETIC FOCUSING OF CONTAMINANTS

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Дослідження присвячене доочищенню оборотної води електромагнітним фокусуванням заряджених частинок забруднювачів. Встановлено залежність висоти параболоїду фокусування забруднень від струму установки. Це дозволило обґрунтувати робочі параметри установки електромагнітного очищення та раціонально розмістити обладнання для відведення забруднюючих домішок з потоку. Розроблено методику визначення робочих параметрів установки під конкретний забруднювач, що розширює область її застосування

Ключові слова: електромагнітне очищення рідини, Ларморовий радіус, заряджені частинки, фокусування домішок забруднювачів

Исследование посвящено доочистке оборотной воды электромагнитной фокусировкой заряженных частиц загрязнителей. Установлена зависимость высоты параболоида фокусирования загрязнителей от тока установки. Это позволило обосновать рабочие параметры установки электромагнитной очистки и рационально разместить оборудование для отведения загрязняющих примесей из потока. Разработана методика определения рабочих параметров установки под конкретный загрязнитель, что расширяет область её применения

Ключевые слова: электромагнитная очистка жидкости, Ларморовый радиус, заряженные частицы, фокусировка примесей загрязнителей

1. Introduction

The concept of “cleaner production” in line with the UNIDO (United Nations Industrial Development Organization) procedure implies the improvement of industrial processes in order to reduce waste levels and decrease environmental pollution for the purpose of preservation of natural resources [1].

There is a growing need for water in the human habitat. To prevent contamination of water bodies and to rationally use water resources, mining enterprises apply circulating water systems. However, it is impossible at present to select a water purification system that would provide the required degree of purification under different conditions [2]. A relevant task is the development of innovative techniques for the purification of recycled water at mining enterprises. Therefore, it is important to devise efficient, resource-saving, environmentally-feasible techniques for the post-treatment of fluid that would make it possible to control parameters of post-purification under variable conditions.

2. Literature review and problem statement

Basic techniques for the purification of recycled water are divided into physical and chemical [3]. Chemical techniques are associated with the use of reagents. Such treatment changes the chemical composition of fluid and can harm the environment. A change in the mineral composition of the fluid does not make it possible to calculating the required and sufficient quantities of reagents. The latter leads to insufficient purification, or to the contamination of fluid by excessive reagents.

Mechanical and chemical methods are employed to clean the aquatic environment from bioactive and suspended substances [4]. High-molecular substances and electrolytes dissociate into ions in fluid. This affects the reliability and durability of hydraulic equipment, and they are more difficult to be cleaned applying traditional purification techniques.

More attention is being paid to innovative physical techniques to impact fluid. These techniques ensure that fluid meets the standards and are not cumbersome. Such techniques include treatment of a liquid medium with electromagnetic field. The electromagnetic field provides the improvement of fluid quality by exerting a physical impact on the structure of fluid. Such physical techniques as electromagnetic, acoustic, gravitational, electrophysical, are effective for reducing harmful impurities [5].

The techniques of magnetic treatment of aqueous medium are based on using mostly permanent magnets, which does not make it possible to flexibly control operating parameters of the purification system. The systems for purifying the aqueous environment, based on alternating electromagnets, employ calculation procedures that apply empirical dependences. Empirical dependences cannot be used as functional dependences under varying conditions.

The practice of water purification [6, 7] lacks studies into functional dependences of working parameters of purification systems on the characteristics of contaminants, though the effect of working parameters on a change in the chemical composition of water was established. Therefore, it is important to study functional dependences of working parameters of a system for reverse water post-purification from the chemical composition of contaminants at mining enterprises. According to the state national program of Ukraine [8], fluid purification is the priority direction in scientific and technical activities. The advantages of magnetic treatment of aqueous medium are described in [9]; techniques for the treatment of fluid by a constant axially-symmetric transverse and longitudinal magnetic field are outlined, respectively, in [10, 11].

Authors of paper [12] examined a filter for removing contaminants from a stream of fluid. The model for the process of fluid purification is proposed. The distribution of fluid flow velocity in different sectors of the disk filter was studied. Conditions for effective purification of fluid by a return flow were determined. A shortcoming in the work is the need for additional equipment to create a reverse flow.

