MACHINERY AND BUILDING IN AGRICULTURE AND AGRIBUSINESS

DOI: https:/doi.org/10.23649/jae.2020.3.15.1

Cherkasova N.G.[1] *, Chepelev N.I.[2]

[1] Reshetnev Siberian State University of Science and Technology, Krasnoyarsk, Russia;
[2] Krasnoyarsk State Agrarian University, Krasnoyarsk, Russia

* Correspodning author (5hat[at]bk.ru)

Received: 14.06.2020; Accepted: 1.07.2020; Published: 11.09.2020

MECHANISM OF DUST PARTICLES SETTLEMENT AND COAGULATION BY ELECTRIC PRECIPITATORS AT GRAIN PROCESSING ENTERPRISES

Research article

Abstract

The article presents the results of modeling the process of dust deposition and determining the most efficient parameters of electric precipitators for air purification of the workplaces of operators of technological lines of flour mills and grain processing enterprises. It also provides a mechanism for dust coagulation during the operation of electrostatic precipitators. The study is relevant because the air working zone and the air of milling and grain processing enterprises, in particular, contains suspended aerosol with volatile fractions of organic substances. It has a negative effect on both the health of workers and the efficiency of production equipment. The efficiency of the proposed model of dust deposition from the air of the working zone is based on the use of electric charges on dispersed particles, which in turn makes the aerosol sensitive to the external electric fields.

Keywords: electric precipitator, coagulation, corona discharge, flour and grain dust, electric charges, dispersed particles.

Черкасова Н.Г.[1] *, Чепелев Н.И.[2]

[1] Сибирский государственный университет науки и технологий имени академика М.Ф. Решетнева, Красноярск, Россия;
[2] Красноярский государственный аграрный университет, Красноярск, Россия

* Корреспондирующий автора (5hat[at]bk.ru)

Получена: 14.06.2020; Доработана: 1.07.2020; Опубликована: 11.09.2020

МЕХАНИЗМ ОСАЖДЕНИЯ И КОАГУЛЯЦИИ ПЫЛЕВЫХ ЧАСТИЦ ЭЛЕКТРОФИЛЬТРАМИ НА ЗЕРНОПЕРЕРАБАТЫВАЮЩИХ ПРЕДПРИЯТИЯХ

Научная статья

Аннотация

В статье приводятся результаты моделирования процесса осаждения пыли и определения оптимальных параметров электрофильтров для очистки воздуха рабочих мест операторов технологических линий мукомольных и зерноперерабатывающих предприятий. А также приводится механизм коагуляции пыли при работе электрофильтров. Данное исследование вызвано тем, что в воздухе рабочей зоны и, особенно в воздухе мукомольных и зерноперерабатывающих предприятий. постоянно содержится взвешенный аэрозоль, содержащий летучие фракции органических веществ. Что оказывает отрицательное воздействие как на здоровье работников, так и на эффективность работы производственного оборудования. В обоснову эффективности предлагаемой модели осаждения пыли из воздуха рабочей зоны заложено присутствие электрических зарядов на дисперсных частицах, что в свою очередь делает аэрозоль чувствительным к наличию внешних электрических полей.

Ключевые слова: электрофильтр, коагуляция, коронный разряд, мучная и зерновая пыль, электрические заряды, дисперсные частицы.

1. Introduction

At present, there is a significant excess of the norms of maximum permissible concentrations (MPC) for the content of dust particles in the air at flour mills and grain processing enterprises in Russia. According to the requirements of sanitary standards concerning dust content and air cleanliness in workrooms should be maintained at a level not exceeding the MPC: 4 mg/m3 for grain dust and 6 mg/m3 for flour dust. As practice shows, in certain workplaces of operators of flour-grinding equipment, the dust content of air exceeds the permissible values established by sanitary standards by 2–20 times, which can cause severe occupational diseases and a decrease in labour productivity. In addition, the high dust content of air significantly increases the wearing of technological equipment [5].

Finely dispersed aerosol of grain and flour dust is suspended in the air. Without exposure, the colloidal system is stable as there is almost no coagulation process. Even weak convection and Brownian motion of the particles in the air are sufficient to neutralize sedimentation. The medium (air) is ionized at the initial moment t_0. The interaction of aerosol with ions leads to the charging of its particles. The material of the particle is a dielectric; therefore, the ion field causes the polarization of the particle. As a result, the ion and the aerosol particle interact with their fields. The nature of the ion-dipole interaction makes the ion attract the particle. The polar fragments of dust molecules in the ion field are oriented so that a charge opposite to the sign ion charge is induced on the particle surface. In addition to polar molecules, molecules with a zero dipole moment (dispersion interaction) also participate in the polarization [3]. In this case, the molecule itself is polarized. Its electron shell is deformed by the ion field.

