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Research and development of coalbed methane extraction by feasible and technical means of selective hydraulic fracturing and horizontal hydrojet drilling

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Dissertation

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Content

Designations and acronyms

ACNGFS - automobile compressed natural gas filling station
VAT- value-added tax
R&D - Research, Development and Engineering
HFT - hydraulic fracturing treatment
MHR - massive hydraulic fracturing
HPF - highly permeable fracture
SF - screenout fracturing
ECT - effective current value
WZ - wellbore zone
TS - tubing string
PAA- polyacrylimide
SSL - spent sulphite liquor
CMC - Carboxy Methyl Cellulose
DBC - deacidized black contact
SAA - surface active agents
UGH - underground gas header
FOCL - focused log
RDS - Radial Drilling Services Inc.
DDM - downhole drilling motor
GG - geomechanic hysteresis

Introduction

Rationale

Unlike the majority of the methane gas deposits, coalbed methane is substantially free of sulfur, which can be used in gas turbine engines and, more importantly, in the internal combustion engines. Gasoline-air mixture has a calorific value of 8850 kcal /m^3, and methane - 8150 kcal/m^3 [1].

Natural gas deficiency in Central Kazakhstan makes it difficult to create a system of automobile compressed natural gas filling station (ACNGFS). Recoverable gas through vertically deviated wells from the surface is of a great concern, since its compositional analysis meet the requirements of utilization, industrial use, the metallurgical and chemical industry as well in the capacity of energy commodities.

The main advantage of coalbed methane in recovering it intimately from coal seams in the basin through the well from the surface is its purity - freedom from impurities. This distinguishes it from gas of oil, condensate and gas fields. Coals are meant to be a natural sorbent.

The criteria for the industrial importance of coalbed methane resources for independent commercial production is its profitability of use along with environmental friendliness. Efficiency is determined by depth exploration, geological and filtration properties of coalbed gas, and most importantly is methane production technology.

In the depths of reclaimed and potentially productive coal-mining fields focuses not only a significant part of the world’s coal resources, but also their complementary dike - methane, the scale of resources that are commensurate with the resources of conventional gas deposits in the world. The concentration of methane in the mixture of natural gas coal seams is 80-98% [2].

Scientifically based assessment of the coal seams role as the major accumulation point of methane in the earth’s crust offers new great challenges in the resource enhancement of hydrocarbon gas. Methane, which is the most dangerous coal companion, is becoming a valuable mineral that is subject to an independent commercial production or simultaneous extraction in mines with comprehensive, phased operation of gas-bearing coal deposits.

Analyzing the work Vengosh and Jackson [3], it can be stated that the world production of coalbed methane will steadily grow, and by 2020 its volume will be brought to 100-150 billion cubic meters per year. In the longer term, experts expect that it will increase up to 470-600 billion cubic meters (15-20% of world production of natural gas).

President of the Republic of Kazakhstan Nazarbayev N.A. entrusted the Government of the Republic to study and make proposals for the organization of production and utilization of methane from coal deposits. In response to this request, the Ministry of Energy developed an action plan for the organization of exploration and extraction of coalbed methane (Roadmap).

Simultaneously, within the framework of the Program of geological exploration in the Republic of Kazakhstan for 2015-2019 years [4] the exploration and pilot projects for unconventional gas (coalbed methane) are provided at the expense of the republican budget in the amount of 4.7 billion tenge. At the same time, in 2014, design and estimate documentation was developed and approved for the gradual study of coalbed methane in the Karaganda coal basin for a total amount of 109.4 million tenge, in the amount of 43.0 million tenge is planned funds for the beginning stage in 2015 which herein after confirmed the lack of funding.

Kazakhstan has significant and practically undeveloped coalbed methane resources that according to various estimates are up 2-4 trillion cubic meters. These include Karaganda (1-3 trillion m^3), Ekibastuz (70 billion m^3), Tengiz-Korzhunkolsky (45 billion m^3) basins, and Zavyalovsky and Samara deposits and other. Such a resource base enables to forecast the possibility of development in the country of new fuel and energy, and chemical industries, based on the use of methane [5].

Relevance of the work

Analyzing more than 70-year history of industrial development of the Karaganda coal basin, wherein more than 110 thousand of exploratory wells were drilled [6], two fundamentally different ways of coalbed methane recovery can be distinguished: a mine (in the fields of active mines) and a borehole.

The mining method is an integral part of the underground coal mining technologies - degassing. The volume of recovered methane is small, and the gas is mainly used for own needs of coal-mining enterprises directly in coal mining area.

The borehole is an industrial method of production. Methane is regarded not as a byproduct of coal mining, but as an independent mineral resource. The development of coalbed methane fields with methane production on an industrial scale is carried out with the application of special intensification technology of gas recovery of layers (the most common options - hydraulic fracturing, pumping air through the hole, or air-to-air mixture, electric stimulus on current layer).

An effective method of forming the optimal system design, as well as increasing productivity to simulate methane production technologies from coal seams is the application of methods of selective fracturing of solid and strong deposits and opening productive layers in soft and weakly cemented coal intervals by horizontal and branched horizontal wellbores - to increase filtering area.

In this regard, the development and application of methods and techniques for large-scale production of methane from coal seams is certainly relevant.

These tasks required an execution of complex works differing methodologically and structurally. These include theoretical studies, experimental studies in the laboratory and in production.

The dissertation examines the complex of theoretical, experimental and methodological problems associated with the development and implementation of the proposed theoretical and technological methodologies of selective hydraulic fracturing and horizontal radial drilling.

In connection with the above, one of the future tasks of today, is the task of the development, creation and implementation into production of new hydraulic fracturing technology and innovative methods of radial drilling, designed for large-scale production of methane from coal seams.

The aim of the thesis is a theoretical and experimental study of gas extraction technology from layers based on the application of the latest technical and technological means of hydraulic fracturing and horizontal hydrojet drilling for methane production.

The principal idea of the thesis is to develop and apply the method of hydraulic fracturing in strong intervals and the radial drilling of horizontal wells in soft coal formations, to prove the positive effects of a combination of two techniques in order to increase gas production depending on the geological and technical conditions of the test well.

The main objectives of the study:

1. To analyze and to define the scope of application and combination of two techniques in order to intensify the gas production;
2. To substantiate the theoretical principles of cutting edge technologies by combining two techniques of enhanced gas production and to identify the advantages for their effective use;
3. To carry out a pilot study under production conditions, and on the basis of the data to create a presumptive method of effective development of coalbed methane;
4. To evaluate the cost-effectiveness of application of theoretical studies and methods in present work.

The object of research - the coal seams on the example of the Karaganda basin.

Methodology - in order to achieve the objectives a complex method of research has been accepted, including a compilation and analysis of literary sources, the application of non-standard technical solutions while using serial equipment, numerical methods of theoretical solutions, of mathematical statistics and logic, feasibility study, full-scale surveillance and testing.

Scientific hypothesis and results of the dissertation:

1. An increase of gas permeability of the coal seam and an intensification of methane production are being achieved through integrated methods of hydraulic fracturing in strong intervals and radial drilling of horizontal wells in soft coal formations.
2. A development of a comprehensive technology, combining two study methods, provides an increase in methane removal on 9,2-14.1 m^3/t and the well production rate up to 20-25 thousand m^3/day and more.
3. Evidence-based guidelines for the selection of the main technological solutions for the reservoir degassing of highly gaseous coal seams are based on the account of the following main factors: predictive rate of gas recovery of coal seams, assessed at the stage of experimental work to determine the basic properties and condition of the coal-gas bearing array (the value of reservoir pressure, gas content, permeability and carbon diffusion coefficients, its sorption characteristics), reserve time for degassing, the value of the "gas barrier" as well as the results of field testing of individual technological solutions or probe operations.

The validity and reliability of scientific statements, conclusions and recommendations are confirmed by:

- the representative volume of borehole studies;
- the results of field tests of the basic technological solutions at conducting the works on approbation of interval hydraulic fracturing and horizontal (radial) hydrojet drilling on wells of Karaganda and Dolin formations;
- the positive outcomes of industrial testing of the developed technological schemes on intensification of coalbed methane production rate.

Scientific novelty of the results is as follows:

1. A change in pressure of methane in undischarged from rock pressure coal seam leads to the geomechanical stresses, substantially exceeding the change in methane pressure causing sorptive deformation.
2. Selective hydraulic fracturing creates conditions for anhydrous methane production by blocking the underground fluid to enter the well due to the pressure of gas in coal deposits, exceeding the value of the hydrostatic pressure of water in the surrounding rocks.
3. A process of reservoir degassing has been simulated, taking into account the hysteresis of mechanical deformations caused by rock pressure and sorption processes in coal, on the basis of hydrodynamic effects of hydrojet radial drilling.
4. An increase in radial drilling speed to 40-50% is being achieved by using alkaline agents (SAA) at a concentration of up to 0.1%, as the adhesive properties soft formations of coal deposits are eliminated and the coefficient of friction is reduced during drilling of wells with jet nozzle.
5. Formation and rationale of methodological guidelines for the selection of key technological solutions for the industrial production of methane from highly gaseous coal seams; identification and approbation of advanced technological scheme and main parameters of complex selective hydraulic fracturing and radial hydrojet drilling as a method of influence on the outburst coal seams subject to intensive and safe development.

The scientific and practical value lies in the development of methods for determining the effective stimulation through production (decontamination) wells and operational applications of either hydraulic fracturing in strong intervals or radial drilling of horizontal wells in soft coal formations.

Implementation of the work. The pilot testing of selective hydraulic fracturing and radial hydrojet drilling had been conducted in the Churubay-Nura district of Karaganda coal basin with experimental methane extraction.

Approbation. The hypothesis and main results of the thesis were presented and discussed at international conferences - Proceedings of the Sixth International Scientific & Practical Conference, Innovative Development Problems in Oil & Gas Industry Almaty, KBTU, (February 20-21, 2014), Problems of Geodynamics and Geoecology inland Orogens; abstracts; Sixth International Symposium, Research Station RAS in Bishkek (23-29 June 2014) and in the materials of the XVII International scientific and practical conference of students, graduate students and young scientists, St. Petersburg, 20-21 September 2016.

Volume and structure of the work. The dissertational work is stated on 111 pages, contains 24 figures, 12 tables, 40 formulas and a list of references of 106 titles.

The hypothesis and main results of the dissertation were published in:

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2. Sabitova D. K. Compilation of geological studies for exploration and production of coalbed methane in the Karaganda coal basin. Herald of The Kazakh-British Technical University; Almaty, № 2 (37), 3 (38), ISSN 1998-6688.
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6. Сабитова Д. К. О перспективах добычи угольного метана на ряде участков карагандинского угольного бассейна. Проблемы геодинамики и геоэкологии внутриконтинентальных орогенов; тезисы докладов; шестой международный симпозиум, научная станция РАН в г. Бишкеке, 23-29 июня, 2014.//Sabitova D.K. About perspectives of coalbed methane production at several areas of the Karaganda coal basin. Problems of Geodynamics and Geoecology inland Orogens; abstracts; Sixth International Symposium, Research Station RAS in Bishkek, 23-29 June 2014.
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1. Survey of world experience in geotechnical coalbed methane production methods

1.1 Development of industrial coalbed methane industry

The first who noticed coalbed methane as an independent mineral resource were specialists from the United States. It should be mentioned that coalbed methane has not been considered as a companion dangerous component of coal mining, but as a full-fledged, albeit unconventional hydrocarbon, which production is actually not related to the activity of the coal companies. Thus, in the United States there are about 250 companies working in the industry, and for the past 10 years, production volumes have been brought up to 60 billion m³ a year. In the US it has been developed and implemented the technology of extraction of coal seams up to 80% of the contained methane therein [7]. Such degree of extraction is achieved by pneumatic and hydrodynamic effects on layers stimulating enhanced gas coals.

Also, intensive work on methane recovery is going in Australia, China, Canada, Poland, Germany and the UK. In Australia, some companies have successfully extracted methane from the mid 90s, where the development is predominantly horizontal wells drilled through the formation at a distance of up to 1500 m. In China, the reserves of methane are about 35 trillion m³. Till now in the territory of China coalfields drilled more than 100 experienced wells; the volume of production is about 10 billion m³ [8]. In the UK, Coalgas company has developed an alternative method of methane extraction by pumping it through the ventilation shafts where it comes from unburnt coal seams. Coalgas is producing methane from two abandoned mines under this technology.

The intensive development of gas fields of coal basins of the United States contributed the competitiveness of coalbed methane to natural gas of traditional fields caused with substantial public support. The impressive growth in gas production from unconventional sources in the United States is explained largely due to two main factors. Tax credit (Article 29, adopted by the US Congress in 1983), which was provided to the leading production companies of unconventional energy resources in the amount of 29$ on ton of oil equivalent [9] The state support in order to reduce oil imports attracted to the development of coalbed methane significant financial, scientific, engineering and technical resources. The second factor is the rapid development of technology and significant reduction in the cost of production of methane from coal seams. Over 10 years of preferential tax treatment companies in the Black Warrior coal mining methane basin were presented by the state tax credits of 270$ million, in San Juan Basin - 860$ million. Most large-scale government support of the development of production of methane from coal seams is carried out in China. The Chinese government has introduced a number of tax incentives to encourage preparation for the exploration and development of coalbed methane fields. The tax on mineral extraction is not currently charged. By analogy with the United States it introduced a tax credit in the amount of 28$ per 1000 m³ of methane extracted from coal seams; Value Added Tax (VAT) is set at 5% for projects carried out in cooperation with foreign companies, enterprises do not pay income tax in the first 2 years of production. Then, the income tax rate is reduced by 50% during the payback period of the project [10]. Import duties are abolished on the import of materials, machines and equipment used for prospecting, exploration, preparation for the development and construction of coalbed methane fields. In order to reduce the cost of the produced gas it is allowed to use accelerated depreciation of special equipment for coalbed methane. In addition, R&D incentives in the development of coalbed methane resources in China have a number of measures to compensate the tax and production costs in the extraction of coalbed methane. VAT that is charged on coalbed methane extraction can be claimed for reimbursement after taxes. Tax compensation can only be used for the purpose of R&D and increase of production, and is not subject to double income tax. From the value-added tax on profits in the current year (in comparison with the previous year) may be deducted up to 40% of investments in the equipment manufactured in China. In addition to reducing the amount of VAT on R&D costs, the taxable income in the current year may be reduced by 50% from R&D costs. The support of Chinese government aims to increase the production of methane from coal seams to the level of 10-12 billion m^3 per year until 2020.

Apparently, in Kazakhstan, as well as throughout the world, the development of production of methane from coal seams, especially at the initial stage, should be more intensive with the financial and fiscal support from the government. This support may include: reduction or complete abolition of customs duties on the import of equipment and materials for the production of methane from coal seams, that has no domestic analogues; introduction of investment incentives on income tax for the payback period of return on investment and tax exemption for mining.

Difference of coal gas production from natural gas is that to obtain the maximum flow rate a large number of drilling holes in different directions are required. In addition, a maximum of debit and stability of the chemical composition is achieved through a significant period of time, when extracting the methane from unloaded coal seams takes up to two years sometimes. Now it is clear that the main components of the price of coalbed methane in these conditions are the cost of drilling and well stimulation, as well as the cost of land preparation equipment and gas utilization. Without the introduction of modern innovative technologies and equipment for the effective implementation of these works of industrial development of CBM fields project will last for many years and, therefore, losing its economic and social importance.

1.2 Distinctive features of coalbed methane fields development

As shown in Table 1 in the world experience for gas recovery stimulation of the formation most commonly used was hydraulic fracturing treatment (HFT), rarely and only under favorable geological conditions, the cavitation methods and expanding the open bottom of the hole. Currently, due to the reduction in the cost of works to intensify the coalbed gas recovery increasingly began to use directional and horizontal drilling - up to 7%, before (until 2002), this method was less widespread - only about 1% of the wells [11].

Table 1 – Intensification methods of coalbed gas recovery in the world practice

Intensification methods	Mining and geological conditions for effective application of the method
Coalbed hydraulic fracturing	Multifunctional, applicable in a variety of geological conditions
Cavitation (pneumo - hydrodynamic drag)	Coal beds with total capacity of> 20 m in the range of occurrence of <100 m, permeability> 30 mD. Reservoir pressure is above hydrostatic. Moderate tensile stress.
Inclined horizontal directional drilling	Low-permeability coal beds with a capacity of > 2 m with sufficiently high gas content in small (up to 600 m) depths.
Expansion of openhole well	High-permeability coal beds from100 mD to 3 D or more.

Natural geological and commercial characteristics of the coal seam (gas content, gas dynamics and filtering options) predetermine the performance and validity of wells, as well as the choice of methods of intensification of coalbed gas recovery. For example, with a low permeability of coal seam the creation of fracturing is necessary; with high permeability the use of pneumatic hydro and dynamic impact with caving that cleans cracks is efficient.

The effectiveness of these methods in specific geological conditions is estimated by production potential of wells and their systems. Mining opportunities quantitatively determined by two indicators: the productivity of wells for methane or flow rate of gas (maximum, current, average over a given period of time) and the total (accumulated) gas production - total (integrated) mining opportunities that characterize the recovery from the depths of the potential resources of methane or gas reserves, as a number of commercial products. These figures together with others will determine the economic viability of commercial methane production.

Issue on methane security

Coalbed methane is another valuable source of energy that assists in coal mining process. Coalbed methane is another valuable source of energy that assists in coal mining process. Currently, with the help of development and introduction of new methane extraction technologies from unloaded coal seams and operating coal mines in the USA, Australia, Canada, and China, the rate of energy consumption of coalbed methane in these countries takes second place after coal among all energy sources. World reserves of coal-bed methane are estimated at 260 trillion m^3 and this index exceeds the reserves of natural gas. The most significant resources are concentrated in the USA, Australia, China, Russia, South Africa, India, Poland, Germany, the UK and Ukraine [12]. Obviously during development of new degassing technologies of coal seams to ensure the methane security in the conditions of intensive underground mining, coalbed methane, as in the form of power source, should be treated more efficiently, despite its relatively small contribution to the final economy of coal mine.

The development of the coal industry is related to the steady growth of the loads on the underground sewage and sinking rock faces; as a result, in the high-performance faces methane emissions increases significantly, which boosts the risk of underground mining. Under these conditions, the mine ventilation system does not provide acceptable conditions for the security of methane concentrations in the mines, so that originates stops of coal mining, which negatively affects the economic production rates. A large number of methane emitted into the shaft atmosphere during the coal excavation negatively affects not only the safety of mining operations, but also reduces the efficiency of modern coal mining and tunneling equipment, increasing pollution of the atmosphere with greenhouse gases. Load growth on the working face is accompanied by increased gassing. Obviously that increase of coal production in gas mines requires the development and application of effective technologies of reducing the methane containing of mining. The case of Karaganda and Donetsk basins shows that two times increase of depth of the development reduced the effectiveness of pre-drainage reservoir in 1.5-2 times as well [13]. This primarily relates to the decrease in the permeability of the coal seams due to increasing overburden pressure. During high work performance of stops in the gas-bearing coal seams the most widespread process is degassing reservoir. However, its effectiveness in low-permeability coal seams (the use of degasification wells without prior physical and geo mechanical effects) is extremely low. Under some estimates the proportion of methane extracted by this method does not exceed 6%. Low efficiency of traditional methods of degassing reservoir of coal seams by underground wells at high loads on stops restrains the intensive development of the mining operations. The greatest difficulties arise in the production of works in dangerous conditions by factor of geodynamic rock bumps and the likelihood of sudden outburst of coal and gas. Obviously, in outburst zones the intensification of degassing reservoir is of paramount importance.

The main focus in solving problems of maintenance of methane is to improve the methane control system in the mine atmosphere and less ventilation and decontamination schemes. The major sources of ignition of methane-air mixtures are explosive works; electrical equipment and apparatus, friction sparking, smoking and even a number of other reasons, which respectively account for about 46, 22, 12.6 and 10% of cases [14]. It should be noted that this does not take into account such important factor as a gas-dynamic phenomena, which solution has a very limited range of possibilities: testing of protective layers, advance degassing and field training. In these circumstances, radical solution of the problem is only possible with integrated approach, covering both the technical and technological, and organizational solutions of increase of methane.

The basic concept of methane security must be a need for methane recovery at all stages of exploration and development of coal deposits.

1.3 Overview of the intensification methods of coalbed degassing

Improving the ways of intensification of coalbed gas recovery aims at increasing the volume of coal production, costs reduction, and mine safety improvements. Also environmental aspect and the possibility of methane utilization are of high importance. We offer a variety of methods for effecting coal array that can solve the problem of outgassing from the various conditions of bedding of layers. There are two ways to intensify the degassing process: the transition of methane from bound to the free state and the increase in the permeability of rocks [15]. The main advantages of the suggested ways to influence the gas-saturated coal array are considered to be simplicity and workability with minimal impact on the coal mining process, harmlessness of agents in use, and economic feasibility. Firstly activities should have a positive impact on the intensification of methane tributaries that can increase the load on the working face. Overview of the well-known methods of coalbed methane extraction showed that the most frequently used effects are hydrodynamic or pneumatic hydrodynamic. Currently, the major routes of exposure to coal and gas array in complex technological schemes are:

- hydrofracturing;
- pneumatic effect using hydrowedge;
- cyclic pneumatic and hydro effect in cavitation mode;
- alternating hydro effect in cavitation mode;
- geoenergy use of coal and gas array;
- mud pulse effects using hydroblow and other effects.