Study [13] reports results of purification of sewage membrane nanofilters. By using a spectrometer and X-ray methods, the authors characterized condition of the membrane surface. The choice of substances and the efficiency of cleaning were substantiated. It is recommended to use sequential treatment of filters with citric acid and NaOH for chemical purification. The drawback of the study is the need for additional chemical reagents. Effect of chemical compounds on a change in the molecular state of the surrounding medium was not investigated.

Paper [14] addresses hydraulic purification of fluid contaminated with humic acid by the method of ultrafiltration (UF). The authors studied cleaning of membranes for UF. They compared membrane cleaning from the point of view of hydraulically irreversible pollution index, full surface tension and the residue. The presence of Ca^{2+} in fluid reduced purification efficiency. A shortcoming of the work is the need for additional consumables – membranes, and a limitation in the mineral composition of the fluid.

Study [15] considers an extraction technique. It is based on the combination of the sorption phase of tissue with ultra-high-efficient liquid chromatography of tandem detection by mass spectrometry. The developed technique enables satisfactory detection (from 1.7 ng to 264 ng L-1), recovery and small deviation in relative standard deviations (below 10 % in tap water purified by osmosis, below 20 % in sewage and urine). The drawback of the study is a wide range of standard deviation, which makes it impossible to discard the null hypothesis of an error in the results.

In article [16], the capturing of dust using magnetic filters was investigated. It was established that the rate of filtration depends on magnetic field strength while a particle size is the main parameter for magnetic filtration. Electromagnetic field improves efficiency of collecting contaminants the size less than 10 mm. The collection of pollutants the size not less than 2.5 mm was effective. The drawback is the particle size limitation.

Study [17] established experimental parameters of the speed of rotation of the magnetic support mechanism, the magnetic field strength, distance between two magnets when purifying a liquid with ultrasonic field. For the final treatment of a liquid, a rotational magnetic moment is used to remove contaminating impurities from the main flow. Electrodes were placed in the flow. During ultrasonic, electromagnetic and chemical treatment, particles of contaminating impurities are deposited on the surfaces of electrodes of arbitrary form. Increasing the speed of the magnetic field rotation increases the quality of purification. Increasing the current density reduces the cleaning time and eliminates the difficulty of discharge. The disadvantage of the study is the use of the surface of electrodes as surfaces for deposition. Reduction in the efficiency of purification of liquid due to the accumulation of a precipitate on the surface of the electrodes was not taken into consideration. The effect of ozonating on the molecular and mineral composition of the liquid was not established.

Paper [18] established that the current and voltage applied to magnetic nanowires cause the occurrence of spin and the accumulation of nonequilibrium charge carriers in the nanosized magnetic cells. In this case, there is a spin torque that acts on the magnetic moment. The use of such moments increases the precession of charge carriers. The disadvantage of the work is the failure to take into consideration the constraints associated with the excess of Larmor radius and the height of the paraboloid of focusing, which may go beyond the effective area of electromagnetic effect.

The general disadvantages of the considered studies are the failure to take into consideration the impact of external forces of the electromagnetic field on the trajectory of pollutant impurities movement. The dependences of height of the paraboloid of impurities rotation under the action of Larmor precession on a change in current in the magnetic field focusing coil are not investigated.

The ions of contaminating impurities in a liquid are chemically active. Ions neutralize the action of external energy fluxes, which perform the functions of physical filters. Under the effect of the magnetic field, state energy of charged impurities changes. Due to the difference in the concentrations of cations and anions [19], local electromagnetic fields appear in the liquid. Electromagnetic fields are caused by an electric charge at the interface of phases and the total volumetric charge of the impurity ions. The interaction between a constant electromagnetic field and contaminating impurities is provided by the Larmor precession of the magnetic moment of impurity ions. This affects the trajectory of the ion movement of impurities, Fig. 1

With an increase in field strength, the radius of circular motion of contaminated particles (Larmor radius) decreases. This concentrates contamination in the removal zone from the total flow. The Larmor radius in a given case is the radius of the spiral motion of a charged particle in a homogeneous magnetic field.

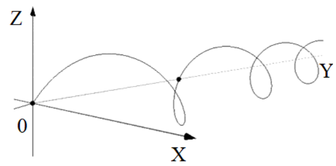

Fig. 1. Trajectory of contaminating impurities movement under the action of electromagnetic field

The most common and most dangerous pollutants include polychlorinated biphenyls [20]. To remove polychlorinated biphenyls from industrial and household wastes, the authors proposed an electromagnetic liquid purification system (EMLPS) [21]. EMLPS winding is positioned in such a way that contaminating impurities moving along the Larmor spiral form a focusing paraboloid in the flow. The peak of the paraboloid is directed to the receiving aperture of the removal of impurities from the total flow. The action principle of the system is described in [21].