At present, mechanical methods of reducing dust concentration are widely used at grain processing and flour production enterprises and namely, supply and exhaust ventilation systems, in combination with cyclones, scrubbers, or cloth filters. The use of mechanical dust collectors in the ventilation system does not significantly improve the air condition of the working area regarding the dust content. This is due to some drawbacks of the devices used, such as the insufficient capacity of capturing the predominant fine dust, high energy consumption, and large overall dimensions.

Based on the foregoing, it is proposed to use as an innovative dust removal technology - a method of electric filtration of dusty air using electric precipitators. According to the research, electrostatic precipitators have some advantages over mechanical and other types of dust collectors. The main advantages of using electric precipitators are the high efficiency of cleaning under various conditions (high dust content, the presence of fine dust in the air, high temperature, humidity, and the presence of high-speed airflow), low energy consumption (as a rule, they do not exceed 100-150 m^3 W per 1000 m^3), simplicity and reliability of the design.

The developed and patented design of the studied electric precipitator (R.F. Patent 2008144413/12 (057920). Publ. 10.11.2008) enables the workers to effectively collect and precipitate dust from the working area of the operators of flour milling and grain processing enterprises.

The electric precipitator contains housing, precipitation, and corona electrodes. The corona electrodes have the form of sets of arcuate metal plates with corona needles placed on two opposite sides, and the corona electrodes are layered in the housing, with increasing linear dimensions of the plates in the direction of the housing, alternating in the direction of gas flow, whereas, the electric precipitator is equipped with a vibration generator of ultrasonic vibrations [7].

2. Methods

A pulsed negative corona is used for electric gas cleaning, i.e., negative voltage pulses of the rectified current will be applied to the corona electrode. This is explained by the high mobility of negative ions in comparison with positive ones; moreover, a negative corona enables maintaining a higher voltage without spark breakdown. In addition, the use of a negative voltage pulse allows applying an even higher voltage to the corona electrodes without the risk of spark breakdown in the interelectrode space, while the use of pulsed power supply significantly improves the quality of cleaning settling and corona electrodes from settled dust in a dust collector [1].

The following factors influence the efficiency of the dust removal device at flour mills:

1) *Um* – the amplitude value of the pulse of the applied voltage at the corona electrodes, kV;
2) *n* – voltage pulse repetition rate, s-1;
3) *V* – air velocity passing through the dedusting device, m/s.

In order to determine the most efficient combination of interrelated factors that influence the object under study, the method of mathematical planning of the experiment is used. The chosen factors that affect the efficiency of the dedusting device are quantitative; they meet the necessary requirements - compatibility and independence.

We take *Y* as an optimization criterion, the efficiency of the electric precipitator. To determine the efficiency of the electric precipitator, we carried out continuous measurements of air dust at the inlet of the airflow into the electric precipitator and at the outlet of the cleaned airflow from the electrostatic precipitator.

We use the planning of a second-order experiment to describe the results of experimental studies, which allows us to obtain a representation of the response using a polynomial of the second degree. For this, a three-level, three-factor Box–Behnken design was used. The three-level Box–Behnken design, are more economical in terms of the number of experiments in comparison with the orthogonal planes and have properties of their own, in addition, the 3-level design is close to the D-optimal one.

In this case, the average experimental error was ε av = 0.000396%, and the maximum ε max = 0.276%. The adequacy of the obtained mathematical model was verified using the Fisher F-test.

3. Results

In accordance with the obtained mathematical model, the surfaces of the response function were constructed (Figs. 1–3). The response surface is nothing more than a five-dimensional paraboloid.