Impact methods on the coal array are implemented through both underground and surface wells. Hydrodynamic method of influencing the gas-saturated coal array has been developed with main advantage of discharge of an array at a large distance from the wells and the improvement of reservoir properties of an array. Method of hydrodynamic effects is significantly different from the fracturing, hydroloosening and hydrofracturing. Currently, there are some works going on to introduce a method for coal mine methane extraction from surface wells using hydrodynamic effects. The most famous and popular method of influence on gas-bearing coal seams is the hydrofracturing method. The main requirements for hydrofracturing technology concern degassing of coal array and host rocks, which will reduce the gas content to a safe level, discharge formation and reducing the risk of manifestations of geodynamic phenomena. The industry tested the following technological schemes:

- Extracting gas from the surface by pumping a working fluid;
- Control the process of disclosing of natural fracture systems;
- Hydrofracturing of layers in a low-amplitude geological faults;
- Hydrofracturing of host rocks technologies.

Hydrofracturing method is widely used in the world.

Hydrofracturing method in the world is widely used. On country level since 1960 the best results of hydrofracturing were achieved in the Karaganda coal basin. Method for treating the coal seam through the wellbore from the surface describes in works [16, 17]. The method comprises injecting a working fluid into the coal seam in its hydrofracturing mode, then reset the wellhead pressure at which the free liquid flow from the wellbore to the creation of hydraulic shock cyclically blocking the flow of the liquid and dropping it into the atmosphere. Creating a hydraulic shock is stopped when the maximum pressure of shock in the cycle becomes smaller than the wellhead pressure of the fluid to its initial flow from wells. In addition, there is a number of famous works related to hydraulic handling of coal seam with various settings. The main disadvantages of hydrofracturing technology are the reduction of permeability of the coal seam. Hydration causes plugging of cracks and pores. For this reason, the effectiveness of the method with increasing depth of the degassed reservoir is lowered. So the next step to intensify was the technical development of using sand or other filler to the pneumatic-hydrodynamic effects. Another disadvantage of hydrofracturing of coal seams is uneven zones of layer processing around the wells. To eliminate this disadvantage technology of hydropulse exposure has been developed using powder pressure generators and fuel and oxidizing compounds. Under pneumatic and hydrodynamic impact method technological measures for dehydration rock mass around the well are carried out. As the wide-ranging experience in operating fishing holes in the US under “Coalbed Methane” technology the water removal from wells and extraction of coalbed methane are two simultaneous arising processes during the work time. Low flow rates of methane from degasification wells can be explained with the following reasons:

- insufficient permeability of treated reservoir for gas;
- decrease in the permeability of the area around the well.

Considering these facts, different approach was implemented to the problem of intensification of methane production - a method of pneumatic impact through wells from the surface. However, this method requires additional material resources and equipment for carrying out the works. The described technology for intensification of gas release from the coal array is based on the experience of the hydrofracturing method [19]. Pneumatic edging is held to release water from the cracks and increase the permeability of the array. Injection compressors produce compressed air under pressure at the wellhead. Under pneumatic impact the edging working fluid does useful operation for the replacement of methane in coal sorption volume. There are also other modes of pneumatic edging [20], where in the areas of exposure the residual gas content of coal is reduced in 1.3-1.5 times and mechanism of lowering the gas content of stops by blocking the methane in the pore space and fractures in remote areas from place of clearing dredging is implemented. Traditionally, in the Karaganda coal basin the construction of wells is used for hydrofracturing implementation, providing the descent of working column below the producing formation with subsequent cementation and perforation. We have noted some problems with this technology, when the near-wellbore area often filled with coal slurry, which leads to complication of dehydration process of formation. To eliminate this drawback the different version of pneumatic impact can be applied. The main feature of the studies carried out in 1996 on Lenin mine field on the early extraction of methane with improved degassing technology [21], was the advance degassing preparation and obtaining the commercially meaningful production rate of methane. To achieve the goal the well design has been developed that provides “perfect” opening of the coal seam, caving in the near-zone and cyclic pneumatic hydrodynamic effects. The direct effect on the coal seam through the degassing hole is divided into two stages. In the first stage after opening of the formation the process of caving is carried out in zone around the wellbore. In the second stage cyclic pneumatic hydrodynamic effect is performed, providing the necessary range effect [16]. There is a method of degassing of unloaded coal seams from the rock pressure by intersecting wells from underground workings, which includes the drilling from threaded development the series of parallel and focused on stops wells. The method utilizes the effect of unloading of coal array at their crossing sites. Formed cracks provide an aerodynamic connection between the series of wells, resulting in evenly degassed array [22, 23]. The disadvantage of this method requires the drilling operations on a large scale, which is not always possible in terms of time and money savings. This drawback is particularly evident at high loads on the working face more than 10 k tones a day, when the extraction pillar is fulfilled in the short term for up to 2 years. Complex degassing is considerably interesting, where the increase of the coal seam permeability is ensured by carrying out hydrofracturing through wells from the surface, and the methane extraction through the reservoir wells. In this case, the degassing reservoir wells produce higher rates of methane because they cross the crack backbone formed during hydrofracturing process. This experience is widely described in the technologies implemented in the mines of Karaganda basin (“Arselor Mittal Temirtau” company) [13]. In certain cases, in combination with conventional methods intensifying active effects such as acoustic, thermal, thermochemical, in situ blast, microbiological effects, physico-chemical and others can be applied. Heat stress is a discharge process in coal reservoir of coolant in the dissection mode, or immediately after the dismemberment of the formation. One of the main goals of the thermal effects on the coal seam is to deepen its degassing by reducing the carbon adsorption capacity with increasing temperature. Research of sorption properties of coal shows that under reservoir pressures of 1-10 MPa, the average value of the expected methane desorption with increasing temperature for coal with volatile of 5-50% is 0.2-0.5 $m^3/(m \cdot K^\circ)$[24]. Thermal effects on the reservoir have the following disadvantages:

- large heat losses in surface heat conductor and downhole particularly at large depths;
- lack of powerful equipment to inject coolant into the well;
- complex and difficult technology to accomplish at the field, of preparation and discharge of the coolant [25].

Theoretical and experimental studies proved the possibility of increasing the permeability of the formation by in situ explosion and the application of methane with oxygen mixtures for this purpose. However, the use of the method in underground conditions is limited due to strict safety requirements in the production of work in coal mines. Regarding commercial production of methane, this method is of great interest, however, is still not widely used. There is also the intensifying method of using seismic and acoustic impact on coal seams. However, this method has not received the widespread use.

In foreign countries a broad industrial extraction of coal and coalbed methane has been produced now, where legislation of these countries contributes to this by stimulating the use of alternative energy sources. Another motivating factor is the high safety standards, excluding the slightest probability of dangerous geodynamic phenomena in gas coal mines.

Thus, necessity, possibility and economic feasibility of large-scale production of methane from coalbeds, using various methods of intensification, supported by the experience of several countries. According to American experts, this trend will develop steadily, and by 2020 the world production of coalbed methane will reach 100-150 billion m^3 a year, and in the future commercial production of coalbed methane in the world can reach up to 470-600 billion m^3 a year, which will amount to 15-20% of the world production of natural gas [12]. Analysis of currently used methods of intensification of gas release from the coal array showed that pneumatic hydrodynamic impact is most effective for mining conditions of coal mine methane through the surface degassing wells. In general, the process of pneumatic and hydrodynamic effects is the closest analogue technology used in the United States and Germany. Commercial value of extraction development and utilization of coal mine methane is greatly enhanced when the complex decision in conjunction with the urgent task of ensuring the production of methane during mining operations with high load on the working face.

Summary of Chapter I

Analysis of the problem of increasing the permeability of the coal seam, and overview of methods for intensifying the process of gas release from coal seams, led to the following conclusions:

1. The world coal production is developing in the direction of increasing load on the working face with the perspective of more than 10 tons/day, which requires the development and implementation of more effective ways to advance and formation of degassing coal seams, without which effective and safe underground mining of coal will not be possible.
2. World and domestic experience in development of gas-bearing coal deposits indicates the presence of technological solutions for the intensification of the advance or current degassing of coal seams, however, significant constraint is the high cost of implementing the technology and insufficiently high efficiency of degassing by pneumatic effects methods using hydrowedge; cyclic pneumatic hydro effect in cavitation mode; alternating hydro effect in cavitation mode; using geoenergy coal and gas array;
3. World experience of advance degassing coal seams and the industrial production of coalbed methane in the United States, Australia, and Canada became possible due to the improvement of the mining legislation, stimulating the use of alternative energy sources and prohibiting the development of gas-bearing coal seams in hazardous geodynamic conditions.
4. Solution of the problem of safe development of gas-bearing coal seams should be based on the creation of cost-effective technologies of mine methane extraction, modern scientific achievements in the field of production of methane in coal seams by fracturing methods in strong intervals or radial horizontal drilling of soft coal rocks.

2 Theoretical studies to develop and create hydro-impact on coal seam in the alternating force mode

2.1 Analysis of hydraulic fracturing peculiarities

For the first time the hydraulic fracturing technique has been applied to improve the productivity of some marginal Kansas wells in the middle of the 1940s (Fig. 1). Following the peak application in the mid-1950s, and a further significant spread in the mid-1980s, a massive hydraulic fracturing (MHR) has turned into the main hole opening technology. This is especially true for the North American low permeability formations. By 1993 the fracturing operation has been applied to 40% of US new oil wells and 70% gas wells [30].

With advanced modern capabilities of fracturing and the introduction of fracturing technology of high-permeability formations (or highly permeable fracture) ("HPF"), in the America professional jargon is also known as the "frac & pack", the method was even more widespread, becoming dominant for all US well types, and in particular for natural gas wells.

Figure 1 - Early operation on fracturing around 1949 [33]

It is now a common view of the enormous benefits offered by the use of hydraulic fracturing for most wells. Even near the point of contact with water or gas, which is considered a problem during operation on fracturing, HPF finds its application, as it allows controlling the fracturing length and limits of the crack parameters [31]. There has been a very rapid increase in the use of the HPF from several separate operations before 1993 up to almost 300 operations a year in the US by 1996. This growth led the foundation for the development of the HPF as a basic tool of optimal wells opening combined into the system and increase of their productivity.

There are many opportunities for further expansion of the application of hydraulic fracturing in the global mining industry, as well as in other industries.

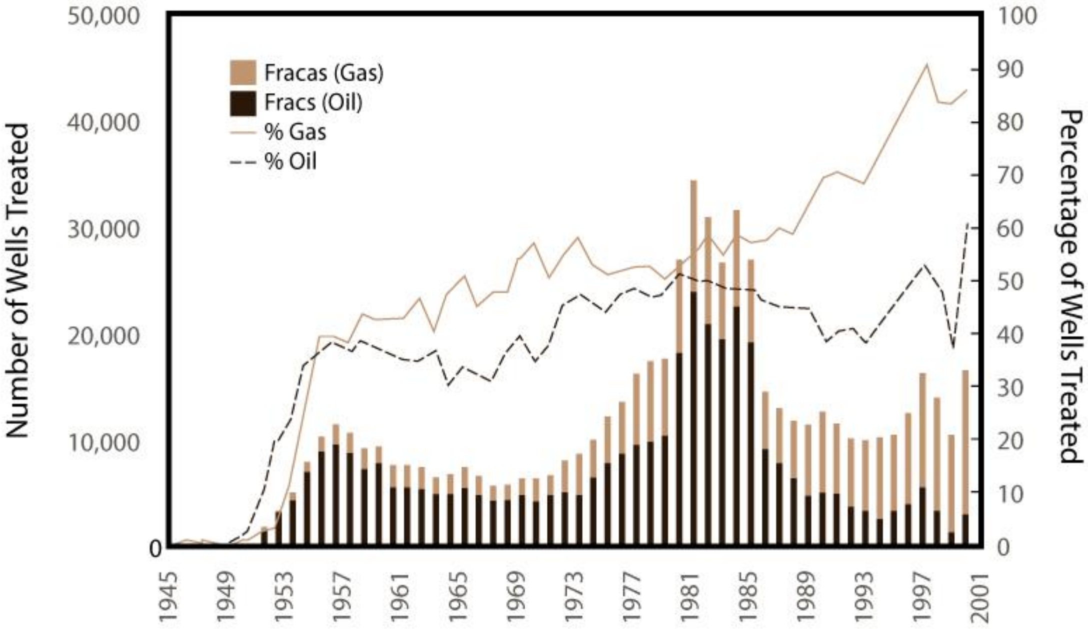


Figure 2 - Hydraulic fracturing as a “final choice” on US oil and gas wells [32]

Hydraulic fracturing is an injection fluid into the subterranean formation at sufficiently high pressures to cause opening of cracks in the rock. Granular materials, called proppants and include both natural sands and quite expensive, synthetic materials that are pumped into formed cracks in the form of slurry. They hold the cracks in the open state (“propped”) after pressure that was used for the fracturing is reduced.

Crack filled with proppant is narrow, but highly conductive path connecting productive areas of the reservoir to the wellbore. The permeability of this path will be very high, often by 5-6 orders higher than permeability formation. In most cases it has a small crack width, but can reach a considerable length and height. A typical value of the crack width in the low-permeability reservoirs is 0.25 cm, with a length of up to several hundred meters. In high permeability formations, the fracture width depending on the scheduling and execution is much larger, about 5 cm, with a minimum length of about 10 m.

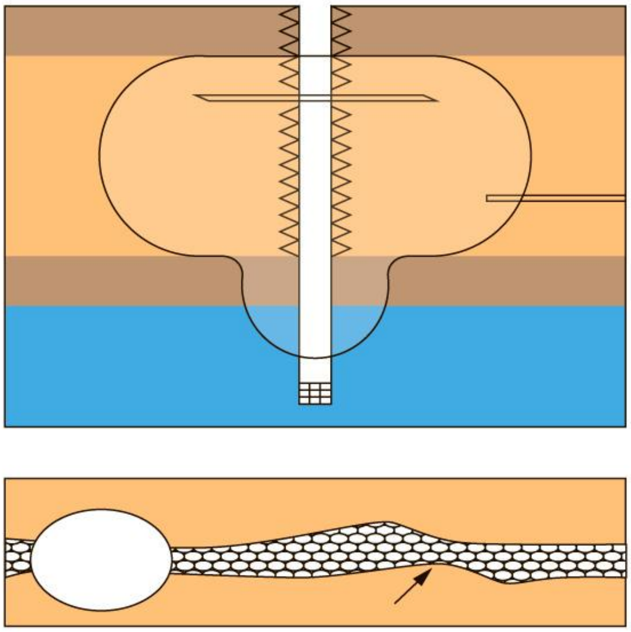


Figure 3 – Increasing the radius as a result of the use of hydraulic fracturing

Almost always a big part of the production goes into the hole on the barrel crack. Thus, the initial damage to bottom zone is prevented, and skin factor [33] before the treatment does not affect the behavior of a well after treatment.

Characteristics of wells undergoing by fracturing, can be described in various ways. The first well-known way is to consider the production of oil, gas and even water as a function of time elapsed since the end of the fracturing operation. However, well productivity after treatment is influenced by many factors which are not critical in planning treatment. Operating pressure in the production well, for example, may or may not coincide with the pressure before treatment; it can be constant in time or not. Even if to do the attempt of comparing well performance parameters before and after treatment, it is still hampered by the high rate of depletion of the reservoir due to the presence of hydraulic fractures.

Thus, the preliminary assessment of optimal size, it is very important to use a fairly simple efficiency index, which describes the expected and the real increase in well productivity because of treatment.

In the uniform design of hydraulic fracturing, we consider a very simple index of efficiency: *productivity index of quasi-steady state*. The increase in this variable shows the real impact of the cracks filled with proppant on the well characteristics. Achieving the highest possible coefficient of quasi-steady state efficiency from a purely practical point of view means that the crack sold optimal placement of proppant, even if the well runs long enough in the so-called “transition” mode. Although this statement may seem unlikely at first sight, an experienced engineer can imagine the establishment of the flow as a steady increase of *area, drained well* where a transitional state is established. Much of the total production may be obtained only by a large drained area, and thus the ratio should be the maximum, which corresponds to completely formed drainage area.

Crack length and dimensionless conductivity of the crack are two main variables that determine the well productivity index subjected to fracturing. The dimensionless fracture conductivity is a measure of the relative flow rate of the fluid inside the crack produced in comparison with the ability to fluid infiltration into the rock fractures. It is calculated as the product of the permeability of cracks on its width, to the product of the permeability of the reservoir at the crack length (by agreement on half the length).

In reservoirs with low permeability the fracture conductivity *de facto* is great, even if a narrow gap is created filled with proppant, and a large crack length is needed. Skin factor value can even reach -7 [34], which leads to a significant improvement in characteristics of the treated wells compared with untreated.

In reservoirs with high permeability for normal behavior of a crack, a large width is a must. In recent years, a new technology called the screenout fracturing (SF) is developed, which allows stopping a longitudinal crack growth and further increasing its width to increase conductivity.

For a fixed volume of proppant injected into the rock, the well will have a maximum efficiency or acceleration when the dimensionless conductivity closes to 1. In other words, the best value of dimensionless conductivity is about 1, at least, for treatments that do not involve a significant amount of proppant. Large values of dimensionless conductivity mean that the crack length is less than optimal, and thus flow from the formation into the fracture is difficult. Values *lower* than 1 imply smaller *width*, creating a bottleneck and thereby lead to a decrease in productivity.

There are a lot of contentious issues complicating the picture: the early establishment of transitional flow regime, the influence of the reservoir circuit, obeying Darcy's law, the proppant crush and others. However, all these effects can be taken into account only if the correct understanding of the role of the dimensionless fracture conductivity is applied.

In some areas, the practical optimum may differ from theoretical. In some cases, theoretically defined fracture configuration is elusive because of the physical limitations imposed by the equipment parameters, lack of necessary materials or rock properties that have to be subjected to fracturing. However, the plan in order to achieve maximum efficiency values or pick-up is only the first step in designing fracturing.

The term “optimum” that was used above means maximizing wells productivity at a given certain value of processing. Consequently, the decision about its size must be preceded before optimization, based on the criteria of the dimensionless fracture conductivity (or taken simultaneously with it).

For a long time practitioners considered half the length of the crack as a convenient variable for the characteristics of its size. This tradition has arisen for the following reasons: firstly, it was impossible to independently vary the length and width of cracks, and secondly, because in low permeability rocks the greatest effect on fracture conductivity is made by its length. In the uniform design of the fracturing, low and high permeable rocks are considered, and therefore the best variable for the performance of created fracture is the *amount of proppant* [35], located within the productive area (layer).

It is evident that the total amount of proppant within the productive layer is less than its total number. From a practical point of view, the assessment of the size of the processing means deciding on the amount of injected proppant. When evaluating the value of processing an engineer has to remember that increasing the amount of injecting element by some value *x* does not necessarily imply an increase in proppant volume in the productive layer by the same amount. Perhaps the most important factor to determine the volumetric efficiency of the proppant is a ratio of height of created fracture to the total thickness of the productive layer. A significant increase in the height limits the volumetric efficiency, so this phenomenon is advisable to avoid. (Another important reason to avoid excessive growth of height is the ability to achieve the level of groundwater).

In fact, the choice of proppant is generally determined by economic factors; for its evaluation the effective current value (ECV) is used. Like in many other types of processing, cost of introducing the proppant increases linearly depending on the amount, but from a certain point, the productivity begins to rise significantly slower disproportionate to costs. Thus, there is an optimum processing size at which ECV of increase in income with deduction of the cost of processing is maximized.

The optimum size can be calculated if the opportunity to predict the maximum value of the increase of productivity when administered certain amount of proppant exists. In the uniform design of the fracturing this fact is widely used as the maximum gain is determined by the volume of proppant within the productive horizon. The decision about the size of simultaneously processing solves many of the operational details that allows designing simple and clear project.

Therefore, we use the term “volume of proppant, reaching a productive horizon” or “volume of proppant in the productive layer” as a key variable in the unified design of hydraulic fracture at the stage of evaluation of sizes [36]. To properly use the variable as the amount of proppant, designed to inject, and its volumetric efficiency must be defined.

While the maximum productivity gains determined by the amount of proppant in the productive layer, for the crack, which will allow realizing this potential increase, some additional conditions must be met. One of the decisive factors is the establishment of the optimal ratio between the length and width of the crack (the deviation from the optimal values should be minimal and only when circumstances require). As shown above, the optimal dimensionless conductivity of fracture is the one variable that allows us to determine this ratio. However, another condition is also important. It characterizes the relationship between the fracture and the wellbore.

The layer is located at a depth in the stressed state characterized by three major strains: the vertical, which is the largest in the case of deep reservoir (more than 500 m), and two horizontal: larger and smaller. Hydraulic fracturing will be normal to the less stress that almost always leads to the appearance of vertical cracks. Crack direction is determined by the natural state of rock stresses. Thus curved and horizontal wells which will be subsequently fractured should be drilled in a direction corresponding to the direction of the crack. Horizontal wells, in this case, apparently, correspond to the plane of crack.

If the azimuth of the well does not coincide with the plane of the fracture, it is likely to start to spread in one direction, and then bending occurs. This will lead to a crack with a high degree of tortuosity; distortion will occur *till reaching* the direction normal to the minimum voltage. Vertical wells with a vertical crack or completely horizontal ones drilled along the crack plane are the most conveniently located systems of well-crack type. Other configurations may give a “surprise” effect that will inevitably reduce the productivity of the well. Perforation and its view can also affect the outcome of the hydraulic operations (for instance, initiation of plurality of cracks or early screening may occur associated with a curved shape).

The dimensionless conductivity of fracture [37] in low permeability formations, of course, is quite high, so the effect of the above phenomena is usually minimal. Often, in order to avoid the formation of winding cracks the method of a point source is used.