The proposed system of electromagnetic purification of liquids is fundamentally different from the existing ones [8–10] by the source of external energy impact. The system of permanent magnets, established for the formation of an axially symmetric magnetic field, was used in the MAKS system [8–10]. For the system of electromagnetic purification of a liquid, suggested in this study, a concept of the use of an alternating electromagnetic field with the formation of turbulences in the flow under the impact of Larmor precession is proposed. In this case, a mathematical apparatus described in (1)–(7), is completely different from [8–10]. The measuring equipment and pipe system used in studies [8–10] were reused, as can be seen from the scheme given in [21]. There was a replacement of the block of permanent magnets MAKS on the coil of focusing, connected to the alternating current network. An experiment was planned, which determined the need to replace the winding of focusing with a winding system with a variable number of turns based on the principle of a "slip rheostat". Thus, at present, the experimental installation is yet to be assembled.

3. The aim and objectives of the study

The aim of present study is to develop a mathematical model for the fluid post-purification from impurities of polychlorinated biphenyls by focusing them with electromagnetic field under conditions of mining enterprises.

To achieve this goal, the following tasks were set:

– to establish a dependence of the Larmor radius of charged impurities on the current of the focusing coil of the electromagnetic system of liquid purification;

– to substantiate parameters for the operating modes of an electromagnetic system of liquid purification from polychlorinated biphenyls;

– to determine a dependence of height of the focusing paraboloid on the Larmor radius of charged particles in contaminating impurities.

4. Materials and methods of research.

A dependence of the Larmor radius of the charged particle in a contaminant on the current in the system of post purification was derived by the method of induction. Initial data for an analysis of the trajectory of impurities movement under the effect of external electromagnetic field are given in Table 1.

Table 1

Initial data for an analysis of the trajectory of i mpurities movement

Parameter	Value	Source
Mass of the charged chlorine particle, kg	5.8852E-26	[22]
Charge of a particle,	1.6E-19	[23]
Magnetic constant, Gn/m	1.2566E-06	
Magnetic permeability of charged particle of chlorine	0.999995	[24]
Pipe diameter (maximum Larmor radius), m	0.18	[25]
Speed of a particle, m/s	1.5	
Number of turns PV-2.5 focusing coil of focusing, pcs.	100	–

We established the dependence of the paraboloid peak on current of the focusing coil based on the flow rate and the time over which the liquid passes from the beginning of the winding to the end of the winding in the system of post-purification.

The exact place of contaminant concentration around the axis of the flow of the reverse water is determined by the value of peak of the rotation paraboloid. At this place, the pipe, through which the water flows, is added with a branch pipe, which takes away part of the flow, in which the contaminant is concentrated, thus purifying it.

5. Results of research into electromagnetic post-purification of liquid from polychlorinated biphenyls

Ions of contaminating impurities, which are in the flow of fluid, are the charged particles. To remove them from the general flow, it is necessary to mount a coil of inductance (focusing) onto the pipeline, creating an electromagnetic field in the flow. This coil is an element of the electromagnetic system of liquid post-purification. Electromagnetic field affects the trajectory of the motion of charged particles in impurities, thereby focusing impurities. In this case, there is the Larmor precession, which enables a spiral trajectory of the charged particle motion. When increasing the intensity of electromagnetic field, the Larmor radius of particle motion decreases. Contaminating impurities form a paraboloid of rotation with a narrow top near the branch pipe nozzle that removes contaminants from the general flow.

Under the effect of the orbital moment, which occurs due to current of the focusing coil, vector of motion direction receives a gain. The gain is oriented by the vector of force moment, which affects the movement of charged particles in impurities. The plane along which vectors of the orbital magnetic moment and induction of the external magnetic field are located is close to the axis of rotation. The Larmor radius of the charged particle in a homogeneous magnetic field is equal to [27]:

$$r_g = \frac{m \cdot v_{\perp}}{|q| \cdot B}, \tag{1}$$

where r_g is the Larmor radius, m; m is the mass of a charged particle, kg; $v_{\perp}$ is the velocity of a particle, perpendicular to the lines of magnetic component of the magnetic field, m/s; q is the charge of a particle, Kl; B is the magnetic induction, Tl.