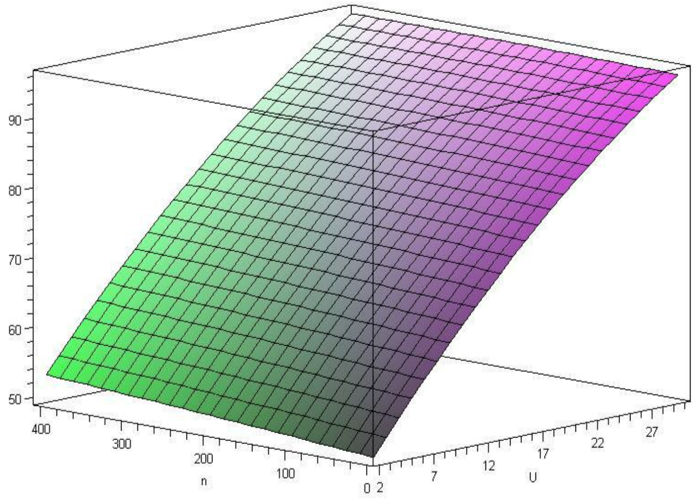

Figure 1 – The surface of the response function with varying parameters: *U* – voltage: *n* – pulse frequency at a fixed value of V = 1.75 (centre of the experiment)

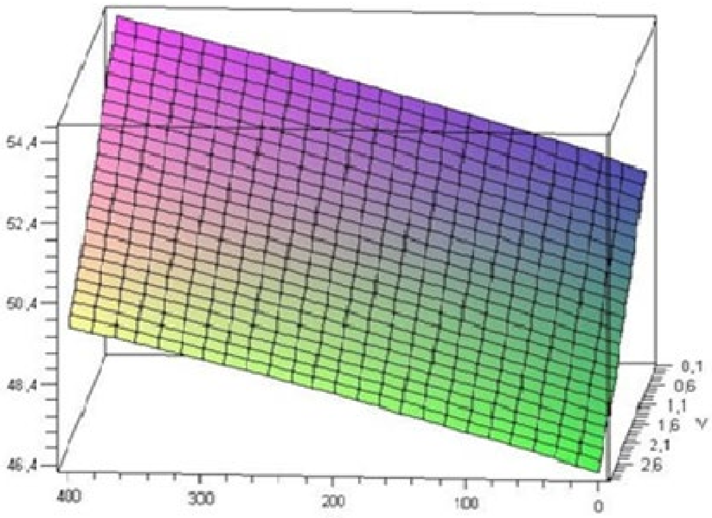

Figure 2 – The surface of the response function with varying parameters: *V* – air velocity; *n* – pulse frequency at a fixed value U = 17 (lower limit)

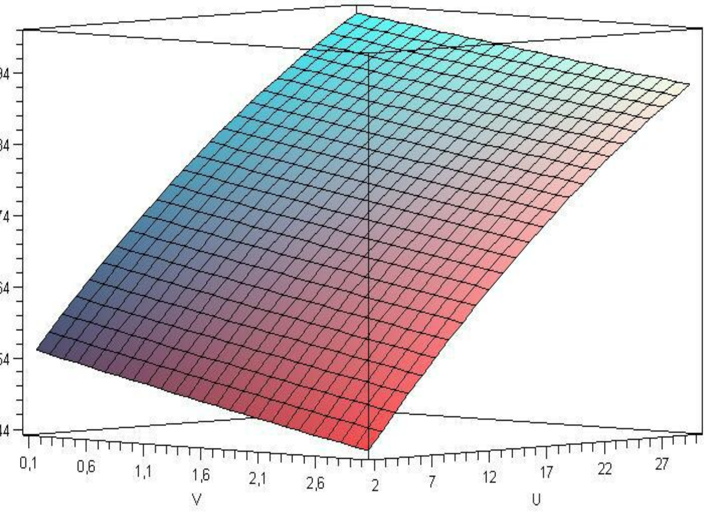

Figure 3 – The surface of the response function with varying parameters: *V* – air velocity; *U* – voltage on the electrodes at a fixed value of n = 500 (upper level)

Analyzing the surface of the response function and the obtained mathematical dependence, we can conclude that the parameters under study influence the effectiveness of reducing dust content in the air ambiguously. A significant dependence of the optimization criterion *Ui* is observed on the influence of the voltage of the rectified current *U*, a noticeable effect is exerted by the velocity of the airflow passing through the dedusting device, and the frequency of voltage pulses is less significant, which fully confirms the theoretical studies.

The data obtained provide the basis for working out the parameters of rational tuning of the proposed device according to the criterion of increasing the efficiency of its operation, i.e., it is required to determine the voltage applied to the electrodes *U*, the pulse frequency n and the airflow velocity through the proposed electric precipitator, whereby the electric precipitator performance would be maximum [2].