Establishing connection between the fracture and the wellbore is currently considered as a critical parameter of successful fracturing of highly permeable formation; it often dictates the shape of the well (for example, drill of S-shaped vertical wells) [38, 101]; or determined the horizontal boreholes, extending along the crack. The leading practitioners consider perforation and alternative methods, such as the erosion of the slots. Some models include complex forms of links of cracks with the well, as well as various effects, and so many uncertain factors do not allow us to predict characteristics. Rather, we are able to explain only options after the test wells and obtaining information on productivity. However, in the planning process, it is desirable to make decisions that minimize the likelihood of decreasing productivity.

2.2 Geomechanical study of the decompression process and the disintegration of the coal seam

Hydraulic fracturing formation is designed for the increase of the permeability of the treated area near wellbore zone (WZ) and includes the creation of artificial and natural expansion cracks. The presence of microcracks in WZ is associated with the process of the initial opening in the drilling phase due to interaction of the bit with the stressed rocks, as well as with the process of secondary opening (perforation).

The substance of HFT is in injecting under pressure in the WZ fluid that fills microcracks and “riving” them, and also creates new cracks. If at the same time inject into newly formed or expanded cracks some fixing material (as sand), after pressure relief the cracks are not going to close.

In unloaded rock mass the stress state of rocks is characterized by the following voltages:

- vertical $\sigma_z = P_g$ determined by the weight of the overlying rocks

$$\sigma_z = Pg = \rho_n gH; \tag{1}$$

- horizontal $\sigma_x = \sigma_y = P_{gg}$ where

$$\sigma_x = \sigma_y = Pgg = \lambda \rho_n gH, \tag{2}$$

in turn ρ_n is density of the overlying rocks;

- H - the depth of the horizon for which voltage is estimated;
- λ - lateral thrust ratio, defined by the formula of academician Dinnik A.N. [39]:

$$\lambda = \frac{\nu}{1-\nu}, \qquad (3)$$

- ν - Poisson coefficient of rock depending on its longitudinal and transverse deformation. For sandstones and limestones ν = 0,2÷0,3; for elastic rock Poisson's ratio ranges 0.25÷0.43. For plastic rocks (clay, shale, rock salt) Poisson's ratio approaches 0.5, resulting in $\lambda \to 1$.

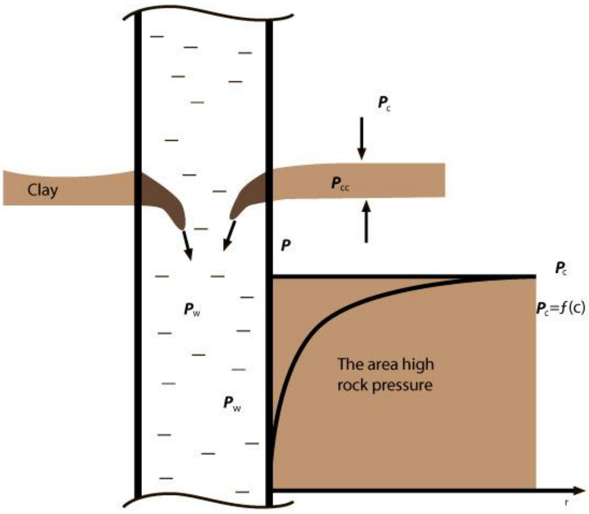


Figure 4 – The formation of the zone of reduced rock pressure in the well section

One of the main parameters of hydraulic fracturing formation is fracturing rock burst pressure [40, 102], which depends on the rock pressure and the strength of the rock. Rock strength even of one development object may vary considerably depending on the type of rock, its porosity, pore space structure, the mineralogical composition and by the presence of clay differences. Consequently, the amount of pressure of fracture P_f is difficult to calculate, but basically it can be related to rock pressure P_r as follows:

$$P_f \geq P_r, \qquad (4)$$

Orientation in space of forming cracks depends to a certain extent on the ratio of P_f/P_r. Thus, the ratio P_f/P_r in real cases can be very different. Experience shows that in many cases $P_f < P_r$

In general, the pressure of fracture depends on the following main factors:

- rock pressure P_r;
- permeability of the WZ and the presence of cracks in it;
- strength and elastic properties of the rock;
- structure of the pore space;
- the properties of the fracturing fluid;
- geological structure of the object;

- technology of hydraulic fracturing and others.

The fracture is carried out by so-called fracturing fluid, and filling of newly formed or expanded cracks with fixing material with a fluid-carrier.

The mechanism of cracks formation

With the implementation of hydraulic fracturing near the wellbore cracks of different spatial orientation can be formed: horizontal, vertical or inclined. Fig. 5 shows a diagram of horizontal and vertical cracks.

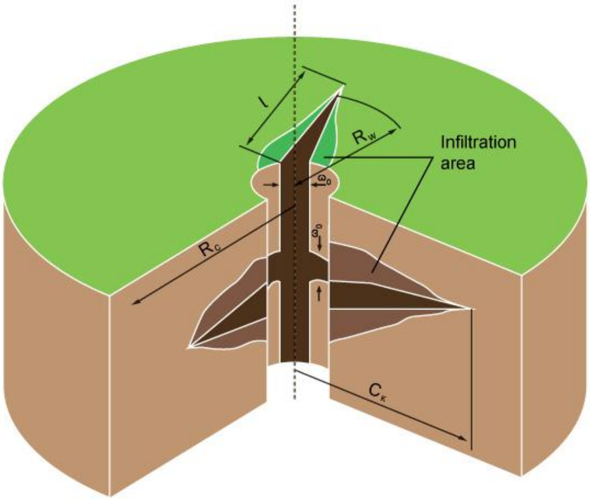


Figure 5 - Scheme of horizontal and vertical cracks

1) Horizontal cracking formation

If the bottom zone of the well is pumped with poorly filtered (medium filter) liquid, filtering starts at the most permeable area of the WZ, defined as a rule by the existence of cracks. Filtering is possible only when the pressure drops ΔP_f [41], that depends on several factors:

$$\Delta P_f = P_{wellbore} - P_{formation} \tag{5}$$

In this case, poorly filtered fluid acts as a wedge, increasing the length and openness of the horizontal cracks. Positive result can be obtained only at a certain pumping rate of the fracturing fluid. Minimum pumping fracturing fluid pace is determined by the empirical relationship:

$$Q_{\min horyzontal} \geq 10^6 \times \frac{\pi R_c \omega_o}{\mu} \tag{6}$$

where $Q_{\min horyzontal}$ is minimum flow of fracturing fluid by a pump to form a horizontal crack, m³/s;

R_c - radius of horizontal cracks, m;

ωo- width of cracks on the wall of the borehole, m (see Figure 5);

μ - viscosity of the fracturing fluid, mPa s.

The formation of a horizontal crack and filtered liquid is principally possible, which is associated with a significant increase in the rate and injection pressure.

2) Vertical (oblique) cracking formation

In case of using a non-filtering fracturing fluid, the tension in the rock increases by increasing the injection pressure. At a certain voltage, exceeding the limit of rock strength in compression, the rock breaks. Physically, the process proceeds as follows. As the injection pressure increased, tension in the rock increases, and its compression is going. Compression occurs to a certain limit determined by the compressive strength. After exceeding this limit, the breed cannot resist the increasing compression and cracks. After removing the pumping pressure the residual cracks (decompressor cracks) of generally vertical or oblique orientation arise.

Minimum rate of fracturing fluid injection is calculated by the following empirical relationship:

$$Q_{\min vertical} \geq 10^6 \times \frac{h\omega_o}{\mu}, \qquad (7)$$

where $Q_{\min vertical}$ is minimum flow of fracturing fluid by a pump to form a vertical crack, m³/s;

h - thickness of layer, m.

Since in the process of injection a certain portion of the liquid is filtered in ΔQ_f rock, forming cracks along the infiltration area, the actual pace of fracturing fluid injection Q_a must be higher than that calculated by the formula (6) and (7):

$$Q_a = Q_{\min} + \Delta Q_f \qquad (8)$$

2.3 Analysis of determination procedures for permeability, deformation and coal rock mass sorption properties

With the development of new methods and technologies of intensification of methane extraction it is important to predict coalbed gas recovery, which is directly connected with the study of the filtration properties of coal seams. A reliable estimate of the permeability in the laboratory conditions is practically impossible because of the substantial differences of cores from the natural state of the coal massif.

Reliable assessment of coal seam permeability is mainly based on the methods of active influence on the coal seam.

The basic method of determining the parameters of a block-fractured environment during the development of wells is the removal of pressure recovery curve. Known methods for determining permeability of reservoirs are:

1) laboratory – based on the cores;
2) hydrodynamic - based on the results of research of wells on the inflow;
3) through correlations - mediated through laboratory data;
4) hydrodynamic logging;

5) profile method based on full-size core.

Determination of the permeability as a result of hydrodynamic studies of wells is based on filtering laws. The solution of inverse problems of hydrodynamic technology allows the development of technology of wells study in the transient and steady-state modes of filtration [25, 42]. Results of profile permeability measurement are used for the rapid assessment of reservoir properties of rocks and are necessary when selecting sampling points for the determination of filtration and capacitive properties of reservoirs.

Laboratory method for determination of the gas permeability is made in a non-stationary filtration rate of nitrogen based on pressure drop on the probe applied to the sample inlet. Measuring range of permeability is from 0.01 to 3000 mD [43]. Geomechanical state of coal rock strata is a contributing factor to the assessment of natural fracturing and permeability promoting the use of technological ways to improve the permeability of the formation and intensification of gas recovery. An important factor to be considered in the projections is variability of permeability and porosity. Near the exposed surface unloaded zone from mountain pressure is formed, where the disclosure of cleavage, tectonic and induced fractures is happening, that significantly increases the porosity and permeability. In this zone the permeability and porosity are not constant: more from the exposed surface and less is deep into the array. The porosity and permeability associated with cracks may change during extraction/absorption of the gas due to swelling and shrinkage. Effect of average stress on the permeability of the coal and surrounding rocks is described by the given formula [44]:

$$C = 1{,}013 * 10^{-\beta\sigma}, \qquad (9)$$

where C - permeability, mD;
β - empirical coefficient, in particular β = 0,31·10-6 Pa;
σ - mean normal stress, Pa;

$$\sigma = \frac{\sigma_x + \sigma_y + \sigma_z}{3}, \qquad (10)$$

It can be concluded that an increase in average compressive stress from atmospheric pressure to 3 MPa, decreases permeability by 10 times. If we know the value of the permeability of C_0 with an average stress σ_0, the permeability C at random mean stress σ will be [45]:

$$C = C_0 \times 10^{\beta(\sigma_0 - \sigma)}, \qquad (11)$$

where σ_0 - average voltage in an array with a known value of permeability C_0.

If you know the value of the permeability C_0 determined in the laboratory or mining conditions, the initial value of the average voltage must be equal to atmospheric pressure. In the presence of information on permeability C_0 in the full-scale object, for the recording of changes of permeability depending on the stress state of σ as a starting point the known value of the medium voltage σ_0 in the array is used. Equation (11) does not take into account the deformation properties of the rock.

However, it should be recognized that the greater the Young's module, the less the factor of rock pressure in the constant change of environment will be manifested, because with large Young's module the deformation is minimal. Therefore, it is lawful, taking into account the stress state, to enter a correction factor as a ratio of Young's module [46], based on which the equation (11) takes the form:

$$C = C_0 \times 10^{\beta(\sigma_0 - \sigma)\frac{E}{E_0}}, \tag{12}$$

where E, E_0 - Young's module of comparable rocks, Pa. Similar empirical relationships are formulated for porosity:

$$\varepsilon_c = \varepsilon_0 \times \mathrm{e}^{-c_f(\sigma - \sigma_0)}, \tag{13}$$

where ε_0 - the initial porosity; a c_f - empirical factor of fracture compressibility. Exceeding the effective stress σ of the initial stresses due to gas pressure changes, shrinkage and swelling is determined by the principle of superposition of stress:

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(\rho - \rho_0) + \frac{\mathrm{E}}{3(1-\nu)}\sum_{j=1}^{n} \alpha_{sj}(C_{\mu y} - C_{\mu y0)}, \tag{14}$$

where ν - Poisson's ratio;
E - Young's module, Pa;
α_{sj} - swelling of the matrix coefficients / shrinkage component j;
p - gas pressure in the pore, Pa.

Using extended Langmuir isotherm [47] the sorption of gas volume for the component j can be calculated as:

$$C_{jy} = \frac{V_{ij} p y_j b_j}{1 + p\sum_{j=1}^{n} y_i b_i}, \tag{15}$$

where V_{ij} - volume Langmuir component j;
yi - molar content of component j in the gas phase;
bj - Langmuir constant component j. Permeability due to cracks can be obtained from the relationship:

$$\frac{C}{C_0} = \left(\frac{\varepsilon_0}{\varepsilon_{c0}}\right)^3, \tag{16}$$

The greatest influence on the permeability of the formation has a width of crack opening. Coal in the natural state has a low permeability. The experimental values of the permeability coefficient, defined in vitro tests with coal cores vary in the range of (0.005-0.05) mD [47]. The largest number of observations of permeability change of the coal seams in the process of methane production is recorded on the "San Juan" pool where the depletion process is more intense than in the other basins. There are also similar findings from "Raton" pool [48]. Considerable data has been collected for developing a method of permeability and porosity prediction of coal seam, as a function of secondary porosity system, pressure and gas content, the composition of the primary porosity system. The method uses information on the drop test and injection using water and/or weaker adsorbing gas than CH_4 and stronger adsorbing gas than CH_4. Calculations of permeability coefficient for water and gas produced from these tests are used with iterative calculation procedure with constraints for solving equivalent system of secondary porosity and absolute permeability at atmospheric pressure. The absolute permeability and porosity of the natural fracture varies as a function of pressure location within a natural fracture system, the gas composition inside the carbon matrix. As a result models of evaluation of porosity and permeability changes as a function of pressure and composition of sorption gas were developed.

The work discusses in detail the theory and the plan of iteration procedures is given to calibrate the model using the well test data. For comparison, it is necessary to explore the three main parameters:

1) the initial permeability and the gas composition in the reservoir;

2) permeability as a function of pressure under the injection of water or poorly sorption gas;

3) permeability during production after the injection strong sorption gas.

Applying of the theory is illustrated by actual test results [34, 36, 49]. Summing up the results of the analysis techniques it can be argued that coal permeability determined in the laboratory gives a description, which may differ from the natural formation permeability by order or greater. This is due to a significant impact on the value of the permeability of rock pressure and the stress-strain state. Therefore, the real coal seam permeability can be judged only in natural conditions as a result of well testing or measurements of gas concentration in the air flow in the specific geological conditions. With this approach it is possible to consider many unpredictable factors, such as stress distribution with taking into account upper mining or undermining the reservoir, as well as the stress concentration around the gob. The theoretical method for calculating the permeability is only for a comparative analysis of the technical solutions, but to claim the accuracy of calculation of the absolute values is hardly possible.

The coal seams are highly heterogeneous in composition and consist of slips and lenses of coal matter of different structures represented mainly by vitrain, fusain, eu-durit and durain, which significantly differ in their deformation properties. The degree of metamorphism of coal seams has a significant impact on the coal properties. Deformation properties are important characteristics of coal seams. The methods for the determination of the elastic properties of the sample-prisms of 100 mm in height and cross-sectional area of 24-25 cm^2 are known. The module of elasticity E is calculated on a load-deformation plot of diagram at the load level in the range of 0.2-0.7 of the compressive strength. The main problems in the selection of cores are their destruction and complexity of manufacture of the necessary samples of correct form from coal. Therefore it is advisable to determine the deformation properties of coal, module of elasticity and dynamic way shear. Dynamic modules of elasticity and shear better characterize the deformation properties, due to the fact that they are determined by the ratio of elastic and inelastic properties, and because coal and rock are elastic - plastic bodies.

The study of deformation properties of coal is also possible by non-destructive impact on coal on the installation to determine the rate of distribution of longitudinal and transverse elastic waves. The average values of the deformation of dynamic modules of elasticity and shear is calculated by measuring the velocity of elastic longitudinal and transverse waves in coal samples from known formulas [50]. Humidity provides a significant influence on the deformation properties of coal. With increasing humidity the dynamic elasticity and shear modules are reduced, which is associated with an increase in coal plasticity and ability to decrease the accumulation of elastic strain energy and brittle fracture.

The sorption parameters of coal seam are included in the Langmuir adsorption isotherm. In various conditions of development of coalbed the sorption parameter values differ. For Australian coals Langmuir parameters vary in the range:

- sorption capacity of coal to methane of 20.1 kg/t (30.0 m^3/t) to 65.7 kg/t (98.0 m^3/t);
- pressure setting from 0,147·10-6 to 1.89·10-6 Pa-1;
- porosity from 4.9 to 10%.

For comparison the settings for "Kazakhstan" coal mine (mine laboratory data) are:

- Langmuir constant pressure 2.6·10-6 Pa-1;
- Langmuir sorption capacity of 24.84 m^3/t.

Traditionally Langmuir adsorption parameters are determined in vitro, using the procedure of sorption methane saturation of pulverized coal fraction. This laboratory tests quite reliably reflect the values of the constants of the Langmuir isotherm, as compared to the indirect measurement methods, because the constant does not depend on the scale factor.

Foreign experience of research of measuring the volume voltage has a rich history. Volumetric voltage must be measured inside the carbon matrix at varying gas pressure [15, 23, 51]. For data analysis of the adsorption isotherm, commonly model of Langmuir is used. Since the pressure-strain data follow the trend of isothermal form, so to the simulate the data on the strain the equation is used that has the same mathematical form as the Langmuir equation and gives enough good comparison with experimental data on the strain [45, 47, 52]:

$$\varepsilon_v = \frac{\varepsilon_L p}{p + p_\varepsilon}, \qquad (17)$$

where v - volumetric strain at a given pressure p,

ε_L and p_ε - model constants which are derived via the best ε comparisons linearized form of the equation, i.e. L_ε represents the maximum theoretical deformation at infinity pressure $p\varepsilon$ - pressure at 50% of maximum strain.

The volumetric deformation is calculated using the average values of the vertical and horizontal deformation with temperature correction. The following equation for the volumetric strain ε for cylindrical samples was derived assuming isotropic swelling/contraction of the sample during adsorption/desorption process:

$$\varepsilon = \frac{\Delta V}{V} = \varepsilon_r^2 + 2\varepsilon_r + \varepsilon_a + \varepsilon_r^2\varepsilon_a + 2\varepsilon_a\varepsilon_r, \quad (18)$$

where V - the initial volume, m^3;

ΔV - change in volume, m^3;

ε_a - axial strain;

ε_r - radial deformation.

The coefficients of swelling/shrinkage of the matrix are a measure of strain change with pressure change. It can be removed in two ways: one way on the basis of the pressure-strain relationship, which is similar to a Langmuir isotherm shape and can be derived by differentiating the equation (16):

$$C_m = \frac{d\varepsilon_v}{dp} = \frac{\varepsilon_L p_\varepsilon}{(p+p_\varepsilon)^2}, \quad (19)$$

The factor derived from the equation (19) has a dimension Pa^{-1}, which quantifies the change in the volume of deformation per unit change in pressure. After Gray gave a quantitative description of the impact of the volume swelling/contraction of coal on permeability cleavage, a series of works focused on depending of the permeability on the pore pressure [15]. Several compression models of coal matrix were suggested [15, 20, 53]. Among the various models for statistical comparison of actual production [54] and data of laboratory tests for permeability Palmer and Mansoori model is widely used. With regard to coal layers water flow and gas permeability was primarily due to a network of cracks and cleavage. Thus, changes in permeability cleavage of broken coal seams as a result of fluid pressure and adsorption or desorption of gas can be described as [55]:

$$\frac{k}{k_0} = \left(\frac{P}{P_0}\right)^3, \quad (20)$$

where k and k_0 - new and initial permeability of cleavage, respectively, mD.

The porosity of the coal seams (P) is given by the equation:

$$P - P_0 = \frac{(1-2v)(1+v)}{E(1-v)}(p - p_0) - \frac{2}{3}\left(\frac{1-2v}{1-v}\right)\left[C_g\left(V_g - V_{g0}\right)\right], \quad (21)$$

where P and P_0 - new and the initial porosity;

v - Poisson's ratio;

E - Young's module, Pa;

p - the pressure in the reservoir, MPa;

p_0 - initial pressure, MPa;

$C_g V_q$ - deformation of the component;

V_q - amount of adsorbed gas, m^3;

V_{q0} - the initial volume of the adsorbed gas, m^3.

2.4 Technical and technological peculiarities of hydraulic fracturing

System requirements of HFT

The process of hydraulic fracturing treatment (HFT) consists of three principal operations: creating artificial fractures in the reservoir (or natural expansion); injection through tubing into WZ the fluid with crack filler; punching filled fluid in the fracture to fix them. During these operations three different categories of fluids are used: the fracturing fluid, the fluid-sand carrier and squeezing fluid [56]. Each of these fluids (working agents) must meet certain specific requirements. However, these working agents must meet the following general requirements:

- Operating agents (fluids) injected into the formation, must not reduce the permeability of the WZ. At the same time, depending on the category of the well (mining; injection; mining, translated by water injection), different in nature working fluids are used.
- Contact of working fluids with the rock of the WZ or with formation fluids should not cause any adverse physical and chemical reactions, except for special cases of using of specific working agents with controlled and directed action.
- Fluids should not contain significant amounts of extraneous mechanical impurities (i.e. their content is regulated for each working agent).
- When using special working agents, for example, oil emulsion, the products of chemical reactions must be completely soluble in the product reservoir and not to reduce the permeability of the WZ.
- The viscosity of the using hydraulic fluids must be stable and have a low pour point in winter (otherwise fracturing process should be carried out with the use of heating).
- Fluids should preferably be readily available and not expensive.

HFT technology is the combination of the following operations:

Well preparation is a study on the inflow or pick-up that provides data for the evaluation of fracturing pressure, volume of fracturing fluid and other characteristics.