Magnetic induction [28] is equal to

$$B=\mu_0 \cdot \mu_i \cdot H, \tag{2}$$

where $\mu_0=1.25\cdot 10^{-6}$ is the magnetic constant, Gn/m; μ_i is the magnetic permeability, a.u.; H is the strength of electromagnetic field, A/m.

Strength of the electromagnetic field, A/m, is equal to [29]:

$$H=\frac{I \cdot n}{l}, \tag{3}$$

where I is the current of magnetizing circuit, A; n is the number of focusing coil turns, pcs.; l is the length of focusing coil, m.

Substituting (3), (2) into (1), we obtain the Larmor radius:

$$r_g=\frac{m \cdot v_\perp \cdot l \cdot n}{|q| \cdot B \cdot \mu_0 \cdot \mu_i \cdot I}. \tag{4}$$

The height of vortex, m [30] is:

$$S=v_\perp \cdot t, \tag{5}$$

where S is the top of the vortex paraboloid, m; t is the period over which a charged particle passes from the radius of the pipe to the minimum Larmor radius, s.

The period over which a charged particle passes to the minimum Larmor radius, s [22]:

$$t=\frac{\ln\left(\dfrac{R_{\max}+\sqrt{R_{\max}^2-r_g^2}}{r_g}\right)}{\omega}, \tag{6}$$

where $R_{\max}$ is the pipe radius, m; $\omega=v_\perp/r_g$ is the frequency of a charged particle rotation around the vortex center [30], 1/s.

Substituting (6) in (5), height of the vortex paraboloid, m, will equal:

$$S=r_g \cdot \ln\left(\frac{R_{\max}+\sqrt{R_{\max}^2-r_g^2}}{r_g}\right). \tag{7}$$

The model of EMLPS (4) and (7) is proposed, which is different from the known ones by the following:

– it describes the trajectory of motion of charged particles in contaminating impurities under the effect of electromagnetic field within the limits of EMLPS;

– it establishes the logarithmic dependence of height of the vortex paraboloid on the Larmor radius of charged particles in contaminating impurities;

– it describes the inversely proportional dependence of the Larmor radius of charged particles in contaminating impurities on the current of focusing coil.

In order to substantiate the operating modes of EMLPS (the design and principle of action are described in [21]), the inverse problem on establishing the parameters of EMLPS for a given radius of the outlet branch pipe (the Larmor radius) is solved. We have developed a scheme for choosing working modes according to the required Larmor radius, separately for contaminants based on their chemical composition, and hence based on the value of their mass of a charged particle in line with models (1), (4), (7), Fig. 2.

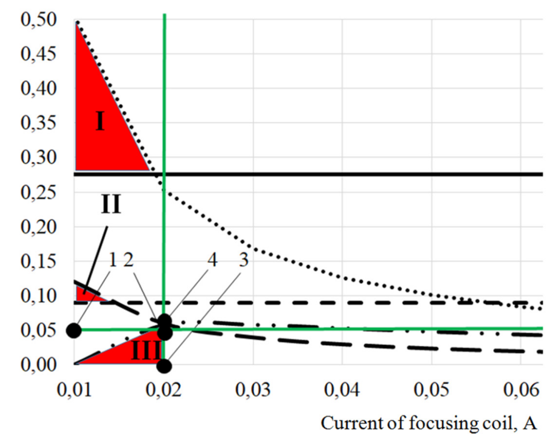

Fig. 2. Scheme of choosing operating modes of the system of electromagnetic post-purification of reverse water for the outlet branch pipe diameter of 0.05 m:
——— – Length of a focusing coil, m;
·············· – Step of Larmor procession, m;
– – – – – – Larmor radius, m; ---------- – Pipe radius, m;
– ·· – ·· – ·· – Height of paraboloid, m

The red zone between the curves of step in the Larmor precession and the length of the focusing coil points to the first banned zone of parameter selection.