4. The mechanism of charging the particles electrostatic precipitators

An electric precipitator activates the ion generation mechanism. Their source is a corona discharge [4]. The generator itself is a high voltage source (of the order of several tens of kilovolts). One of its poles ends with a metal tip (needle); the second one is grounded. The configuration of the first electrode determines the high intensity of the electric field at the tip of the needle. In this regard, a corona discharge emerges at its end. It serves as a source of ions.

The formation of the equilibrium state of the adsorbate is associated with the compaction or dispersal of the adsorbate with an increase in its mass and suggests the molecular exchange of the adsorbate with the gas phase.

A particle located in a suspended aerosol of air from the working zone is affected by the total field from the corona electrodes and created by the charges on the dispersed particles themselves, that is, the field strength in the aerosol depends on the degree of electrification. As this relationship is most obvious for the ionic charging mechanism, we consider it in this model.

When a dielectric particle is charged in a corona discharge field, the charge density is determined only by the number of ions deposited at a given point on its surface. Thus, the distribution of the ion flux density over the particle surface at any moment depends on the distribution of the ion flux density. The ion drift velocity depends on the field strength and ion mobility.

The bipolar effect is more durable than unipolar due to the Coulomb interaction, which allows increasing the efficiency of dust-air stream cleaning. In an electrostatic field, Coulomb attraction prevails, which leads to the lateral attraction of particles in the electric precipitator. In the case of a bipolar medium, the stationary charge can be determined from the expression:

$$q_{S\text{б}} = 4\pi\varepsilon_c\left[1+\frac{2\varepsilon-1}{\varepsilon+2}\right]Er^2\frac{\lambda_1+\lambda_2}{\lambda_1-\lambda_2}\left\{1-\left[1-\left[\frac{\lambda_1+\lambda_2}{\lambda_1-\lambda_2}\right]^{1/2}\right]\right\}, \tag{1}$$

Where $\boldsymbol{\varepsilon}$– polar conductivity of the medium.

An analytical expression for the frequency of the capture of ions by a particle in an electric field is given in the work of Klett, and is presented in the form:

$$\beta_i(x,r) = \beta_i(x,r)\left\{1+(-1)^i\frac{\alpha x}{2x_0\left[1-exp\left[(-1)^{i+1}\cdot {}^{x}/_{x_0}\right]\right]}\right\}, \tag{2}$$

$$x_0 = \frac{4\pi\varepsilon_0 rkT}{e^2}, \qquad \alpha = \frac{eEr}{kT},$$

where$\boldsymbol{\beta_i(x,r)}$ – diffusion capture coefficient.

The analysis of the particle charge distribution shows that the stationary spectrum in the electric field differs more from the normal one and provides an increase in the efficiency of ion charging of particles.

Due to the foregoing, the principle of the device operation is as follows. Dusty air enters the input shaft falling on the corona electrodes located closer to the centre of the electric precipitator. When air with suspended dust particles passes through the interelectrode space of the arcuate plate-shaped corona electrodes, the dust particles acquire a negative charge, move in the direction of the gas flow to the precipitation electrodes, and are deposited on positively charged precipitation electrodes under the influence of the electric field. Dust particles acquire a negative charge with the help of corona needles. The electrons converge in the direction perpendicular to the gas flow. A step-by-step cleaning of dusty gas occurs when gas passes through the levels of alternately arranged cylindrical settlement and arcuate plate-shaped corona electrodes towards the body. Further, purified air leaves through a plastic case. Dust settled on the precipitation and partly on the corona electrodes is supposed to be removed to the dust collecting hopper using an ultrasonic vibration generator that propagates vibration to the precipitation and corona electrodes through a metal hose.

Dust is a colloidal system suspended in a gaseous medium, which means that generally, it is not uniform on a scale of the average particle size of an aerosol. By this, we mean density fluctuations and randomly directed microflows in the medium (convection, thermal diffusion, and diffusion). Highly dispersed aerosol particles are carried away by microflows and are pushed by density fluctuations. All of the above leads to the random movement of aerosol particles in a Brownian picture. Moreover, as is easily shown, the Stokes law serves as its determining factor.

$$F_c=6\pi\eta r v_{\text{ч}}, \tag{3}$$

where F_c- viscous friction force, η - dynamic viscosity of the medium, r – particle radius, $v_{\text{ч}}$ – particle velocity.