Well cleanout is a process when well washed with the washing liquid that contains certain chemicals. If necessary, decompression processing is carried out, torpedoing or acid treatment. It is recommended to use a tubing of 3-4 inches in diameter (smaller diameter pipes are not desirable because of large frictional losses) [57].

Breakdown agent injection. Breakdown agent is the one working agent by injection of which needed pressure is created to break the rock for the formation of new and existing disclosure of cracks in WZ. Depending on the properties of the WZ, and other parameters filtered or poorly filtered fluid is used.

As fracturing fluids can be used the following:

in producing wells

- degassed oil;
- thickened oil, black oil mixture;
- hydrophobic oil emulsion;

- hydrophobic water-oil emulsion;
- acid emulsified kerosene, etc.;

in injection wells

- clean water;
- aqueous solutions of hydrochloric acid;
- thickened water (starch, polyacrylamide - PAA, spent sulphite liquor - SSL, carboxy methyl cellulose - CMC) [57];
- thickened hydrochloric acid (a mixture of concentrated hydrochloric acid with SSL), and others.

When choosing a fracturing fluid swelling clays process must be taken into account and prevent by introducing into it the chemicals, stabilizing clay particles when wet (water-repellency of clay).

As it has already been mentioned, the bursting pressure is not constant and depends on several factors.

Increasing bottomhole pressure and the achievement of bursting pressures are possible when meeting as follows. The rate of fluid injection of fracture of certain viscosity and permeability of the WZ must meet at each time of pumping the condition when the injection rate is ahead of the absorption rate of the formation fluid. From this condition it is obvious that in the case of low permeability rocks burst pressure can be achieved by using as fracturing fluid viscosity liquids at low limited speed of injection. If the rock is well permeable, that when using low-viscosity fluid injection requires a large injection speed; with limited injection speed is necessary to use high viscosity fracture fluid e. Should the WZ is represented by collector of high permeability, large pumping speed and high viscosity liquids should be used. It is definitely obvious that the thickness of the productive horizons (seams) that defines the well injectivity should be taken into account.

An important technological issue is the definition of moment of crack formation and its characteristics. The moment of crack formation in the monolithic collector is characterized by a break in the relation of the “volume flow rate of fluid injection - the injection pressure” [58] and significant reduction in injection pressure. Disclosure of pre-existing cracks in the WZ is characterized by a smooth change of “flow – pressure”, but reduce the injection pressure is not marked. In both cases, the sign of cracking is the increase of the coefficient of injectivity. HFT practice shows that disclosure of natural fractures is achieved at much lower injection pressures than it is in monolithic rock.

Fluid-sand carrier injection. Sand or other material is injected into the crack, served as crack filler, being substantially inside as the frame and prevents closing of cracks after removing (reducing) pressure. Fluid-sand carrier performs transport function relative to the filler.

The main requirements for fluid-sand carrier are high sand containing capacity and low filterability.

These requirements are dictated by the terms of the efficient filling of cracks and to avoid settling of the filler in the certain elements of the transport system (mouth, tubing, slaughter), as well as the premature loss of mobility of the filler in the crack. Lower filterability prevents filtering of fluid-sand carrier fluid to the wall of fracture, keeping constant concentration of the filler in the fracture and preventing clogging of crack with filler at the beginning. Otherwise the filler concentration at the beginning of cracks increases due to filtration of fluid-sand carrier to the wall of fracture and carrying the filler in the fracture becomes impossible (blockage of the crack).

As fluid-sand carrier in production wells are used viscous liquids or oil, preferably with structural properties; black oil mixture; hydrophobic water-oil emulsion; thickened hydrochloric acid, etc. In injection wells as fluid-sand carrier SAB liquids; solidified hydrochloric acid; hydrophilic oil-water emulsion; starch and alkaline solutions; neutralized black contact and others are used [57].

To reduce friction losses during motion of these liquids with the filler through tubing special additives (depressants) are used - soap-based solutions; high molecular weight polymers, etc.

Overflush. The main purpose of this fluid is punching of fluid-sand carrier prior to slaughter, and squeezing it into the cracks. In order to prevent blockages of the filler, as practice shows, the following conditions must observe [59]:

$$\upsilon \cdot \mu \geq 1, \tag{22}$$

where υ – velocity of the fluid-sand carrier in the tubing string, m/s;

μ - viscosity of the fluid-sand carrier, mPa s.

As the cracks filler can be used:

- sorted quartz sand with grains diameter of 0.5±1.2 mm, which has a density of about 2600 kg/m³. Since sand density is substantially greater than the density of fluid -sand carrier, the sand can settle, which determines the high injection rates;
- glass beads;
- grains of sintered bauxite;
- polymer beads;
- special filler - proppant.

The main requirements for the filler are high strength on compression (collapse) and geometrically correct spherical shape.

It is obvious that the filler should be inert to the product of reservoir and do not change its properties for a long time. Practically it is established that the concentration of the filler ranges from 200 to 300 kg per 1 m³ of fluid-sand carrier.

After injection of the filler into the cracks well is retained under pressure. Time of well staying under pressure should be sufficient for the WZ system shifted from the unstable to the stable state where the filler is firmly fixed in the fracture. Otherwise, during the process of call flows, the development and exploitation of wells, the filler is removed from the fractures in the well. If the well is operated by pumping means, removal of filler leads to a failure of the submersible unit, not to mention the formation of traffic jams at the bottom of the filler. The abovementioned is an extremely important technological factor, if neglected can dramatically reduce the efficiency of hydraulic fracturing to a negative result.

Inflow stimulation, completing the well and its hydrodynamic research. It should be emphasized that the conducting of hydrodynamic studies is a mandatory element of technology, since its results are the criterion of technological efficiency of the process. Schematic diagram of well equipment for hydraulic fracturing is shown in Fig. 6. When carrying out the hydraulic fracturing the tubing string must be puckered and anchored.

Important issues during fracturing are the issues of positioning, spatial orientation and size of cracks. Such definitions should be mandatory in the production of hydraulic fracturing in new regions, since they allow developing the best process technology. These named problems are solved by the method of monitoring the change in intensity of gamma radiation from a crack, which is injected by a portion of the filler, activated by radioactive isotope, such as cobalt, zirconium and iron. The essence of this method is to add to a clean filler a certain portion of an activated filler, and in carrying out the gamma ray [97, 98] immediately after the formation of cracks and in the injection into cracks a portion of the activated filler; comparing the results of the gamma-ray logging, judging about the number, location, spatial orientation and size of the crack. These studies are carried out by specialized geophysical organizations.

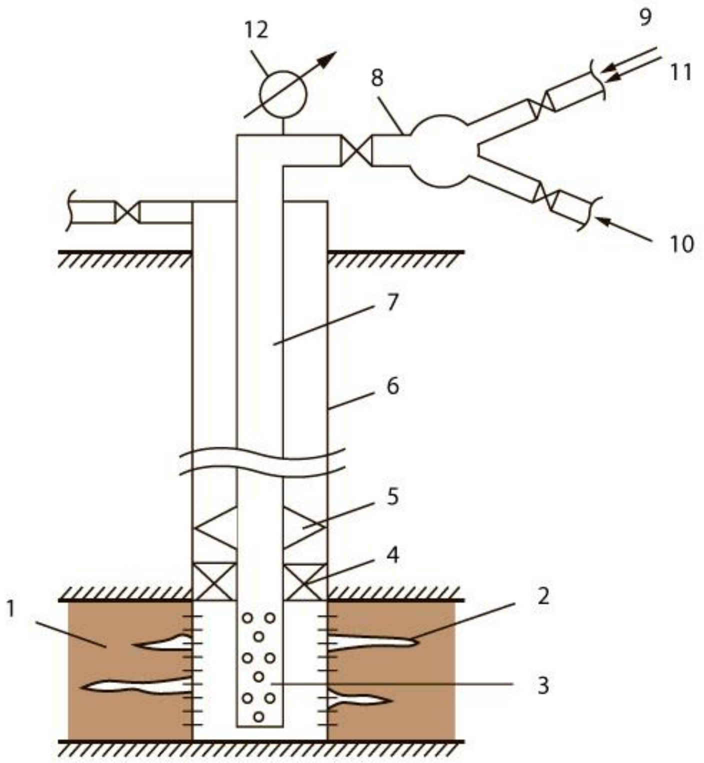


Fig. 6 - Schematic diagram of well equipment for hydraulic fracturing:
1 - producing formation; 2 - crack; 3 - shank; 4 - packer; 5 - anchor; 6 - casing; 7 - tubing; 8 – wellhead equipment; 9 - fracturing fluid; 10 - the fluid-sand carrier; 11 - squizeeng liquid; 12 – gauge [60]

Equipment requirements during the hydraulic fracturing

Usually, hydraulic fracturing is performed on the tubing string, and lowered into the well fixed on the estimated depth by the packer and anchor. Packers are divided into packers relying on slaughter and packers without reliance on the slaughter. The elastic elements of the packer when it is sealed withstand high pressure differences. Packer internal passageways have different diameters and are designed for passing through the packer tube, equipment or tools. During the process of fracturing high pressure is created under packer which is substantially greater than the hydrostatic pressure of the liquid column above the packer in the annulus, packer has impact of large force act on the ultimate joint that can cause it to move up and buckling of the tubing. To fix the tubing string with a packer in the casing above the packer anchor of hydraulic ram type to be fixed. When creating excess pressure inside the anchor gear dies are moved apart and pressed into the casing securely fixing deflated into the well equipment.

Surface equipment for production of hydraulic fracturing includes special pumps of wear-resistant performance, for example, 4AN-700. Drive of power pump of this unit is diesel engine, which is connected through a gearbox to the drive shaft of the power pump. Features of power pump unit depend on the type of unit.

To prepare the "sand carrier-fluid" mixture sand blender unit with automatically controlled dosing and liquid filler is used. In principle, this unit includes a pump drive motor, centrifugal pulp pump, a special two-chamber tank filling, mixing device with four-stirrer and a system of two horizontal and one inclined screw [61]. Horizontal screws transfer filler from one chamber or the other, to an inclined auger, through which the filler is sent to the mixing device. Simultaneously, from tank truck to the mixing apparatus fluid-sand carrier is tranfered through conduit. Cooked mixture by pulp chamber is pumped to the main reception of the high-pressure pump of the pump unit and further into the hole.

An essential element in the production of hydraulic fracturing are the tanks, which are equipped with various pumps (centrifugal and plunger, usually triplex plunger). A centrifugal pump is designed to feed a fliud-sand carrier on sand blender unit. Triplex plunger pump is designed to fill the tank with fluid, sampling fluid from the tank and pumping the fluid to the consumer from any other bucket. Tanks are equipped with coils for heating the fluid in the cold time, as well as the necessary automation tools. Typically, the tank is mounted on the chassis of a sports utility vehicle.

In the production of hydraulic fracturing binding element is manifold high pressure unit for binding of flow pumps and connecting them to a special fixture wellhead. Manifold unit is transported on a car platform. It includes:

1. The pressure forged steel manifold with taps for joining flow lines pumps. The pressure manifold has pressure sensors, flow meter and density meter. Pressure manifold is equipped with the necessary remote control, monitoring and recording of process parameters, valves, safety valves, etc. All control and measuring and automation systems remotely associated with the control and management station of hydraulic fracturing process, installed on the vehicle chassis and equipped with sound systems and telephony (radio) connection.

2. Manifold with safety valve, which serves for the distribution of the working fluid between the pump unit and has a large orifice. The collector can be connected to ten connecting lines.

3. Set of auxiliary high pressure pipelines, as well as a set of quick-pivot high pressure connections.

4. Crane valves, high pressure hoses, accessories and tools for assembly, disassembly and crimp of connecting manifolds.

5. Armature wellhead, for example, 1AU-700 or 2AU-700. The valves are designed for working pressures up to 70 MPa. The upper part of the valve has side bends with flexible joints, as well as a pressure gauge with oil separator. The lower part of the valve is designed for pressures up to 32 MPa and has two connection lines with valves, tees and quick connections and communicates with the annulus of the well.

Currently in Kazakhstan there is set of equipment for fracturing under pressure up to 105 MPa-KO GRP-105/50 K through conditional string diameter of 50 mm.

The complex includes:

- pumping stations UN-1000x105 K (5 units);
- installation for the delivery of bulk materials and the preparation of liquid-sand mixture UDKPS-50/12 K (2 units);
- pump installation with a tank UCHSH- 60x25/14 K (4 units);
- installation of fast assembled manifold MB-105/50 K (1 unit);
- fuse of x-mas tree PFA-105/50 K (1 unit);
- fitting mouth AU-105/50 K (1 unit);
- station of centralized autonomous control and management TSAC (1 unit).

The complex is characterized by the following parameters:

- the total power consumption - 5400 m^3/s;
- the greatest pressure of discharge -105 MPa;
- the greatest total flow - 200 m^3/s;
- discharge of piping manifold - a one- or two-jet;
- conditional string pass - 50 mm;
- the collection and processing of information - independent mobile facility of management and control;
- weight -160 tons.

The basis of installation UN-1000x105 K is a new generation triplex plunger pump NP-1000 K. This high pressure pump is without a split frame, four crankshaft, valve assemblies with an improved hydrodynamics, plunger pair with abrasively corrosion resistant sealing packages of variable rigidity. This pump based on efficiency, weight and size and other characteristics is superior to known foreign analogues.

To drive the pump NP-1000 K a power unit is created based on the gas turbine engine GTD-1250 with a multi-speed planetary transmission, which significantly exceeds the power units with a diesel engine. The unit UN-1000x105K [56] also includes piping with new shut-off and safety valves of high pressure.

It should be noted that all kinds of complex equipment CO GRP-105/50K are self-contained and can be used alone or when combined with other installations.

Summary of Chapter 2

1. The analysis of domestic and foreign practice of borehole coalbed methane extraction is made and results are summarized of pilot work on the extraction of methane in the Karaganda coal basin.
2. The mass transfer of methane in coal seams is determined by the fundamental laws of conservation of mass, the law of Darcy filtration and Langmuir equation and the equations of gas state, allowing in the form of a differential equation of the theory to describe the gas pressure distribution patterns.
3. The volume of coal deformation during adsorption or desorption of coal in the range of reservoir pressure of methane reach values comparable with limit strength characteristics, which may lead to fracture the formation and distribution that significantly affects the permeability of the coal seam.
4. The gas permeability of the coal seam depends on the natural rock pressure and significantly varies with the stress-strain state, depending on geological conditions of coal seam design and geometry of the underground workings.
5. Main technical and technological parameters of hydraulic fracturing in conditions of Karaganda coal basin are described.

3 Intensification of geotechnological process on methane recovery from underground headers through the borehole surface

3.1 The critical parameters of the research object

3.1.1 The geological structure of Karaganda coal basin

The rocks of Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Jurassic and Cenozoic age take part in geological structure of the Karaganda basin. Meanwhile distinctive feature is zoning facies due to the northern part belonging to the region of Caledonian folds, and the south to the region of geosynclinal mode. The junction zone of these regions covering the southern edge of the Karaganda basin is confined to thick series of Devonian igneous rocks. Thick carbonate rocks of Famennian and Tournasian stages overlie extrusive and clastic Devonian rock mass. Thick sequence of coal formation occurs higher that is primarily represented by coastal and then continental carbonous sediments. Later continental formations are represented by Jurassic and Cenozoic sediments [62, 63].

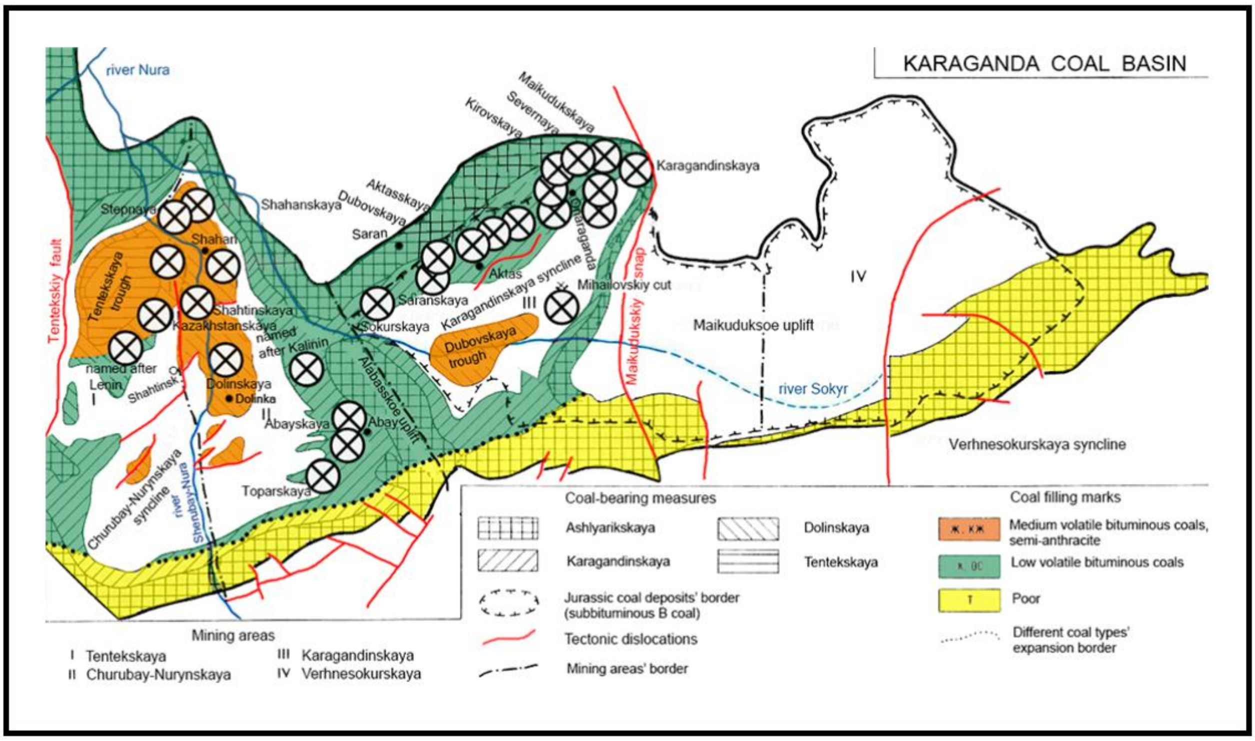


Figure 7 – Geological map of Karaganda coal basin [64, 65]

Karaganda suite is the major producing formation of the basin. The lower boundary of it is bottom formation, the upper boundary is top of formation. The thickness of suite is 630-800 m increasing in the southern and western directions. The suite is divided into three sub-suites: the lower, the middle and the upper.

The lower sub-suite thickness of 130-180 m is limited to the top of formation and represented by argillites, aleurolites with plant remains and coal seams. There are six coal seams situated in sub-suite with complex structure, large capacity and high ash content.

Middle sub-suite has thickness of 340-440 m, and it contains the main minable seams and a number of thin seams and sublayers.

The upper sub-suite of 160-200 m [65] is allocated between seams $к_{15}$ and $к_{20}$ is and described as a de-emphasis of sandy deposits. Argillites and aleurolites dominate in the lower part. There are several coal seams and sublayers in sub-suite, only the seam $к_{18}$ whereof has economic value.

Dolin suite is the second producing formation of the basin. Its lower boundary is a seam $д_1$, the upper is bottom formation $т_1$. Thickness of the suite is 430-560 m. The nature of coal-bearing capacity of the suite is subdivided into three sub-suites.

The lower sub-suite is allocated in the interval of coal seams $д_1$-$д_6$ and has a thickness of 190-310 m. The lower part has evolved lacustrine and fluvial deposits; and it confines the lower strata series $д_1$-$д_5$. The seam is practically overlaid with coalless rock mass of 130-185 m thickness represented by greenish grey argillites, aleurolites and pack sand.

The middle sub-suite of 135-160 m thickness lies between bottom formations $д_6$ and $д_9$. One of the thickest and the most consistent among three strata series ($д_6$, $д_7$, $д_8$) is a seam $д_6$.

The upper sub-suite occurs between seams $д_6$ and $т_1$ and has a capacity of 150-190 m [66]. The lower part of sub-suite is represented by lacustrine and fluvial deposits and contains three operating coal seams ($д_9$, $д_{10}$, $д_{11}$). Over the seam $д_{11}$ lays coalless rock mass of lacustrine argillites.

Tentek suite is the third producing formation of the basin. Its lower boundary is held on the bottom formation of $т_1$, the upper is along the top formation of $т_{17}$. The thickness of the suite is 515-560 m. The suite on the type of coal-bearing capacity and lithologic and facies features is divided into three sub-suites.

The lower sub-suite of 40-55 m thickness is bounded above the horizon of conglomerates unconformably overlying a seam $т_4$. It is represented by lacustrine argillites and aleurolites. The seams have an operating value among four coal seams.

The middle sub-suite has a capacity of 110-130 m. The lower part of the suite with thickness of 40-55 m is represented by argillites and aleurolites. Four coal seams embed among the specified rocks.

In the upper part of the formation section coal seams are generally unstable, often waste operating power and distinguished by significant mineralization of coal mass.

Shakhan suite crowns sequence of the Carboniferous coal-bearing strata of the Karaganda basin. Its deposits from fluid wash are preserved only in the northern part of Tentek region. The lower boundary of the suite serves top of formation $т_{17}$. The suite section is heterogeneous and clearly divided into two parts.

The lower part is represented by greenish gray unstratified argillites and aleurolites. Among them there are thick sublayers (up to 30 m) of medium and sandstones, gravelites and finely pebble conglomerates with pebbles of igneous rocks [65, 67].

The upper part of Shakhan suite is composed of sorrel, greenish gray unstratified argillites and aleurolites. Subordinate position in the sequence is occupied by sublayers of gray, red packsand in places. The thickness of the sequence part is

200 m; the total capacity of Shakhan suite is 350 m. Coal-bearing capacity of formation is generally missing.