The presence of banned zone I is due to the fact that charged particles do not go beyond the limits of EMLPS influence when they have not reached the given radius. Length of the focusing coil is determined based on the characteristics of the wire PV-2.5 for 100 turns, Table 1. The red zone between the curves of the Larmor radius and the diameter of a focusing coil points to the second banned zone. The presence of barred zone II is due to the insufficient current of the focusing coil to create a paraboloid of rotation with spirals of smaller diameter than the diameter of the pipe. The red zone between the curves of the paraboloid height and the Larmor radius points to the third barred zone. The third zone is explained by the possible larger Larmor radius than the initial random distance of the contaminating impurity than the flow axis. Therefore, it is not recommended to assign the Larmor radius within the limits of the third zone because there is a possibility of change in the vector of motion direction of a particle along the axis of the fluid flow.

A change in the Larmor radius and height of the contaminating impurities rotation paraboloid due to an increase in current of the focusing coil is given in Table 2, based on the results of calculations (1), (4), (7).

With an increase in current of the focusing coil from 0.01 A to 0.1 A, the Larmor radius decreased inversely proportional by an order of magnitude, from 0.120 m to 0.012 m. This is due to an increase in the gain of the moment of force, which affects the movement of charged particles in impurities. With an increase in current, moment of force increases in direct proportion and focuses contaminating impurities, forming a paraboloid of rotation. Herewith, height of the paraboloid is reduced by a logarithmic dependence by 43 %, from 0.057 m to 0.032 m. This was due to that the moment of force centers contaminating impurities in the direction of the rotation axis. With increasing strength, which is directly proportional to the current of the focusing coil, charged particles focus until reaching the value of the Larmor radius over a less period. The height of the rotation paraboloid decreases.

Table 2

Dependence of the Larmor radius and height of the contaminating impurities rotation paraboloid of polychlorinated diphenyl on current of the focusing coil

Current, which provides the required induction, A	Calculated Larmor radius, m	Length of focusing winding, m	Step of the Larmor precession, m	Radius of pipe, m	Height of paraboloid, m
0.01	0.120745281	0.275	0.506	0.09	unacceptable value
0.02	0.06037264		0.253		0.057601305
0.03	0.040248427		0.169		0.058104948
0.04	0.03018632		0.126		0.053012539
0.05	0.024149056		0.101		0.048061594
0.06	0.020124213		0.084		0.043836424
0.07	0.017249326		0.072		0.040292206
0.08	0.01509316		0.063		0.037304388
0.09	0.013416142		0.056		0.03475983
0.1	0.012074528		0.051		0.032568965

To determine parameters of EMLPS system, the value of the radius of the outlet branch pipes is set. It is required to determine the rational location of their placement in order to remove contaminants from a general flow. Along the axis of ordinates, the value of the radius of the outlet branch pipes is set, point 1, and a straight line is drawn perpendicular to the ordinate axis, Fig. 2. At the intersection of the straight line with a curve of the Larmor radius we set point 2. This is the point at which the vortex radius of the contaminating impurities will be smaller or equal to the radius of the outlet branch pipe. A straight line is drawn through point 2, perpendicular to the abscissa. The intersection of this straight line with the abscissa, point 3, is the current of the focusing coil, necessary to reach the Larmor radius (point 2). Intersection of the line and the paraboloid height curve, point 4, determines the value of height of the paraboloid. This enables the choice of a rational distance from the beginning of the focusing coil to the place where the outlet branch pipes are to be located. The value of point 4 is the height of the contaminating impurities rotation paraboloid.

EMLPS working parameters are as follows:

– required current of the focusing coil, 0.025 A;

– height of the rotation paraboloid (distance from the beginning of the focusing coil needed for the installation of the outlet branch pipe), 0.07 m.

Since points 2–4 are outside the boundaries of red banned zones, the EMLPS mode is an operational mode.

6. Discussion of results of research into electromagnetic post-purification of liquid from polychlorinated diphenyl

This research is aimed at the post-purification of liquid from the ions of contaminating impurities by physical fields. This allows moving away from methods of chlorination. At present, there are studies [2–18] described above that propose a solution to the problem on post-purification of liquids by physical methods. However, their common disadvantage is the use of empirical dependences.

The functional dependences, derived in the present study, of the Larmor radius of focusing the ions of contaminants on current of the magnetization circuit, the number of turns in a focusing coil, length of a focusing coil (4) allow us to justify operating parameters of an electromagnetic system for the post-purification of liquid. The developed model of an electromagnetic system of liquid post-purification from the charged ions in contaminants made it possible to choose the required Larmor radius for focusing the polychlorinated diphenyl in order to remove them effectively from a flow of liquid.