The velocity of the aerosol particle at an arbitrary time t will be equal to the derivative of the distance x traveled in time, i.e.

$$v_ч=dx/dt=x'. \quad (4)$$

In a stream of air, two forces act on a particle: Stokes (3) and inertia, which, according to the D'Alembert principle, is equal to the derivative of the particle's mass m by the acceleration of its movement, determined by the time derivative of velocity (4):

$$F_и=mv_ч \quad (5)$$

As the flow-particle system in the selected representation is isolated with respect to the entire colloid system, the sum of these forces is zero. Hence, the equation of motion of the particle is as follows:

$$mv_ч+6\pi\eta rv_x=0 \quad (6)$$

Once in a flow with v_0 velocity, the particle is carried away by force Fc and is simultaneously slowed down by the force of inertia. Therefore, its velocity in the coordinate system moving with the flow is

$$v_ч=v-v_0 \quad (7)$$

As a result, equation (6) is rewritten in the form

$$mv=6\pi\eta r(v-v_0) \quad (8)$$

Equation (8) is conveniently rewritten in exponential form

$$v=v_0[1-\exp(-t/T)] \quad (9)$$

Thus, for the motion of a particle in a viscous medium, we distinguish two sections: with a variable (slowed down or accelerated) and constant (uniform) velocity.

In addition to this, to precipitate a colloid, one must also consider the motion of the particle in the field of gravity. At the initial moment t=0, a spherical particle with radius r moves under the influence of gravity in a viscous medium with v_0 velocity. Two opposing forces act on it: the gravity mg and Stokes $6\pi\eta rv_h$. The resulting force $mg-6\pi\eta rv_h$ according to the d'Alembert principle is equal to the product of mass on acceleration, i.e., the equation of motion of the particle should be written as

$$mv_h= mg-6\pi\eta rv_h \quad (10)$$

Equation (10) is integrated; it is enough to separate the variables

$$mdv_ч/mg-6\pi\eta rv_ч=dt \quad (11)$$

This implies

$$Ln\ (mg-6\pi\eta rv_h)=-6\pi\eta rt/m+C, \quad (12)$$

where C is the integration constant.

For t=0 $v_ч=v_0$. This means that

$$C=\ln(mg-6\pi\eta rv_0) \quad (13)$$

After substituting the found value of C in (10) and potentiating, we obtain

$$mg-6\pi\eta rv_h/mg-6\pi\eta rv_0=\exp(-t/T), \quad (14)$$

where $T=m/6\pi\eta r$ is the characteristic time of motion of the particle.

As in the previous problem, for t>T, i.e. for a sufficiently long time

$$\lim\exp(-t/T)=0 \quad (15)$$

Therefore, for t>T, the difference $mg-6\pi\eta r v_h$ also tends to zero and, thus, the particle begins to move uniformly with the velocity

$$V_{oc}=mg/6\pi\eta r \tag{16}$$

The characteristic time T is rather small. Therefore, we can assume that the settlement of particles generally proceeds with the velocity v_{oc}, given by the formula (16) [6].

5. Conclusion

In terms of statistics, the coagulation of dust in the air at grain processing enterprises should be considered as the result of an inelastic collision of particles in a colloidal system. With a decrease in aerosol concentration, the probability of collision of aerosol particles decreases quite quickly. In other words, at the initial stage, settlements proceed with coagulation or even as a result of coagulation. With a decrease in particle concentration, the contribution of coagulation decreases, and the aerosol settles mainly under the influence of gravity.

As a result of solving the system of equations by the Cramer method, we determined the conditions that will foster the most efficient work of the device:

U=30 кВ, n=400 с-1, V=1,5 м/с.

The obtained values of the operating parameters of the proposed model of an electrostatic precipitator can be used to develop dust removal technology based on the phenomenon of corona discharge at the enterprises of the milling and grain processing industries. The presented mechanism of aerosol electrification of flour and grain dust showed that this process is a factor that significantly affects the kinetics of the aerosol; therefore, charging dispersed dust particles is considered an important element in the aggregation of particles and, as a consequence, their removal from the air.

Conflict of Interest

None declared.

Конфликт интересов

Не указан.

References

1. Веселов С.А. Вентиляционные и аспирационные установки предприятий хлебопродуктов: учеб. пособие для вузов / С.А. Веселов, В.Ф. Ведентьев. – М.: КолосС, 2004. – 240 с.