Thus, the following patterns are settled in the structure of Carboniferous coal strata:

– in the sequence of the coal-bearing sediments two essentially different sediments by a nature of coal-bearing type. The lower part of the formation (Akkuduk, Ashlyarik suites and lower part of Karaganda suite) is represented by coastal-marine sediments with complex structure of ash coal seams. Almost without any bracit these deposits are replaced by coastal-continental, and then intercontinental coal-bearing sediments with limnetic type of coal formation. The coal seams are described as a more simplified structure and less ash coal mass comparison with seams of paralic coal formation;

– in the section of productive strata coal seams occur in two large groups corresponding Ashlyarik-Karaganda and Dolin-Tentek coal formation cycles, which are separated by barren of coal over Karaganda suite;

– shift of coastal marine sediments by continental comes sharply and above the coal seam κ^{3}_{5} marine sediments do not occur. An exception is the south-western part of the basin, where the horizons with marine fauna are found under the coal seam κ_{8};

– a coal-bearing capacity of all formations decreases from the east to the west.

Mesozoic continental terrigenous formations differ from coal-mining by completely different type of sequence and much less thickness. They are specified by facies variation, variegated composition and rhythmic structure.

Saran suite is composed of conglomerates with sublayers of malmrocks and aleurolites. On the northern wing of Karaganda vug conglomerates are replaced by fine grained rocks. The thickness of the formation is from 140 to 230m [66].

Dubov suite lies over Saransk, and wherein the last is missing, – with angular unconformity on Paleozoic rocks. The suite is represented by sandstones, aleurolites, argillites and seams of bevey coal. Fine-grained rocks are replaced by rudaceous ones only in the south-west and south-east of Karaganda vug and the north of Upper-Sokur vug. The capacity of the suite grows towards the south from 50-120 to 190 m [66].

3.1.2 Coal bearing capacity

Conditioning resources of coal to the depth of 1800 m is estimated for 25,2 billion tonne, including stocks A+B+C_1 - 7,49, C_2 - 1,15 and undiscovered potential resources 16,62billion tonne [68].

Industrial coal bearing capacity of Karaganda basin is connected with Ashlyarik, Karaganda, Dolin and Tentek suites that contains up to 80 coal seams and interlayers. 65 of them have operating capacity. Total capacity of all coal seams is in average 110m.

The most coal bearing and valuable in industrial concern are seams of Karaganda and Dolin suites, as well as the lower seams of Tentek. The coal bearing capacity of Ashlyarik suite is underexplored.

Generally, the capacity of coal seams as well as coal bearing capacity of the suite recedes along the basin from the east to the west, and within the coal bearing capacity of each region is from the south to the north. The half of basin minable seams (33 out of 65) refers to thin (0,7-1,2m of thickness), up to 29 seams has average capacity of 1,3 -3,5m and only three seams (κ_{10}, κ_{12}, ∂_6) have capacity more than 3,5m. The coal seams commonly have complex structure [66].

Coal bearing capacity [65, 99] of the lower Mezozoic sediments connected with Dubov suite reaches its maximum Karaganda coal region (Dubov mine) and in the east part of Upper-Sokur region (Kumyskuduk mine). Coal seams and interlayers forms two coal horizon the lower of which is more consistent. On Dubov mine the upper coal horizon contains only interlayers of coal, and the lower consists of five unbalanced seams of complex structure that reaches its operating capacity of 2,5-4,5m in confined area. On Kumyskuduk mine the upper coal horizon of 20 m thickness also consist of coal of the low-powered lentils (0,1-1,5m), the lower (capacity up to 40 m) is represented by five coal seams with a capacity from 2 to 12 m.

Coal-bearing ratio reaches its maximum in Industrial field. The coal bearing capacity decreases in 1,5-2 times westward.

Industrial field of Karaganda region has the simplest tectonic structure, and the north part of Tentek region specified by flat dip of coal seams and inconsiderable development of fracturing. Furthermore, with the depth ultimate strength for compressing and stretching, rock density increases and its porosity and humidity decrease. The strength metrics contained in the rocks of Dolyn suite are fewer than Karaganda, and their humidity is greater.

Density of Karaganda coal is 1,27-1,6 t/m^3, gravity is 13,26-16,69 kN/m^3.The upper-range value of density (1.5-1.6 t/m^3) refers to coal seams of Ashlyarik suite in Karaganda region, the lower-range value (1,27-1,5 t/m^3) belongs to seams of Dolyn suite. Most of the seams of Karaganda and Tentek suites has average density of 1,4-1,45 $t/m^{3.}$

Coal hardness in Karaganda basin depends on its petrographic composition. Hardness ratio on scale of professor M. M. Protodyanov fluctuates from 0,47 to 2 [69, 96]. The hardest coals are seams of κ_7, κ_{12},κ_{14}, κ_{18}.

Coal resistance to cutting varies from 800 to 2250 H/cm, its maximum peculiar to seams κ_{13}, κ_{14} in Industrial and Saran field.

Seams ∂_{11}, ∂_{10}, ∂_9 in Tentek region and seam κ_{18} in Churubai-Nura region are distinguished with low resistance to cutting. Generally, decline in coal resistance to cutting is determined in the direction from industrial field to Tentek region.

The operating humidity of coal is within the range from 3,5 to 6,5 %.

3.1.3 Methane content

In different times M. A. Ermekov, Y. L. Ettinger, N.S. Umarkhodzhieva, E. Y. Preobrazhenskaya, A. D. Kyzryakov, E. Y. Fominyh and others dealt with issues studying gas content in Karaganda basin [70-72]. The methane content of coal is stipulated by the influence of various factors, including metamorphism and material constitution of the coal, tectonics of mine fields, groundwater conditions and etc.

A separate aspect of the research concerned the issue of the form of the gas enclosed in coal. In accordance with modern concepts of methane in the coal-bearing strata of coal mines is contained in the following main forms:

- in the form of free gas filling the pores and voids of the coal;
- in the occluded state;
- in the state of physico-chemical bond with organic mass of the coal;
- in dissolved form in the groundwater.

Occluded methane contains up to 80 - 95% of the total volume in the coal seams, interlayers and carbonaceous rocks. In the rock mass with poor organics the gas can be in the pores, cracks or solutions in free state.

In special thermobaric conditions methane can be in the form of crystalline hydrate. The maximum amount of gas (up to 50 m^3/t) contained in coal seams, the minimum (1-4 m^3/t) in the host rocks [69] which determines the unevenness of the gas content in the coal-bearing strata in section, and in the plan.

In coal mines there are usually two kinds of headers distinguished: header of retained gas - coal seams, seams, interlayers, carbonaceous rocks with high (greater than 20%) organic content and header of free gas - host rock with a small (up to 10%) content of organic substances [73, 94]. The volume and nature of the coal methane saturation are determined by its porosity, gas pressure, temperature and material constitution of coal. The porosity of coal and coal-bearing strata is one of the main indicators that define the content of the gas in the occluded and free state. Free gas occupies the pore space and various cracks and voids. Its content in the coal and rocks depends on their porosity and fracturing and pressure at which the gas is in. If the pores and cracks of rocks to some extent are filled with water, the amount of gas contained in the voids is accordingly reduced.

In the coal seams there are major numbers of gases in occluded state: predominantly in the form of a solution in solid substance (absorption), in the concentrated form is on the pore surface (adsorption) and in the condensate form is in supramolecular pores. Studies of coal porosity [44,52] indicates that the bulk of their volume is stipulated by molecular burrows size of a few angstroms, i.e, equal to the size of gas molecules encountered in the coal seams (methane, carbon dioxide gas, nitrogen, hydrogen, homologs of methane and others.) The voids origin is linked to elimination of methane and water from substances of coal in the process of its metamorphism, with the presence of atomic voids in molecules substance of coal or with the distances between the carbon layers in the crystallites.

Table 2 - Distribution of methane according to forms of its existence in the coals of the Karaganda coal basin, middle stages of metamorphism at depths of over 800 m [19, 65].

Localization of methane in coal	Form of methane existence	Quantity of methane, %
Within the macropores of microcracks and other defects in the continuity of coal under natural conditions	Unobstructed	2-12
On the surfaces of coal of natural pores and defects of continuity, interblock gaps (including volumetric filling of transition pores and macroscopic defects)	Absorbed	8-16
In the intermolecular space of the coal substance	Solid methane solution	70-85
In the defects of aromatic layers of crystals	Chemicallyadsorbedmethane	1-2
Inside clater like structures	Interstitialsolidsolution	1-3

Supramolecular (transitional) pores in large volumes of practical importance are found only in some low metamorphosed mineral coals.

The volume of the macropores of a size in the hundreds and thousands of angstroms is filled with gas and occluded gas in the free state, which is subject to the laws of gaseous media.

In the coal seams with fields or zones of milled (prepared) coal packed in natural conditions of mountain pressure until the briquette state without gaps between the individual pieces of coal, expandability of coal is created during unloading coal from the rock pressure. This can occur as a result of elastic expansion of coal matter and also due to the transition of the methane from occluded state into the adsorbed on the surface of the coal pieces; in this case the gaps are formed between them measured in fractions of a nanometer. Under pressure and as a result of the work done by the gas passed from the occluded state to the free, these gaps under favorable conditions may increase.

Thus, most of the gases coming from the coal seam in mining in natural environment cannot be considered in the strict sense of gases, since they are not subject to gas laws in the occluded state; and only those are such which are in free state in the coal seam [65]. In the occluded state “future” gases cannot implement the internal energy until they go into the free phase, and to this effect it is necessary that the gas pressure is reduced or it would be possible to expand the coal saturated by gas.

Depth zone of gas weathering ranges from 40 to 300 m. The minimum depth is typical for seams of Aashlyarik suite and the lower strata of Karaganda suite. Most often it fluctuates in the range of 100-200 m, but it increases to 250-300 m in the mines of Tentek region.

Natural methane content rapidly increases with the depth of 200 m and below the gas weathering zones, reaching 15-20 m 3 / t or more [92]. The maximum growth rates of gas content are peculiar to the central part of the industrial filed and Churubay-Nura region.

According to [17], methane content of coal seams in depth changes on the S-shaped curve, and can be determined by formula 23.

$$\boldsymbol{x = \frac{1{,}3(H-H_0)^{\alpha}}{1+b(H-H_0)} \times \frac{100-A^C}{100}}, \tag{23}$$

where a,b– is an empirical coefficient;

H_0, H– is a gas weathering depth, depth for which methane content is defined, m;

A^c– is ash content of coal seams, %.

Methane-bearing capacity of mines [17] in the Karaganda basin in the depth of 250-350 m is in two times higher than in the mines of the Vorkuta mines. In the depth of mining operations of 300-350 meters methane-bearing capacity of mines exceeded the value of 50 m^3 of methane per tonne of produced coal [19]. According to recent data of the Coal Department of JSC “ArcelorMittal Temirtau” absolute volume of gas of production faces in Karaganda basin reaches 100-120 m^3 per minute and higher.

Forms of methane emission into the mine atmosphere: ordinary emission and emission in sudden outrush form of coal and gas. Monitoring of sudden outrush of coal and gas from the end of the 50s when the mining operations fell to the depth of 250-300 m. By increasing the depth of mining operations the number of emissions and their intensity is increased. Currently all mines belong to very gassy or dangerous for sudden outrush of coal and gas. The seams of $к_{18}$, $к_{12}$,$к_{10}$, $к_7$, $д_6$ are subject to emissions.

As the industry experience shows, at a capacity of rocks parting up to 60 m all emissions occur in non-overworked block, or under the solid block left on the overlying seams. Under parting more than 60 m 40% of all emissions it is observed as mined-out space. Minimum power of parting at which emissions are registered under the open area is 86 m.

An important parameter of the feasibility study on commercial production of methane is evaluating the potential resources of methane in coal seams of the Karaganda basin. M.V. Golitsyn estimates methane resources in the coal seams with operating capacity in the depth interval of 300 - 1800 m at 440 billion m^3 (22 billion tons of coal resources, the average methane content of 20 m^3/t). The content of methane in the surrounding rocks is estimated at 1 trillion m^3. M.V. Golitsyn estimates the total amount of methane in the coal-bearing strata is at 2 trillion m^3 [65], and V.A. Sadchikova at 3-3.5 trillion m^3.

According to A. T. Airuny and others [73] general resources of methane within the budgeted depth of bank excavation in the main mines of the Coal Department of JSC “ArcelorMittal Temirtau” (Table 3) [13] contains about 100 billion m^3. Meanwhile, general industrial methane resources within the depths of the mines operated, i.e. methane, which can be recovered in coal mining and industrially used, comprises 10-12 billion m3^3 (Table 3).

Table 3 Estimation of methane resources in the Karaganda coal basin

Region	Depth-range, m	Methane content, m^3/t	General methane resources billion m^3				Resources of commercial value, billion m^3
			in seams	in inter-layers	in rocks	overall	
Industrial	270-835	10-22	6,8	3,1	14,9	24,8	1,98
Abai	140-800	10-25	6,1	2,1	12,3	20,5	1,68
Saran	264-830	10-25	6,2	2,8	13,6	22,6	1,81
Shahktyn	100-685	10-25	7,4	8,1	23,2	38,7	4,65
Total:			26,5		64,0	106,6	10,12

The problem of coal methane in modern mining production has the following main aspects [74, 75]:

- as a problem of accident prevention and cost-effectiveness of high coal production;
- as a problem of industrial use of methane in the energy sector and other industries;
- as an environmental problem associated with the methane emission during underground operation of coal seams into the atmosphere.

In underground coal mining the methane problem, first of all, is important in terms of mine safety and economic efficiency of their functioning. At present, close attention is paid to the methane from coal deposits as an independent energy source. However, despite the importance of energy and environmental problems of methane, they are of secondary importance, as solving the problem of accident prevention in coal mining and its economic efficiency by means of degassing for forced extraction and isolated drain of methane, simultaneously the problem of the industrial use of mine coal and methane as an independent energy resource and the problem of reducing the environmental matters can be solved.

Due to the large capacity of the developed formations of the Karaganda coal basin and high natural gas content of coal, in present mining depths the bulk methane volume released from this source. Therefore, an important task to ensure mine safety is a degassing prepared to operation and mined bed. The parameters adjustment is necessary for means of degassing based on the constant load growth in the mining face.

3.2 Process research of hydraulic fracturing on Karaganda coal basin

3.2.1 Work on the intensification of methane production in Karaganda coal basin.

In order to intensify the strata degassing in Karaganda coal basin, torpedoing of boreholes, hydrochlorid acid treatment of formation and its hydraulic fracturing from underground wells were elaborated. Works on torpedoing of boreholes were carried out in 1956 - 1959 years. This torpedo length was 2.5 m in a weight charge of 12.5 kg. During simultaneous blasting in one well of two - three torpedoes, the total weight charge reached 24 - 37 kg. Increasing flow rate of methane to 30 - 40% has been established by mine observations continuing for 3 - 4 months. In 1967 - 1972 experimental work on hydrochlorid acid treatment of seams κ_{13}, κ_{12}, κ_{10} through the seam wells at a number of mines were held in the Karaganda coal basin. The results of the gas flow rate studies have shown that hydrochlorid acid treatment of formation can increase gas recovery in 3 - 4 times [66]. Currently, wide use in the Karaganda coal basin has found hydraulic fracturing through special stratal wells. The intensity of the gassing to the stratal wells in underground fracturing zone has increased by 2.0 - 4.7 times, and the overall intensification ratio has reached a value of 5.2.

For the first time in the world practice the extraction of methane from discharged of the rock pressure of coal seams through wells drilled from the surface by actively influencing seams on disclosure natural cracks was carried out in 1963 in the Karaganda coal basin at the mine number 22 (later - mine named after 50. Anniversary of the October revolution). In the mine number 22 processing of seam κ_{12} was carried out through the 4 wells (№№ 2, 3, 4, 5). The seam thickness of “Upper Marianne” was 8,6 - 9,25 m. The depth of bed position was. 335-350 meters. From the 522 to 1 549 thousand m^3 of methane was removed on the surface. The effective radius of the impact was 52-98 m. Methane removal through the wellbore to the surface per tonne of reserves fluctuated from 3.14 to 7.25 m^3/t. Methane flow rate was varied from 3 to 5 m^3/min. For more than 50 million tons of coal reserves over 140 wells in 10 mine fields were processed during the pilot testing and implementation of technologies in the Karaganda basin. In zones hydrofracturing there were produced more than 20 million tonnes of coal [69]. The main technology research before degasification of mine fields through wells from the surface hydrofracturing coal seams were carried out at the mines named after Kalinin (9 holes), “Churubay-Nura” (3 wells), named after Kostenko (44 wells), “Saran” (18 wells), “Sokur” (7 wells), named after 50th Anniversary of the October Revolution (4 wells), “Karaganda” (2 wells), named after Lenin (20 wells), “Stakhanov” (4 wells) and some others.

In mines there were used various methods actively influencing the coal seams based on hydrofracturing. Coal seams have low permeability, therefore a prerequisite for the extraction of methane from discharged coal seams is an artificial increase in permeability. The basic influence is hydrofracturing coal seams providing increased permeability on the order of 2-3. In the course of implementation of the method various technological scheme of impact have been tested. The radius of the impact was mostly 120-140 m, in some cases, water seepage was marked at a distance of 400 m from the injection well. Cracks were secured with sand, it was subsequently established the possibility of saving at the expense of permanent deformations. Depending on the conditions hydrofracturing technology were used for complex schemes and early degassing of coal seams. The bulk of the wells were used in the current horizons of mines on the first scheme - integrated degassing. Hydrodynamic effects in this case, is used to enhance the permeability of seams with subsequent extraction of methane through the hydrofracturing wellbore and seam well. Exploration term and operating life of hydrofracturing wellbore under the scheme shall not exceed 1.5 years, the amount of recoverable methane given reservoir wells reaches 8-10 m^3/t. To improve the penetrating ability of the working fluid in the cracks and the small pores effectively use surface-active compounds (surfactants) type DB, DC-10. In the presence of coal over 0.3% carbonates for improving seam porosity, hydrochloric acid array processing is used.

In terms of mining coal methane greatest interest presents advance preparation of degassing, in which well operating life should be at least 3-4 years. By the end of the XX century this criterion corresponded to all four sites in two mine fields: on the eastern wing, the south-west wing of the deep horizons of mines “Sokur” and the east wing of the mine named after Lenin, which was drilled and processed, respectively of 3, 3, 16 and 14 wells. According to the mining-and-geological and technological conditions, among these sites three groups were allocated: I - mine named after Lenin (wells number 1-14.) and 35 on the east wing of the mine “Sokur” (wells number 98 and 99.); II - in the east wing (well number 8.) and south-west wing (well .№ 1-3.) mine “Sokur”; III - in the deep horizons of mines “Sokur” (well № 12-27). For the first and second group the depth of processed seams does not exceed 450-480 m. In the first group a powerful seam is processed, in the second there were strata series. In the third group the depth of seams are more than 550 m, reaches up to 700-800 m. On sites of the first and second groups (occurrence depth up to of 500-550 m) were obtained stable, positive results. In the south-west wing of the mine “Sokur” methane extraction through hydrofracturing wells number 1 and number 2 was, respectively, 1.38 and 1.6 million m^3. Methane removal from the formation was 3.3 and 3.8 m^3/t. It should be noted that due to the prevailing trend of that time towards an integrated process for degassing were not provided with maximum terms of development wells. In the future, some zone sections were drilled by reservoir wells (wells. №1, 2, 98). The total removal of methane was 8-9 m^3/t. In mine named after Lenin through 13 wells (well number 14 was undercut by mining operations) for 8 years of operating life the more than 20 million m^3 there was withdrawn methane of concentration of 95-98%. Maximum volume of recovering from one well was 2,9 million m^3. On the sites of the third group – the deep horizon of mine “Sokur”, there were received low results. Thus, rate of recovery from most wells was 4-6 times lower the rate of recovery of well in mine named after Lenin, accordingly the total volume of recovery was decreased. This result was due to the fact that, firstly, hydrofracturing technology was used without fixing the cracks that at depths greater than 600 m is unacceptable, secondly, disorders of processing technology and well completion. The maximum production rate was achieved at 3,47 m^3/min. Average flow rate has varied between 0,49-1,04 m^3/min [76]. The service life of wells was 7-12 years. Recent works on the mine field named after Lenin in the Karaganda coal basin, where the borehole from the surface functioned for over 12 years and provided degasification of a special outburst seam d_6, enabled to prove reliably the economic viability of advance preparation. In the operating life of the wells there were removed more than 20 million m^3 of methane, which reduced the gas reservoir to 6-9 m^3/t. Gas recovery continues at the present time, a number of discharge holes are 2,1 m^3/min. In addition to these positive factors, an increase in mine safety in the areas of hydraulic fracturing should be noted. In addition to reducing the gas content of mine workings outburst observed a significant improvement in the situation. During mining operations in this area in mine field on seam d_6 106 gas-dynamic [13] phenomena of varying intensity were recorded, with almost all are outside the influence of hydraulic fracturing wells. The environmental aspect of the operations is also positive. In the conditions of mine named after Lenin at the facility for recycling methane efficiently used in currently 20 m^3/min of methane and in the nearest future it is planned to use 60 m^3/min, of which 40 m^3/min - methane recovered from fracturing wells. It should be noted that the utilization of 510 m^3 [77] of methane saves one tonne of thermal coal and reduce 55 kg of environmentally harmful gas emissions into the atmosphere.

In addition to these positive factors, it should be noted also negative aspects of the massif hydraulic fracturing. The extensive dissection of coal seams entailed a material breach of the stability of surrounding rocks, characterized by a large water abundance. In turn, the technogenic water abundance negatively affected the methane production rate, breaking the pressure inside the well by forming a hydraulic "cork". In this regard, the efficiency of using massif hydraulic fracturing has been low.