Based on the research conducted, we are preparing an experimental installation in order to perform the approbation of research results. Present study is continuation of work [21]. We confirmed the character of dependence of height of the paraboloid of focusing on the Larmor radius of charged particles in contaminating impurities. The difference of this study from [21] is in the substantiation of parameters for the system of post-purification of reverse water from polychlorinated biphenyls with the introduction of a schematic procedure of the sequence of steps when choosing operating modes. The limits are defined, expressed by banned zones, which must be taken into consideration when substantiating operating parameters for the system of post-purification by the electromagnetic focusing of contaminants.

The advantages of the conducted research are the following:

– the possibility of using the developed model of an electromagnetic system of liquid post-purification in order to set the system for the post-purification from various types of contaminants;

– a simple procedure for the reproducibility of present research.

The disadvantage of the conducted research is the lack of experimental data. However, an experimental installation is being prepared, specifically the replacement of stationary winding of focusing with a system of coils with a variable number of turns in order to match the procedure of experiment design. In line with the procedure of planned experiment, the study will be conducted into established dependences of the Larmor radius of charged particles in contaminating impurities on current of the post-purification system, as well as height of the focusing paraboloid on the Larmor radius of charged particles in contaminating impurities.

In the future, it is planned to investigate the possibility of decontamination of a liquid by the external variable electromagnetic field. Prerequisites for this are the lack of electromagnetic systems of water decontamination (chlorination, ozonating, and irradiation are typically used). The possibility of setting up a system of post-purification using the electromagnetic focusing of destroying antibacterial effect would make it possible to develop a combined system of post-purification and decontamination of water.

7. Conclusions

1. The inverse-proportional dependence of the Larmor radius of charged particles in contaminating impurities on current of the focusing coil is determined. When increasing the current of the focusing coil from 0.01 A to 0.1 A, the Larmor radius was decreased by an order of magnitude, from 0.120 m to 0.012 m.

2. The choice of parameters for the electromagnetic system of liquid post-purification from polychlorinated biphenyls is substantiated:

– the required current of the focusing coil is 0.025 A;

– the height of the rotation paraboloid (a distance from the beginning of the focusing coil to the place of installation of the outlet branch pipe) is 0.07 m.

3. The model of an electromagnetic system of liquid post-purification from the charged ions in contaminants is developed, which differs from the known ones by the following:

– it describes the trajectory of charged particles motion of contaminating impurities under the effect of electromagnetic field within the electromagnetic system of liquid post-purification;

– it establishes the logarithmic dependence of height of the focusing paraboloid on the Larmor radius of charged particles in contaminating impurities. The height of the focusing paraboloid for polychlorinated biphenyls is decreased by two times, from 0.057 m to 0.032 m, with a decrease in the Larmor radius of the charged particles in polychlorinated biphenyls from 0.06 m to 0.01 m.

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RESEARCH INTO EMISSIONS OF NITROGEN OXIDES WHEN CONVERTING THE DIESEL ENGINES TO ALTERNATIVE FUELS

Розроблена математична модель розрахунку викидів оксидів азоту у відпрацьованих газах дизельних двигунів та двигунів переобладнаних на газове паливо. Виконані в лабораторних умовах експериментальні дослідження дизельного двигуна моделі X17DTL автомобіля Опель Астра на викиди оксидів азоту у відпрацьованих газах дизельного двигуна та двигуна конвертованого на газове паливо

Ключові слова: альтернативні палива, дизельний двигун, оксиди азоту, конвертація двигуна на газ

Разработана математическая модель расчета выбросов оксидов азота в отработанных газах дизельных двигателей и двигателей, переоборудованных на газовое топливо. Выполнены в лабораторных условиях экспериментальные исследования дизельного двигателя модели X17DTL автомобиля Опель Астра на выбросы оксидов азота в отработанных газах дизельного двигателя и двигателя, конвертированного на газовое топливо

Ключевые слова: альтернативные топлива, дизельный двигатель, оксиды азота, конвертация двигателя на газ

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1. Introduction

Oil reserves in the depths of the Earth constantly reduce. According to the optimistic forecasts, at existing explored reserves and current levels of oil extraction, petroleum will last for about fifty years. The second energy resource after oil that can be utilized as fuel for engines is natural gas. Many countries of the world have long come to understand how serious and necessary it is to develop alternative energy generation. At present, against the background of different