2. Системы вентиляции и кондиционирования. Теория и практика / В.А. Ананьев, Л.Н. Балуева, А.Д. Гальперин [и др.]. – Изд. 3-е, перераб. и доп. – М.: Евроклимат, 2000. – 416 с.

3. Результаты экспериментальных исследований эффективности работы электрофильтра на зернопе-рерабатывающих предприятиях / Н.И. Чепелев [и др.] // Вестн. КрасГАУ. – 2010. – № 10. – С. 155–159.

4. Чепелев Н.И. Улучшение условий труда при пойменном кормопроизводстве совершенствованием технологии снижения концентрации пыли: автореф. дис…канд. техн. наук. – СПб. – Пушкин, 1994.–16с.

5. Адлер Ю.П. Планирование эксперимента при поиске оптимальных условий / Адлер Ю.П., Маркова Е.В., Грановский Ю.В. – М.: Наука, 2006. – 279 с.

6. Черкасова Н. Г. Улучшение качества очистки и оздоровление воздушной среды искусственной ионизацией : диссертация ... кандидата технических наук : 03.00.16.- Красноярск, 2002.- 286 с.: ил. РГБ ОД, 61 03-5/1064-9

7. Патент № 2383393 Российская Федерация, RU2383393 C1 (2008.01). Концентрированное полимербитумное вяжущее для «сухого» ввода и способ его получения : № 22008144413/12 : заявл. 10.11.2008 : опубл. 10.03.2010 / Едимичев Д.А., Чепелев Н.И. – 6 с. : ил. – Текст : непосредственный

References in English

1. Veselov S.A. Ventilyatsionnye i aspiratsionnye ustanovki predpriyatii khleboproduktov: ucheb. posobie dlya vuzov [Ventilation and Aeration Devices in Bakery: Textbook for Universities] / S.A. Veselov, V.F. Vedentiev. – M.: KolosS, 2004. – 240 p. [in Russian]

2. Ventilation and Air Conditioning Systems. Theory and Practice / V.A. Ananiev, L.N. Balueva, A.D. Halperin [et al.]. - 3rd ed., rev. and suppl. - M.: Euroclimate, 2000. – 416 p.

3. Rezultaty eksperimentalnykh issledovanii effektivnosti raboty elektrofiltra na zernope-rerabatyvayushchikh predpriyatiyakh [Results of Experimental Studies of the Efficiency of Electric Precipitator at Grain Processing Enterprises] / N.I. Chepelev [et al.] // Vestnik KrasGAU [Bulletin of KrasSAU]. – 2010. – No.10. – P. 155–159. [in Russian]

4. Chepelev N.I. Uluchshenie uslovii truda pri poimennom kormoproizvodstve sovershenstvovaniem tekhnologii snizheniya kontsentratsii pyli: avtoref. dis…kand. tekhn. nauk. [Enhancing the Working Conditions in Floodplain Fodder Production by Means of Improving the Technology of Reducing Dust Concentration: Thesis Abstract of PhD in Engineering] – SPb. - Pushkin, 1994. – 16 p. [in Russian]

5. Adler Yu.P. Planirovanie eksperimenta pri poiske optimalnykh uslovii [Planning an Experiment to Find the Most Efficient Conditions] / Adler Yu.P., Markova E.V., Granovskii Yu.V. – M.: Nauka, 2006. – 279 p. [in Russian]

6. Cherkasova N. G. Uluchshenie kachestva ochistki i ozdorovlenie vozdushnoi sredy iskusstvennoi ionizatsiei. [Improving the Quality of Cleaning and Improving the Air by Means of Artificial Ionization]: Thesis of PhD in Engineering: 03.00.16 – Krasnoyarsk, 2002. – 286 pp., Ill. Russian State Library Thesis Department, 61 03-5/1064-9 [in Russian]

7. Patent No. 2383393 Rossiiskaya Federatsiya, RU2383393 S1 (2008.01). Kontsentrirovannoe polimerbitumnoe vyazhushchee dlya «sukhogo» vvoda i sposob ego polucheniya: № 22008144413/12: zayavl. 10.11.2008: opubl. 10.03.2010 [Patent No. 2383393 Russian Federation, RU2383393 S1 (2008.01). Concentrated Polymer Bitumen Binder for "Dry" Input and its Production Method: No. 22008144413/12: claimed. 11/10/2008: publ. 03/10/2010] / Edimichev D.A., Chepelev N.I. – 6 p.: ill. – Text: Direct[in Russian]