However, commercial production of methane requires the creation of technological conditions, primarily of selective hydraulic fracturing ensuring the stability of enclosing rocks.

3.2.2 Research of the coal seam structure influence on coal methane recovery process

The coal seam represents crumbling porous solid; void sizes range from a few angstroms to millimeters. Coal seam voidage is related to a variety in their genetic nature of the coal deposit formation processes. According to the conventional view, in the voids of the coal seam there is basic amount of methane formed in the process of metamorphism. By the nature of methane motion and size of pores in coal it is common practice to divide into several classes [78]:

1. Molecular pores (0.4-0.7 nm). They are the smallest pores, sizes of which are comparable with sizes of methane molecules (0.416 nm).

2. Folmerov pores (1-10 nm). In the pores of such diameter the number of collisions of gas molecules with walls exceeds the number of collisions between molecules. The free-path length is less than the pore diameter.
3. Knudsen pores (10-100 nm). In these pores free-path length is less than pore size and nature of the gas flow is molecular.
4. Macropores (greater than 100 nm). Along the channels of such sizes gas diffusion is carried out definable by the concentration gradient.

Further, pursuant to the accepted classification features it would be rational to allocate the pores in which gas flow is subject to the laws of laminar and turbulent filtration. The pores larger than 10^{-4} cm (1000 nm) is usually classified according to genetic traits. In the class of voids 10^{-4}-10^{-2}см there are microcracks, voids coming from the organic genesis of coals, and voids coming from the weathering process. Coal voidage coming from its cleavage is estimated at 3-12%. In this regard, endogenous cracks account for no more than 3% of microvoidage of the coal. Exogenetic cleavage is the result of tectonic processes causing compression and seams movements. Tectonic movements of coal seams create varying degrees of disturbance in the coals that are distinguished by the frequency of cracks. With various parameters of coal cleavage (crack density, specific cleavage and others) their permeability correlates that is directly related to solving the problems of degassing and methane production.

As it is known, during hydraulic fracturing several basic systems of cracks are uncovered in the coal seam. While conducting subsurface observations in the impact area a dip azimuth of cracks, a slope angle of cracks, an average opening, a density of cracks, a nature of mineral filling are measured for each system, where the most considerable parameters are average value of the crack opening and density of cracks (or average distance between the cracks).

Two basic systems of cracks were observed in the Karaganda coal basin. The average value of opening varied from a few tenths of a millimeter near the injection well and a few hundredths of a millimeter at the boundary of impact area to several millimeters. The average distance between the cracks varied from 0.001 to 0.003 m [66]. As shown by pilot tests, in specific mining and geological conditions in coal seams there are (available, but often in the closed state) between 2 and 4 joint systems. Cracks are generally vertical extending over the entire depth of stratum. In each joint system under hydraulic dismemberment single trunk cracks from 10 to 18 are unfolded. Length of opening cracks depends on the rate of operating fluid charge and averages 120-150 m. However, at the stage of pilot testing there occurred single cracks with far more length to 400 and even 800 m. The cracks formed as a result of hydraulic fracturing, within a long time (proven period - up to 10 - 12 years) they remain their high permeability due to stored depths up to 600 meters by using proppants (particularly arenaceous quartz as a crack binder).

In accordance with modern geological and geophysical research, a coal seam is a fractured porous sorbing medium. With cracks and macropores it is divided into separate blocks. In blocks it mainly contains adsorbed gas that is desorbed in the diffusion mode. The cracks and macropores contain free gas moving in them in the mode of filtration.

Coal seam after hydrodynamic force acquires signified properties of block-fractured medium. The distinctive feature of such medium is that desorbing methane is filtered from the central regions, which are artificially created under influence of the blocks towards periphery, and then by the system of trunk cracks into the well. Well flow rate in the given medium is defined as a permeability of cracks and gas recovery rate of blocks as well. A theoretical analysis on the cracks development under hydrodynamic forces enabled to ascertain that size of the blocks, under of which the coal seam is divided, is considered by quadratic dependence on size of order of the seam thickness in the region of well towards periphery. In this regard, the average size of the block along area is estimated 5-15 m.

To estimate the hydro-dismemberment of coal seams during hydraulic fracturing it is necessary primarily to define indicators determining hydro-dismemberment efficiency for improving water permeability and gas recovery of the coal seam.

The degassing efficiency all other conditions being equal depends on the degassing time, the formation *pressure*, the degree of wells pumping, gas-supply capacity of degassing site [79].

Seam pressure, except geological factors, in a complicated way depends on interaction in the system “coal-liquid-gas”. During water injection there is a pore pressure increase due to volume water filling of pores and cracks, as well as substitution of methane by water in sorbate bulk coal. Substitution process is long term and dated in years (3-5 or more) for the real substitution of methane part by water in sorbate bulk. It is predetermined by the fact that in the pore diameter of less than 100 nm there is substantially no viscous flow and capillary penetration. Transferal is realized primarily by transfusion (Knudsen diffusion), diffusion and capillary condensation, i.e. extremely slowly. However, the substitution process probably is still the case that confirms essential dependence of reduction of natural gas-bearing coal on moisture taking place in all world coal basins.

The permeability of the coal seams and surrounding rocks fluctuates considerably and is equal to 0.1-0.001 mD when crack permeability is determined by the equation Boussinesq [21]:

$$K_{\text{тр}} = \frac{b^2}{12} \times 10^6, \tag{24}$$

where: b - is *a* cracks opening (hiatus), cm.

Consequently, a crack b = 0,001 mm provides necessary permeability for the degassing of coal seam (on condition that it is continuous and connected with a well).

For degassing efficiency of coal-bearing strata is important not only permeability in general, but also the relative permeability of degassing site (seam, strata series, host rocks, and etc.). Water saturation greatly reduces gas permeability (K_f) of coal seam for methane.

Thus, operating fluid in hydraulic fracturing based on water plays contradictory role; on the one hand, general permeability of the seam increases and methane in sorbate coal bulk is replaced, on the other hand, relative permeability of seam to methane is reduced. Selection of injected amount is great challenge. Experience shows that when there are 5-7 years and more time for degassing, injected amount of water at hydrofracturing can be roughly about 1000 m^3 per 1 m of thickness of degassed seam. With degassing time about 3 years specific volume has to be reduced to 200-300 $m3^3$ per 1 m of thickness [80] with a significant increase in the injection rate.

Reducing gas content of lava after hydrofracturing by means of replacing methane in coal sorbate coal bulk by liquid and pushing it aside into the host rocks, and reducing relative permeability of the gas can be described by the dependence:

$$q_{\mathrm{c}} = \frac{A}{R} \times \left(\frac{Q}{h}\right)^{n}, \ \mathrm{m^3/t}, \tag{25}$$

where Q – is injected amount, m^3;

R- is a radius of the hydraulic processing, m;

h – is a seam thickness, m;

A = 116 and n = 1/3 – is empirical coefficients derived for Karaganda coal basin [66].

Gas recovery of coal is described closely enough by the formula:

$$I = \frac{I_0}{\sqrt{t}}, \tag{26}$$

where I_0- is an initial methane emission rate;

I – is current intensity;

t – is time.

This is due to the fact that in initial and the most intensive period gases are evolved that are in free and occluded state, and further - the gases that filling meso- and micropores. In practical terms while estimating the potential gas recovery of coal seams determining gas content and gas permeability of coals. Gas content and kinetics of gas recovery are governed by the factors such as the degree of metamorphism, occurrence depth, petrographic composition, mining and geological conditions of deposit.

Gas permeability of coal seams is determined by their cleavage that is formed in the process of coal genesis, and as a result of the tectonic and other activities. Cleavage formed during the coal genesis mainly is defined by the content of vitrinite and the degree of metamorphism. Analysis of degassing results shows that the maximum methane capture is observed in mines with vitrinite content greater than 80% [51].

The most likely reason of it is the ability of vitrain coals to discrepitate into microcracks while removing geostatic pressure in processing coal seams or their hydrofracturing.

3.2.3 The research on gas and hydrodynamic conditions and microstructural occurrence in seams of Karaganda and Dolin suites

In gas-coal seams there is methane predominantly in occluded the state in the pores with a size of less than 10^{-5} cm. Occluded gas molecules in the molecular pores are located in the close contact with a sorbing agent. Vital importance to the gas transfer rate has repulsive forces.

The migration of methane in solid is possible only with high gas permeability of gas-coal seams, host rocks depending on the active impacts on solid mass.

As shown by experimental studies on seams of Karaganda (κ_{10}, κ_{12}) and Dolin suites (∂_{10}, ∂_{6}) [76], the rate of gas passing through a porous medium depends on the nature of stressed state of rock mass, properties of the fluid, pressure gradient (or concentration) with active physical or physicochemical impact on the seam. Depending on the combination of mentioned factors gas migration can be represented by one or plurality of the following processes: diffusion in the pores; laminar filtering under Darcy's law; turbulent filtration in default of gas flow conditions under Darcy's law [81].

The process of the centuries-old migration of gases towards the earth surface is close to stationary due to the processes of denudation and degassing of coal-bearing strata occurring simultaneously. The process of the centuries-old migration of gases towards the earth surface through the gas-coal seams and host rocks proceed under the diffusion law.

When the system is in equilibrium, saturation with free gas is insignificant. As recovering operating fluid, dismemberment of macropores the seam pressure in reservoir is decreased, and upon that gas is desorbed from the microporous surface and diffused into the macropores. Saturation with free gas in the macroporous system is increased as continuation of the desorption process, unless critical saturation comes at which the gas becomes mobile and enters into the cracks of macroporous system. Exceeding the limit state manifests itself in the form of spontaneous fluid flowing from the well that is often observed in experiments and pilot tests (mine named after Kostenko, Sokur, Lenin and others.)

Accordingly, the macroporous system can be considered as part of an underground gas header (UGH) that feeds fluds in macro- and microporous structure in the process of mass-transfer of liquids under influence of seam pressure.

Calculations in conditions of κ_{12} and κ_{10} seams demonstrate that under seam pressure P_{res} = 50 kgf/m^2 water owing to capillary forces could move only in the pores of a size less than 72A°, when $P_{cap}>P_{res}$ the capillary pressure is determined by Laplace's formula [81]:

$$P_{cp} = \frac{2\sigma \cos\theta}{r}, \tag{27}$$

where σ – is a surface tension of the liquid at the boundary with gas, dine/cm;
θ – is a limiting wetting angle, degree;
r – is a radius of the capillary, cm.

Increased percentage of capillary fluid flow through the pores can be achieved by using additive agents to the water that increases the wettability of the coal. Except that, these additive agents shall not reduce the surface tension of water. It is known that wettability is mainly determined by interaction intensity of solid and liquid phase. The given physical effect is experimentally confirmed with pilot testing of hydraulic fracturing wells (mines named after Kostenko, Lenin, Sokur). In the process of industrial tests the selection of surface active agent (SAA) was manufactured on the basis of studying their coal wettability and their impact on the gas recovery. Wetting was assessed on volume of interfacial angle (θ) measured by a drop photograph (for $\theta > 0$) and the radius of schlieren effect of equal mass ($\theta \sim 0$). It was also studied the influence of the SAA on the surface tension of water (σ_{l-g}) [66].

Laboratory research has shown that addition of 0.1% and DS 0.1% ML to the water leads to the reduction of limiting wetting angle. However, by measuring the spreading radius, it is established that with the increase of SAA concentration in the solution the spreading improves. The volume of the capillary pressure pursuant to Laplace's equation is determined by the product of σ_{l-g}x $cos\theta$, so optimum concentration of the SAA in the water is the one for which the product σ_{l-g}x $cos\theta$ is maximum. Calculations made on the basis of measurement θ and σ_{l-g}, showed that for aqueous solutions of DS the optimal concentration is 0.005%, whereas for ML is 0.08%. Volume of capillary pressure for DS is increased 3.6 times, and for ML is 4 times as compared with a similar volume for pure water. In this case, owing to capillary forces at P_{cp}=50 kgf/m^3 solution would spread very intensively in large pores of the rocks.

The use of SAA may give effect not only by increasing the spreading speed on the walls of capillaries, but also opening of microcracks. Spontaneous opening of primordial cracks is set under Griffith's formula [81]:

$$\mathrm{P}_{cr} = \sqrt{\frac{2\mathrm{E}\sigma}{\pi L}}, \tag{28}$$

where E – is modulus of elasticity of a solid body, dyne/cm^2;

σ – is a free surface energy of the solid body at boundaries with the medium (gas - g, liquid - l), erg/cm^2;

P_{cr} – is an ultimate load, dyne/cm^2;

L – is a length of primordial cracks, cm

Widely known fact of wet coal strength reduction in moisturizing is quite understandable, since sorption capacity of coal in relation to water is considerably higher than methane (adsorption heat of water is 10 kcal/mole, methane is 5.9 kcal/mole). The quantity of SAA adsorption on coal should be higher than water. The main role of SAA is to facilitate the access in sorption amount to water.

Calculations show that flow rate is not constant, but decreases over time and approaches to zero as the approximation system of "coal-water" to equilibrium. Therefore in the pores of a size less than 10^{-5} cm (transitional and macropores) water is able to move further into the interstitial phase. In this case, mechanism changes to the diffusion. Vapour diffusion of water in coal can be obtained under the normal molecular (Knudsen) and surface laws. Transferal of the gaseous phase by normal diffusion can take place in the pores of r>10°cm and described by well-known Fick's equation. In the pores of radii less than path length of molecules, there is a molecular diffusion (Knudsen). For water vapour size of such pores are less than 630 A^0 [52]. With a decrease in the size of capillaries, the role of surface diffusion increases.

The sharp decrease of water flow rate in coal micropores in comparison with macropores and cracks should influence the rate of methane displacement from the coal, accordingly, the rate of gas evolution from the seam.

Immediately after the water injection in the seam filtering pores and cracks are blocked by water. It fills them with a continuous layer by having not formed adsorption film over the entire surface of the micropores yet. Confirmation of it are the results of experiments on hydrofracturing κ_{12} seam in mine field named after 50th Anniversary of the October Revolution. The aim of this experimental research was to study the gas recovery rate with an exposed surface of coal block in the process and after hydrofracturing the coal seam, and determination of gas recovery dependence on time past after the exposure, i.e. a kinetics of gas recovery process.

Experimental studies in the laboratory and in field environment of relative permeability of gas and water as the fluid in the seam enable to determine the specific changes of gas-hydrodynamic occurrence in microcracks and pore spaces.

3.3 Procedure on preliminary degassing of a seam

Analysis of the experience of works preliminary recovery of methane from unrelieved coal seams shows that it is indispensable to conduct the stimulation of formation providing a radical increase in its permeability. The main specific features and negative factors affecting the extraction efficiency are:

- occluded state prevailing portion of the methane in the coal seam;
- low natural permeability of the coal that in most cases contains tenths or thousandths of mD;
- relative permeability reduction of the seam on gas as a result of the operating fluid injection leading to the necessity of deployment;
- healing the opening cracks in the process of active impact as a result of rock pressure and changes in the physical and mechanical properties of coal under the influence of the operating fluid.

The basic elements of methane recovery method from coal seams are direct impacts on the seam and well completion. The main mandatory stages while executing the project methane recovery from coal seams are as follows:

- analysis of mining and geological and mine engineering specifications of the site including the natural gas content of the seams, occurrence depth, porosity, broken condition, strength and rheological properties of coals, and etc.;

- compilation and analysis of the experience of preliminary methane recovery in similar geological conditions, definition of well design, producing intervals and predication of gas-emission rate of wells [95];
- choice of technological scheme of influence upon the solid and definition of its parameters;
- site preparation to the active impact on the solid providing well-drilling, gathering additional information during the drilling process, the construction and equipment of the surface complex, uncovering the producing horizons, complex of gas-hydrodynamic tests;
- adjustment of scheme and the parameters of impact on the basis of the specified data;
- directly active influence and evaluation of its efficincy;
- well completion and intensification of gas evolution from wells having insufficient flow rate.

The next stage of preliminary methods of degassing preparation is the process of forming the industrial headers in the coal seam by pumping working agents at a rate greater than natural acceleration. Enhancing the dismemberment methods of the coal seam was conducted in the following directions; elaboration parameters of upgraded baseline technology; elaboration parameters and processing methods of intensification of operating fluid recovery from the industrial header.

While hydrofracturing coal seam, along with opening system of cracks in the emerging header, the processes of the subsequent reduction of opening the cracks under the impact of rock pressure, which increases with seam depth growth and under action of the coal turgescency in moisturizing with operating fluid. This circumstance was the cause in some cases, transition to the technology of pneumohydraulic influence. Sufficient high energy output of the process is determined by the fact that a crack opening in the tense gas-saturated seam is possible only under the pressure provided by overcoming rock pressure and back pressure of the gas contained in coal.

Selecting a specific direction on upgrading technologies should be based on scrutinous and thorough study of the properties and state coal-gas bearing solid on degassing sites with use of seismic survey.

Summary of Chapter 3:

1. Complete object of research on mining and geological specifications considering methane and coal-bearing content of the basin has been represented.
2. Direct dependence of coal methane recovery efficiency and impact parameters on the coal seam influencing the specification of industrial header has been determined.
3. The mechanism of hydrofracturing “dry” outburst coal seams providing a significant increase in the seam permeability for the gas at the main stage of methane recovery works to the surface has been justified.

4. The properties and gas-hydrodynamic conditions on gas bearing seams of κ_{12},κ_{10}, ∂_{10} and ∂_{6} have been investigated; strength and deformation properties of the seams have been determined.
5. The gas-hydrodynamic mode and distribution of seam energy while intruding fluids in unworked coal under laws of underground hydraulics have been determined.
6. The mode of active gas-hydrodynamic stimulation on the seam providing an effective permeability, filtration properties, injectability, piezo- and water permeability has been theoretically justified.

4 Experimental studies of interval (multiple) hydraulic fracturing on solid and strong intervals of coal deposits and radial hydrojet drilling of denty coal rocks

4.1 Industrial tests under the investigation method of impact on petrous seams of Karaganda suite

Each type of hydraulic fracturing has not only advantages but also disadvantages, and is engineered for certain types of headers and geological structure of the wellbottom zone. Since a simple hydraulic fracturing is described in sufficient detail, we shall consider the most acceptable for our research on efficiency - interval or multiple hydraulic fracturing on solid and strong intervals of coal deposits.

This type of hydraulic fracturing is either for large producing horizon thicknesses or for producing horizon represented by alternation of permeable and impermeable differences (fissile seam, for instance, hard coal deposits and clay layers). In these cases, hydraulic fracturing efficiency is determined by the number of cracks in the large thickness of the producing horizon or a crack in every coal interlayer (in the case of the fissile seam).

We shall consider interval hydrofracturing for the case of the fissile producing horizon, diagram of which is shown in Figure 8.

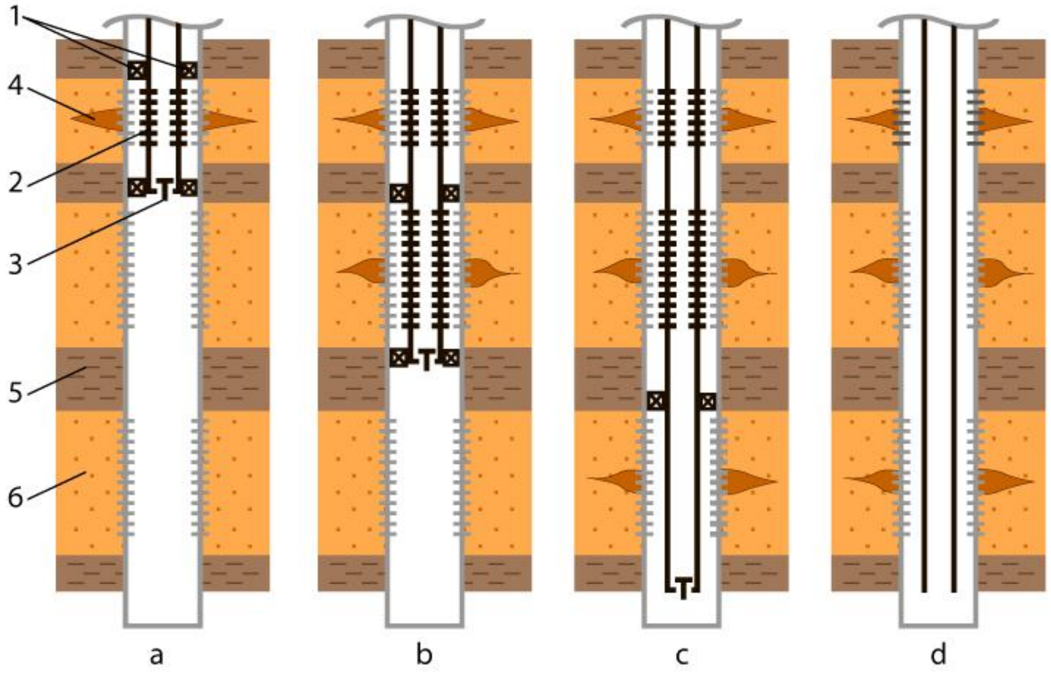


Figure 8 – Diagram of interval hydrofracturing in the fissile seam:
a – is a gap in the upper coal interlayer; b – is a gap in the middle coal interlayer; c – is a gap in the lower coal interlayer; d – is a well after hydrofracturing; 1 – is a packer; 2 – is a tubing string shank; 3 – is a back pressure valve; 4 – is a crack; 5 – is a clay interlayer; 6 – is a seam [adapted version - 82]

Producing horizon represented by three coal varieties, separated by clay interlayers. Only coal interlayers are uncovered by perforation. The gap is conducted from the top downward.

Under the diagram of Figure 8 multiple (interval) directional hydraulic fracturing is realized by using two packers by means of which interlayer is isolated for conducting hydrofracturing from other coal interlayers. After hydrofracturing in the upper interlayer (Figure 8a) system is disanchored and unpackered; access to the the next site is made, the system is anchored. After hydrofracturing equipment access to the lower interlayer is conducted.

Advantages and disadvantages of this type of hydrofracturing appears from the represented diagram. Technical realization and basic requirements for working agents and filler are not distinguished from those of a simple hydraulic fracturing sufficiently considered before.

Stimulation technology of coal seams in Karaganda suite with an aim to improve their gas recovery envisaged the following operations sequence:

- blowing of wells;
- perforation of the required coal seam interval;
- test hydrofracturing (mini hydraulic fracturing);
- hydrofracturing of coal seams;
- lowering of deep well pump, installation and maintenance of equipment for water and methane recovery (testing and well completion).

Blowing of wells

Well drilling of 50-100 m below the soil of the lower target seam is planned by the project. Such drilling is connected with the cost cutting for drilling rig down time in the well due to the time-consuming operations on perforation and hydrofracturing at least 5 intervals of the well, when drilling till the lower seam. The lower 100 m [33] are necessary for the collection of formational waters carried out of the perforated intervals of coal, rock fines and proppant, and also as dehydration tank for formational waters that will be collected throughout the operating period of the well (10-15 years); its volumetric capacity has to be enough to reduce the number of launch operations depleting pump life.

Blowing of the well was fulfilled out with an aim to remove screenings of drill fines from it before casing pipe perforation and hydrofracturing requiring operating seam interval. The blowing was carried out with compressed air supplied from compressor of the drilling rig to complete termination of drill fines removal.

Perforation

Perforation of casing pipe was stipulated for hydraulic fracturing in coal seams through the wellbore. Perforation intervals were specified under the data of previously accomplished logging (GGK-P method). For perforation reusable rock drilling machine with oppositely oriented pairs charge in the same plane (180 deg.)

with the gravitational tracker, charge of Innicor 3/8” SDP type with density of 12 holes/m. Parameters of the charge are shown in Table 4.

Table 4 – Shaped charge parameters of Innicor 3/8 SDP type, Canada [33]

Denomination of parameter	Unit of measurement.	Quantity
Explosive consumption per a shot	kg	1,7
Quantity of shaped charge per a shot	pcs	68
The diameter of the perforating pipe	mm	89
Weight of shaped charge	gram	25
The average diameter of the entrance hole	mm	19,6
The average channel depth of the combined target API	mm	981,7
Phasing	deg.	180
The maximum acceptable temperature for the shaped charge and perforating pipe	deg.	163
Shot density for the given perforating pipe	holes/m	12

The charges were placed on the two opposite forming lines in a vertical line with a density of 12 holes per 1 m, directions alignment of the holes was chosen at a bearing of maximum ground pressure in solid specified by the logging method FOCL. The producing (working) layer was perforated and as well as its host rocks at a distance of 5 m from the soil and the top of the formation.

Technology testing involved initiation of vertical cracks parting both sides of the hole in the direction of maximum pressure. In this regard, it was necessary to create cracks, which would appear in hydrofracturing by joining perforation tunnel at a length up to 900mm in solid, in coal bearing solid mass. The perforation of casing pipe, cement sheath and adjacent to the well was performed by means of jet perforator. Hollow-carrier jet-type perforators of one-time use were lowered into the well on a cable or tubing string. The length of the assembly in going on the logging cable was limited of 10 meters [76]. While lowering in tubing string in a single trip one might carry out perforation interval to 200 m. The length of the perforation assembly in going of it into the tubing string virtually is unlimited that enables to unfold the seam of long-haul, as well as several discrete seams that are located at a considerable distance from each other in depth.

The use of jet perforator provided a clean perforation tunnel, deficiency of casing pipe deformation and preservation of the cement sheath integrity.

Table 5 - Perforation parameters working strings of wells

Well number	Predetermined well depth, m	Seam designation	Occurrence depth of bottom formation	Seam thickness, m	Stage length of perforation, m	Charge quantity
1	2	3	4	5	6	7
X-5	880	$к_{16}$	214	4,37	14,34	172
		$к_{13}$	305	2,99	12,99	156
		$к_{12}^{2}$	318	1,39	11,39	137
		$к_{18}$	438	1,34	11,34	136
		$к_{16}$	454	3,17	13,17	158
		$к_{13-12}^{2}$	574-576	3,79; 3,22	19,01	228
		$к_{12}$	678	7,7	17,70	212
		$к_{11}$	708	1,62	11,62	139
		$к_{10}$	761	5,0	15,00	180
		$к_{7}$	830	2,4	12,40	149
						1667
X-6	770	$к_{16}$	194	2,52	12,52	150
		$к_{13-12}^{2}$	296-304	3,53; 2,22	23,75	285
		$к_{13-12}^{2}$	406-410	3,81; 2,91	20,72	249
		$к_{13}$	440	3,81	13,81	166
		$к_{12}$	514	6,8	16,80	202
		$к_{11}$	551	1,21	11,21	134
		$к_{10}$	612	5,65	15,65	188
		$к_{7}$	718	3,03	13,03	156
						1530
X-7	750	$к_{16}$	158	3,48	13,48	162
		$к_{13-12}^{2}$	264-275	4,29; 2,66	27,95	335
		$к_{12}$	365	2,99	12,99	156
		$к_{14}$	422	1,03	11,03	132
		$к_{13-12}^{2}$	448-453	3,55; 2,76	21,31	256
		$к_{12}$	529	3,49	13,49	162
		$к_{11}$	572	1,41	11,41	137
		$к_{10}$	612	5,81	15,81	190
		$к_{7}$	696	3,34	13,34	160
						1690
X-8	780	$к_{10}^{н}$	170	2,02	12,02	144
		$к_{7}$	272	3,44	13,44	161
		$к_{12}$	376	2,9	12,90	155
		$к_{13-12}^{2}$	462-465	4,55; 2,81	20,36	244
		$к_{12}$	565	2,01	12,01	144
		$к_{11}$	596	1,21	11,21	134
		$к_{10}$	650	5,86	15,86	190

		κ_7	730	3,4	13,40	161
						1333
					Total	**6220**

Rationale for choosing structural parameters of the installation

Analyzing the long-term international experience in hydraulic fracturing it was found that structural parameters of the installation is mainly influenced by the depth and thickness of the coal seam, the maximum operating pressure, the maximum capacity of the pumping unit, the maximum flow of sand and maximum power consumption.

Table 6 shows the thickness and occurrence depth of the coal seams of Karaganda suite.

Table 6 - The occurrence depth and thickness of coal seams

Well number (target depth)	Seam designation	Occurrence depth, m	Normal seam thickness, m
X-5 (880 м)	κ_{16}	214	4,37
	κ_{13}	305	2,99
	κ_{12}^{2}	318	1,39
	crush zone		
	κ_{18}	438	1,34
	κ_{16}	454	3,17
	κ_{13}	574	3,79
	κ_{12}^{2}	576	3,22
	κ_{12}	678	7,7
	κ_{11}	708	1,62
	κ_{10}	761	5,00
	κ_7	830	2,40
X-6 (770 м)	κ_{16}	194	2,52
	κ_{13}	296	3,53
	κ_{12}^{2}	304	2,22
	crush zone		
	κ_{13}	406	3,81
	κ_{12}^{2}	410	2,91
	uplift17		
	κ_{13}	440	3,81
	κ_{12}	514	6,8
	κ_{11}	551	1,21
	κ_{10}	612	5,65
	κ_7	718	3,03

X-7 (750 м)	$к_{16}$	158	3,48
	$к_{13}$	264	4,29
	$к_{12}^{2}$	275	2,66
	$к_{12}$	365	2,99
	crush zone		
	$к_{14}$	422	1,03
	$к_{13}$	448	3,55
	$к_{12}^{2}$	453	2,76
	$к_{12}$	529	3,49
	$к_{11}$	572	1,41
	$к_{10}$	612	5,81
	$к_{7}$	696	3,34
X-8 (780 м)	$к_{10}^{н}$	170	2,02
	$к_{7}$	272	3,44
	crush zone		
	$к_{12}$	376	2,9
	crush zone		
	$к_{13}$	462	4,55
	$к_{12}^{2}$	465	2,81
	$к_{12}$	565	2,01
	$к_{11}$	596	1,21
	$к_{10}$	650	5,86
	$к_{7}$	730	3,4

The maximum operating pressure was limited to the fluidness inner limit of production casing string.

Table 7 - The internal pressure of the seperate columns

Nominal outside diameter of the string, mm	Strength class	Weight of 1m pipe, kg	Weight of 1 m pipe sleeve, kg	Internal pressure, bar
114	J – 55	15,6	10,5	330
	k – 55	15,6	10,5	330
	N – 80	17,3	11,6	536
	P -110	17,3	11,6	737
140	J – 55	23,1	15,5	332
	k – 55	23,1	15,5	332
	N – 80	25,3	17,0	534
	P – 110	25,3	17,0	734
168	J – 55	34,2	23,0	301
	k – 55	34,2	23,0	301
	N – 80	34,2	23,0	437
	P - 110	38,7	26,0	687

During performance of mining tests, we were taking into account that the typical gradients of formation fracturing in the wells of coal methane fluctuates from 0,124 bar/m to 0.271 bar/m. When using high rate (0.271 bar/m) on the assumed deep-lying coal seams (956 m), the maximum assumed pressure of hydrofracturing was determined in 259 bars (0.271 bar/m x 956m). At the same time in order to effectively initiate hydrofracturing it is necessary to ensure the maximum working pressure for equipment of hydraulic fracturing from 345 bars or higher.

The main hydrofracturing of coal seams

This stage is one of the most important in the complex projected works. The purpose of hydraulic fracturing is stimulation of coal seams for increasing their gas recovery and radius designation of dewatering. The nature of the coal seam hydrofracturing is to create an industrial header with a developed system of cracks connecting through the well from the surface in the coal seam. Formation of fracture network in the radius of 100 m from the well is produced by injection into the coal seam of working fluid at a rate greater than the natural acceleration of the solid.

Hydraulic seam fracture was carried out with a set of specialized units. The main ones were represented by diesel units mounted on a car platform with a capacity up to 630-1000 m^3/s and capable to develop a working pressure of 40-70 MPa and a water capacity no less than 6 m^3 /min.

In the wells the hydrofracturing technology of producing formations, with operating fluid supplied by primary (working) string with diameter of 127 mm, was employed. To prepare the working fluid and supplying it to the pump the mix preparation device of a type LK5231THS300 was used (one unit). Equipment unit was mounted on the vehicle chassis NorthBenz with independent diesel engine enabling to transfer the total power (450 m^3/s) for driving the hydraulic pump station.

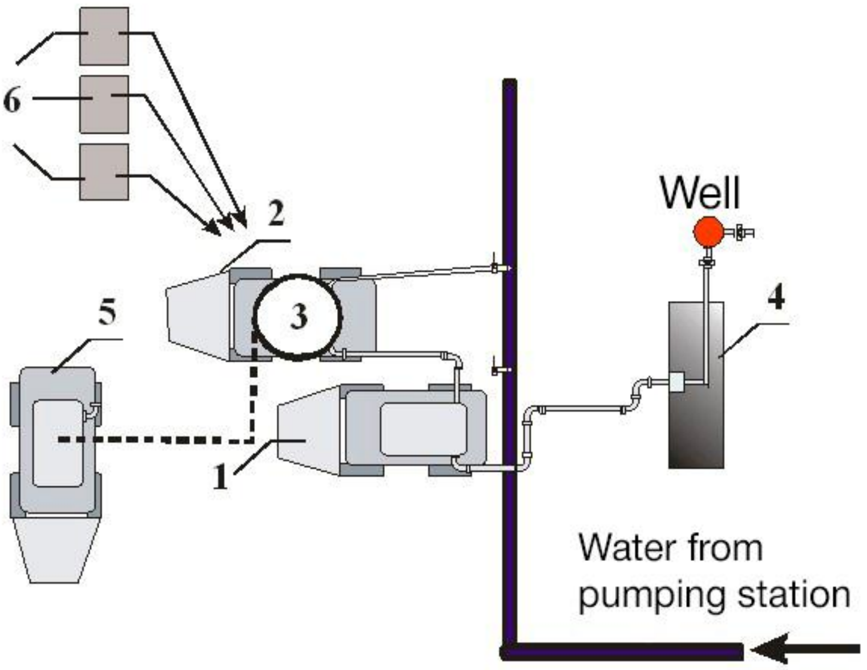


Figure 9 – The diagram of equipment spotting in hydraulic fracturing: 1 – is a pumping unit, 2 – is a blending equipment (blender), 3 – is a tanker with sand; 4 – is a manifold block; 5 – is monitoring and control station, 6 – are tankers for jel, SAA and breaker

Technical specifications of the unit:

- maximum supply sand – 12 m^3/ min;
- maximum fluid pressure – 0.5 MPa;
- the number of pipe junctions in the headers: 12 pcs discharge, 12 pcs input;
- overall dimensions – 10860 x 2500 x 3980 mm;
- total weight of the equipment – 24 000 kg.

For working fluid injection into the well under pressure and with the production rate, which provided hydraulic fracturing process, a pumping unit of a type YLC-1200 on base of the vehicle NorthBenc was used.

Technical specifications:

- power of the working equipment of 1 200 hp;
- maximum developed pressure at the outlet of the unit is not less than 35 MPa;
- maximum capacity of the unit is not less than 4.75 m^3/min;
- automatic control system based on the microprocessor provided smooth control of the unit performance rate in the range from 0 to 4.75 m^3/min; modulating control of moulding pressure rate generated by the unit while operating within the range of 0 to 35 MPa;
- range of operating ambient temperatures - from -50 ° C to + 50 ° C;
- unit operation control was performed from ground control console from distance up to 30m.

In the technical process of hydraulic fracturing of formation engineering staff were accommodated in the remote operator site (one unit) on the basis of NorthBenz car.

Operating site was consisted of:

- autonomous diesel-driven genset;
- workstation including industrial PC, LCD monitors, universal software for data collection;
- data collection unit from the detecting device;
- set of detecting devices and connecting wires;
- remote control of technological units.

The diagram of equipment spotting in hydrofracturing formations is shown in Figure 9.

According to the diagram, for hydrofracturing formations a specialized unit through a special high-pressure fittings and manifold block for high-pressure pipes supplied operating fluid to the wellhead 2AU-700 of the well (Figure 10).

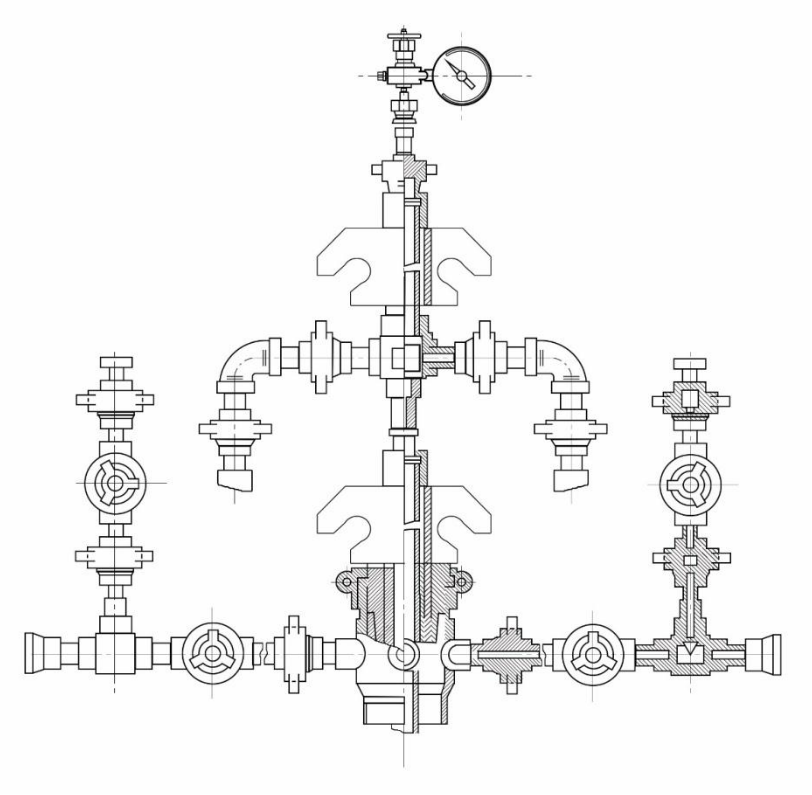


Figure 10 - wellhead 2AU-700 [61]

The lower part of the production wellhead had a screw enabling to fasten mountings directly to the casing tube, and by means of an adapter to flow string with a diameter of 127 mm.

After hydrofracturing the producing formation the well was sustained till the pressure decline to a level that excludes spontaneous emission of coal fines formed from industrial header (up to 3-6 MPa). After that, through a gradual opening of the shut-off valve at the wellhead setup bleeding residual hydraulic pressure was conducted, and treated interval was poured out with sand pack (Figure 11).

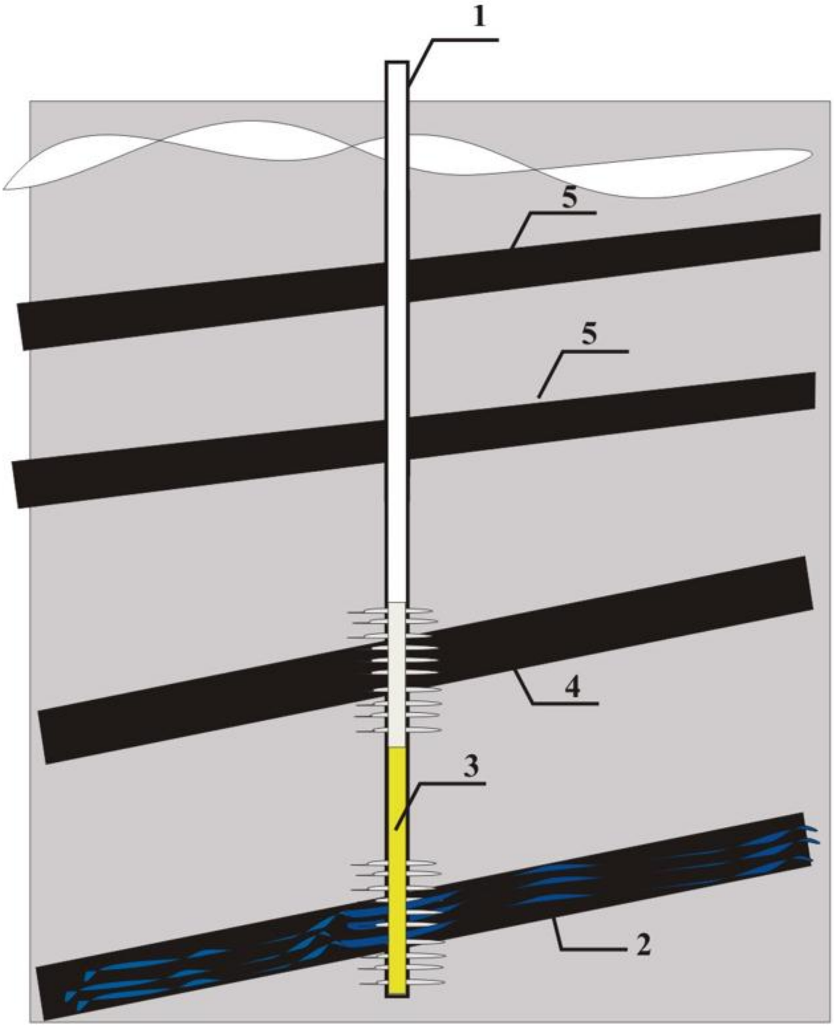


Figure 11 – The diagram of sequential hydrofracturing mineable seams:
1 – is a well, 2 – is a seam subjected to hydrofracturing, 3 – is sand pouring, 4 – is a seam penetrated by perforations, 5 – is an overlying virgin seam

Injection of the working fluid was conducted with the rate at 4.75 m^3/min. As working fluid of hydrofracturing water was used, into which for the purpose of healing the cracks added quartz sand of 0,85-1,6 mm fraction. The volume of supplied sand was calculated based on the amount of 5 tons per meter of thickness of fracturing productive strata. Sand concentration in the supplied working fluid constituted 10-20% by weight. In some wells to increase the efficiency hydrofracturing working additive jells, surface active agents (SAA) and breaker (jell breaker) were added into the working fluid.

Table 8 - Design parameters of hydrofracturing coal seams in the experimental-industrial wells

Well number	Seam	Seam	Amount of	Amount of

	designation	thickness, m	sand, t	water, m^3
X-5	κ_{16}	4,37	21,85	196,65
	κ_{13}	2,99	14,95	134,55
	κ_{12}^{2}	1,39	6,95	62,55
	κ_{18}	1,34	6,70	60,30
	κ_{16}	3,17	15,85	79,25
	κ_{13}	3,79	18,95	170,55
	κ_{12}^{2}	3,22	16,10	144,90
	κ_{12}	7,70	38,50	346,50
	κ_{11}	1,62	8,10	72,90
	κ_{10}	5,00	25,00	225,00
	κ_{7}	2,40	12,00	108,00
				1601,15
X-6	κ_{16}	2,52	12,60	113,40
	κ_{13}	3,53	17,65	158,85
	κ_{12}^{2}	2,22	11,10	99,90
	κ_{13}	3,81	19,05	171,45
	κ_{12}^{2}	2,91	14,55	130,95
	κ_{13}	3,81	19,05	171,45
	κ_{12}	6,80	34,00	306,00
	κ_{11}	1,21	6,05	54,45
	κ_{10}	5,65	28,25	254,25
	κ_{7}	3,03	15,15	136,35
				1597,05
X-7	κ_{16}	3,48	17,40	156,60
	κ_{13}	4,29	21,45	193,05
	κ_{12}^{2}	2,66	13,30	119,70
	κ_{12}	2,99	14,95	134,55
	κ_{14}	1,03	5,15	46,35
	κ_{13}	3,55	17,75	159,75
	κ_{12}^{2}	2,76	13,80	124,20
	κ_{12}	3,49	17,45	157,05
	κ_{11}	1,41	7,05	63,45
	κ_{10}	5,81	29,05	261,45
	κ_{7}	3,34	16,70	150,30
				1566,45
X-8	$\kappa_{10}^{\text{н}}$	2,02	10,10	90,90
	κ_{7}	3,44	17,20	154,80
	κ_{12}	2,90	14,50	130,50
	κ_{13}	4,55	22,75	204,75
	κ_{12}^{2}	2,81	14,05	126,45
	κ_{12}	2,01	10,05	90,45
	κ_{11}	1,21	6,05	54,45

	κ_{10}	5,86	29,30	263,70
	κ_7	3,40	17,00	153,00
				1269,00

Consumption of the working fluid in fracturing was defined by technical specifications of the unit and controlled with its rig. Working pressure was determined by the airgauge installed on the wellhead.

After completion of the hydrofracturing of the upper mineable seam the shut-off valve on the wellhead was overlapped, and the well was sustained under pressure until its decline to the level of 3-6 MPa. After that, by gradually opening the shut-off valve on the wellhead bleeding residual hydraulic pressure was carried. The well then was washed prior to mine face and equipped with a beam-pumping unit.

One of the breakthrough technologies has become the use of our proposals and probe-tested multifold (interval) hydrofracturing, i.e. use of selective effect on the seam. Thus, in the conventional single fracturing fluid injected under pressure the opened perforations are all layers simultaneously by selective - only the selected formation or interval having, for example, underestimation productivity and in multifold HFT repeated exposure is performed successively for each layer individually or seam. Due to the mechanical isolation of different portions of the reservoir in the provides precise placement of bundles of proppant, and due to this there is full coverage of the intensification zone ensures maximum effective permeability fractures, as well as reducing the risk to increase the water cut wells and are the wave of “shake”, which has a positive effect on the increase in gas showings throughout the coal deposits.

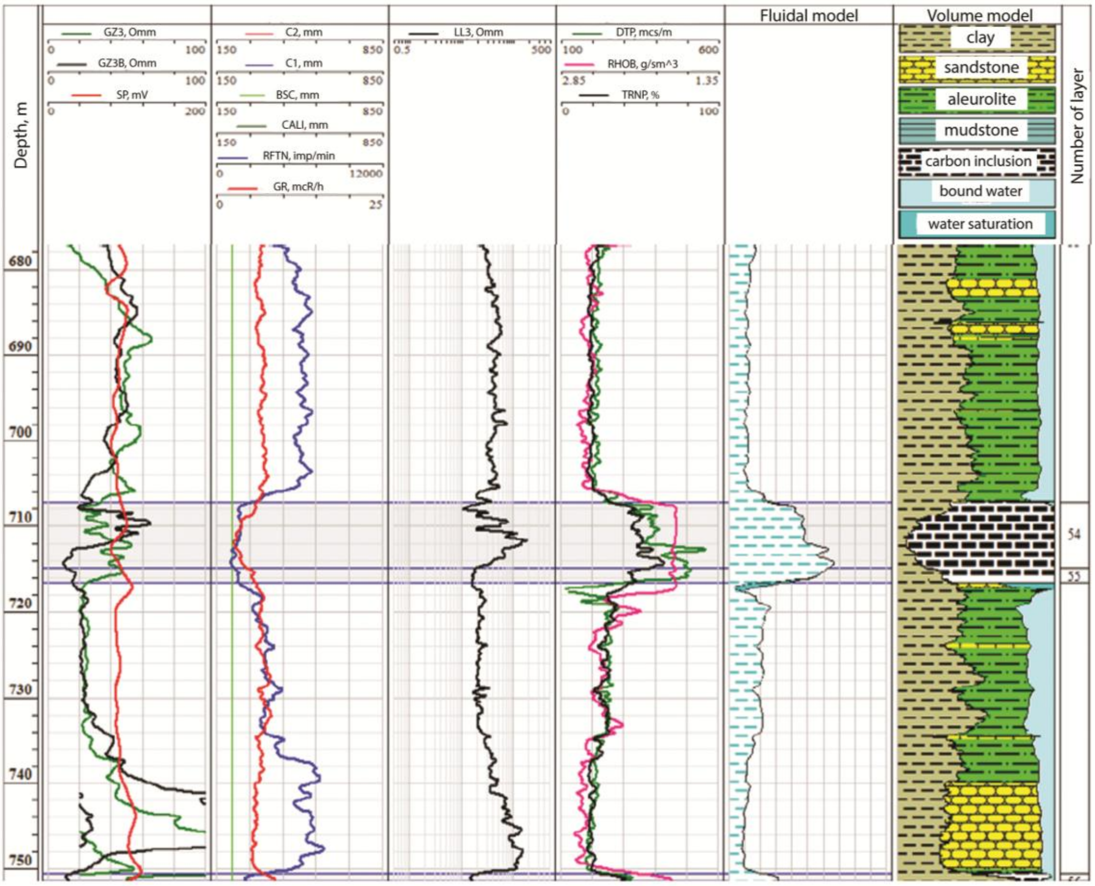


Figure12 – Reservoir Log Interpretation (after hydraulic fracturing)

One of the breakthrough technologies was the use of our proposals and probe-tested multiple (interval) hydrofracturing formation, i.e. use of selective stimulation on the seam. Thus, in the conventional single hydrofracturing under the pressure injected fluid there are all uncovered seams by perforations simultaneously in selective there is only chosen seam or interval having, for example, underestimation productivity and in the multiple hydrofracturing sequential impact on each seam individually or interlayer.

Due to the mechanical isolation of various reservoir compartment precise placement of proppant slug is provided, and due to this there is complete coverage of the intensification zone, the maximum effective permeability of cracks are ensured, and the risk of water content increase is reduced, and the wave of “shakeup” is created that has a positive effect on the increase in gas shows at all the coal deposits.

Thus, the following results were achieved during the test of interval hydrofracturing formations: the wells №№ X-5; X-6; X-7; X-8, the intensity of methane release in the Karaganda region gradually increased from 2.0 to 11.7 times, removal of recoverable methane reached 9,2-14.1 m^3/t that is not the limit. Granting the above-mentioned modern equipped technology for hydraulic fracturing formations and, especially, high-productive pumping stations and quality gas flow rate can reach up to 25 thousand m^3/day or more that is correlated directly with the research of the company “Ernst & Young” (the United Kingdom).

In addition to that described in the thesis methods of hydraulic fracturing performance with water and quartz sand, at present the new hydrofracturing technologies have been developed. An important factor in the success of hydraulic fracturing procedures is the quality of hydraulic fracturing liquid necessary to crack growth, the main purpose of which is the transfer energy from surface to the well bottom required for the crack growth and proppant transportation along the crack.

Specially designed chemical additives impart special properties to liquid; in particular, to improve the thickening crosslinking agents are used that connects polymer chains. However, this liquid may get into ground water and then into the water supply. Many scientists are working on develop more environmentally friendly liquids (ClearFRAC, CleanSuite, EcoClean technologies and others.)

As an alternative to hydraulic fracturing-liquid company Gas Frac Energy Services [83] offers waterless fracking method technology or propane fracking. The principle of the method is the fact that thick gel from liquefied propane (LPG fracturinggel) is pumped into the seam, and not a mixture of water, proppant and chemicals, as in hydraulic fracturing. Operating company claims that along with the same efficiency on fracturing formation as during hydraulic fracturing, this method is safer, since the entire liquid propane, the injected into the seam, transfer to the gaseous state and is removed together with the produced gas.

Also in the alternative to an aqueous hydrofracturing technology, froth and foam-flecked hydrofracturing are used. While the froth hydrofracturing owing to the replacement (on average 60% volume) gelled part of the aqueous solution to a compressed gas (nitrogen or carbon dioxide), penetrability and dimensionless fracture conductivity are increased. In addition, during the froth hydrofracturing the compressed gas, which was injected, consisting froth, helps to squeeze the residual liquid from the seam, which increases the volume of residual liquid and reduces well performance time. Another promising technique is the “jet” hydraulic fracturing, including a hydraulic jet perforation technology and the actual hydrofracturing fromation.

4.2 Increasing the productive capacity of wells - construction of offshoot in radial drilling manner

As noted earlier, the entire course of the hydraulic fracturing process is determined by concepts of *net pressure* and *fluid leak*. At the same time, soft rocks of coal deposits have low modulus values. In addition, the fluid volume is relatively small, however, but leak rate is high.

Theoretically net pressure means difference between the pressure at any point within the crack and the pressure at which the crack closes. This definition implies the existence of some specific *clamping pressure*. The issue whether clamping pressure is integral feature of the rock or in large amount dependent on the pore pressure (or rather from its deviation compared with stable value) is still a pending question. [43]

In the soft rock it is difficult (if at all possible) to provide a method for determining the clamping pressure, as it is classically determined from pressure decline curve. Moreover, due to the small values of the elasticity modulus, even a small inaccuracy in the determination of net pressure will lead to large errors in finding the gap width.

Despite the availability of multivariable three-dimensional models, crack propagation is a very complex process. It is difficult to describe, even in the best case due to the large number of physical processes that are often competing among themselves. Physics of crack propagation in soft rocks is even more complicated, as compared to the hydrofracturing of solid rock it is necessary to consider an increase in energy dissipation, and other more serious end effects. Again, due to the low elasticity modulus the inability to predict the value of the useful pressure can lead to a divergence of results of the planning and the actual results of the processing. Besides, the classic model of crack propagation may not reflect the basic properties of propagation in soft rocks.

Much effort has been spent on laboratory tests of fluid leak in the process of hydraulic on fracturing high-permeability cores. The results led to the raising a questions about how effective hydraulic fracturing is for soft rocks.

Practice has shown that in such circumstances, apart from fluid leak of hydraulic fracturing the seam itself is experiencing the same voltage pressure in all directions of flat surface, and as a result obtains a form of “coin” and not a crack. Therefore, hydraulic fracturing under mild conditions is not a tool to increase productivity, but rather by the method of destructing the coal seam in the bottomhole formation zone.

In order to solve the complex problems associated with the problem of implementing the proposed ways to recover methane, defining value has understanding of regularities of behaviour of gassy coal seams which are reflected in real conditions of its occurrence under various external influences on the mined rock. While recovering methane from coal seams there is a change in the stress-strain state of coal bearing formation. Extraction of methane from high gassy coal seams (their degassing) leads to a change in deformation properties that are appeared in the volume of coal compression and seam shrinkage, in consequence of which there is a host rocks disintegration and rock mass decompression.

It is necessary to conduct special studies on geomechanic processes in coal bearing formation [91], the determination of change patterns of the stress-strain state composing its rocks while creating extended oriented cracks to intensify the methane recovery from coal seams.

Drilling of horizontal drainage wells in soft coal seams, among which the most low-cost and high-performance is radial hydrojet method described in section 4.2.4., should be considered as the most successful method of increasing the production rate of methane.

4.2.1 Complex of machinery and technology for the radial drilling of a seam

The technology of radial opening of a seam was developed by the American company RadTech International Inc., the founder and head of which is Hank Jelsma, the holder of the technology patent. First the technology of radial drilling was implemented in the New World; then it was widely recognized in the USA and Colombia and later was applied in Canada, Bolivia, Argentina, Chile and the Middle East.

The leader in the market of radial drilling services is the international Radial Drilling Services Inc. company (RDS), the headquarters of which is located in Houston. Nowadays, almost all the production companies took this method into practice. Industrial testing of the radial drilling technology was also carried out in Kazakhstan.

According to its inventor, Hank Jelsma, the technology was initially intended for the wells with falling productivity that produced a very small flow rate at the end of their life due to complete blocking of the vertical wellbore within productive formation. The system was commonly used by companies with low budget. However, after its developing and testing in the USA, the technology is used in the standard procedure of well completion, as well as for inflow stimulation, directed acid treatment, and chemical treatment. Generally the radial drilling technology is applied for:

- deep drilling of sustained (carbonate) well seams;
- drilling the wells by multiple formations in the bottom hole formation zone, in the form of cavern-storage, in unconsolidated terrigenous formations of production wells;
- well drilling after their isolation under high-pressure by plugging materials (resin, cement), with water cones and crossflows;
- drilling the injection wells with terrigenous seams polluted by oil field wastes.
- With slight modification, this technology may be used to restore the injection wells with collapsed (displaced) columns. This technology is generally aimed at extension and optimization of drainage zones in productive seams. Radial drilling is also used to create the necessary directions of injection channels and geological exploration works.

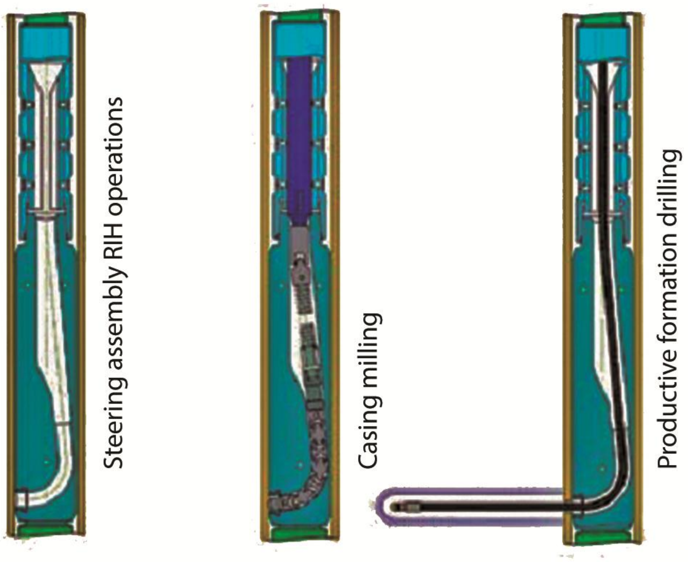


Figure 13 – Equipment set for radial drilling, Operating stages [34]

With cyclic steam impact on a well, radial wellbores help to warm up a significantly larger zone in comparison to traditional methods.

It is extremely important to select a well as a candidate for radial drilling. Experts mark the necessity of pre-project and projects activities. For example, the experience of Lukoil company has shown that the radial drilling has its highest efficiency in carbonate reservoirs. As for terrigenous reservoirs, the results left much to be desired, since clay swelling under the influence of fresh water led to the blockage of drilled channels with 25–30 mm in diameter. To some extent this problem can be solved with the help of polymeric additives that prevent the clay swelling. It should also be noted that for radial drilling it is common to choose those wells that were unresponsive to other methods.

The principle of the technology is based upon hydraulic erosive destruction of hard rocks. Before radial drilling, the crew carries prepares the well: retrieves the downhole equipment, and carries out the gauging of production casing. A deflector shoe with a special channel for instrument (milling cutter) and a hose with a jetting nozzle goes into the cleaned well at the length of the drilled area.

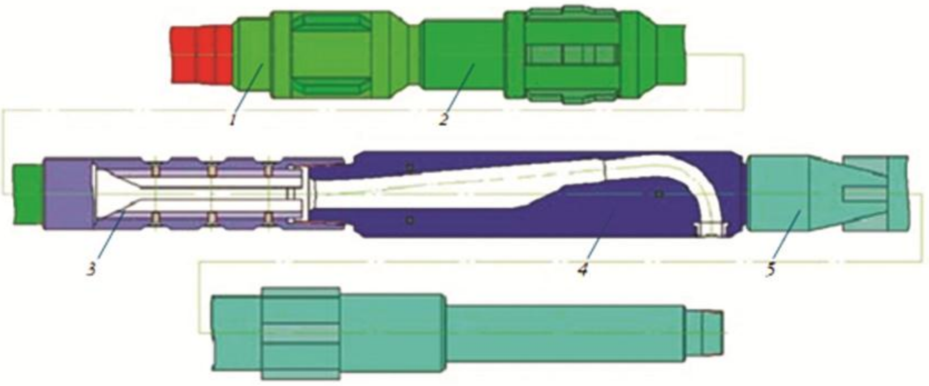


Figure 14 – Steering assembly
1 –friction unit; 2 – collar locator; 3 - guide arch; 4 – deflector shoe; 5 - anchor [34]

Then a unit for milling a window is assembled. With the help of the milling cutter driven by a screw downhole motor, the size of the hole is dependent on the tubing penetration rate and averages at about 25–50 mm in diameter.

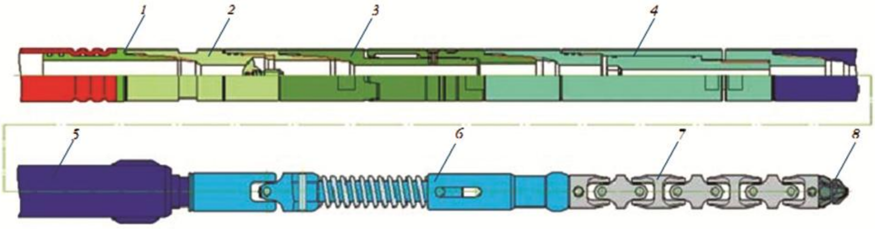


Figure 15 – Milling assembly
1- connector; 2 – fluid control valve; 3 – emergency breaker switch;4 – turning device; 5 –screw downhole motor; 6 – loading device; 7 – flexible drive; 8 – millingtool [34]

The penetration process is controlled from the surface by the coiled tubing tension (in the shallow wells) and by the tubing weight sensor. The process of making one channel of 100 m in length takes about 20–30 minutes.

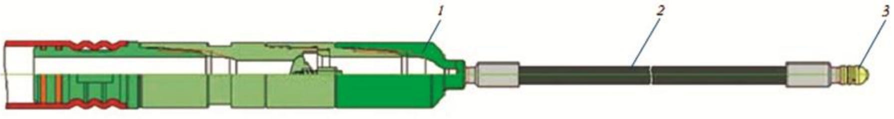


Figure 16 – Formation Drilling Assembly
1- adapter; 2 – high pressure hose; 3 – jet nozzle [34]

The number of radial bores drilled from one well is not limited. They can be made either at one or several levels. After completing all these operations on radial drilling, the tubing with deflector shoe is retrieved, the production assembly goes into the well and the well is put in production. The process respectively takes up from two to four days; the well shutdown period takes up about two-four workdays. The fluid goes to the jet nozzle by a jet thrust and by the high-pressure pump through flexible tube, which produces jets of rocks destruction.

4.2.2 Content and technical characteristics of coiled tubing complex for radial drilling

The complex includes a semitrailer, operator’s cab, coiled tubing spool assembly, hydrostation of drive unit of flexible pipe winding, guide chute, blowout preventer equipment, the pumping unit block, working capacity, control and recording system, the guide arrangement, the arrangement for cutting a window in the production string, arrangement for creating a filtering channel in a productive reservoir.

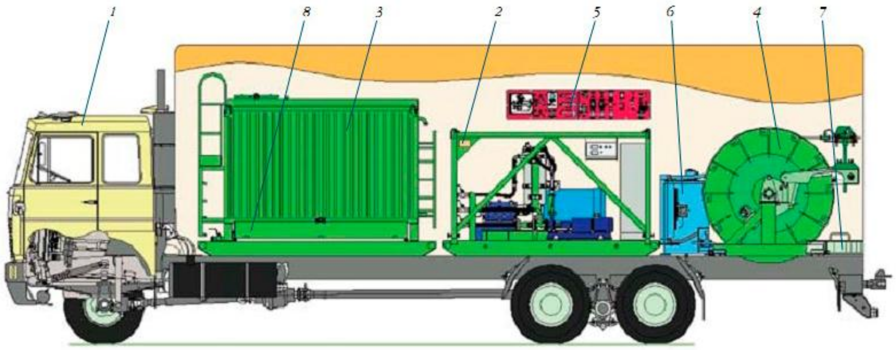


Figure 17 - Radial Drilling Unit:
1 – Maz-type chassis; 2 – pumping unit; 3 – tank; 4 – tubing spool assembly; 5 – control system; 6 – hydraulic system; 7 – assembled platform; 8 – downhole equipment [86]

The mobile station of control and management of production processes

Purpose: Creating a deeply penetrating filtration channels in the reservoir of producing formation for the purpose of intensifying the production of hydrocarbons.

Table 9 - Unit specification [86]

Maximum pulling force of the tubing spool assembly (when operated without injector , at the first layer), kg	2700
Cofled tubing diameter, inches	12.7, 15.85, 19.05
Cofled tubing conveying speed in the tripping process	0, 015 (0.9) 0,6 (36)
Maximum cofled tubing length on the spool, m	4200
Maximum well mouth pressure, MPa	80
Maximum injection pressure of the working fluid, MPa	103
Production casting string diameter appropriate for operation, nm	140; 146; 148

Maximum filtration channel length, m	90
Maximum bottomhole temperature, ^{0}C	150
Maximum running and operating depth for the equipment, m	400
Overall dimensions, maximum, mm Length Width height	 12000 2500 3950

Structure:

Ground Equipment

- All-wheel drive off-road chassis.
- The pump unit.
- Stand-alone electric generator.
- Hydrostation.
- The capacity for the purified solution.
- Mini-coiled tubing unit.

Downhole equipment

- Guide arrangement
  - ✓ Packer
  - ✓ Shoe
  - ✓ Collar Locator
- Arrangement for cutting
  - ✓ Above-motor layout
  - ✓ Screw downhole motors
  - ✓ Flexible shaft
  - ✓ Cutter
- Arrangement for seam opening
  - ✓ The connector to a pipe
  - ✓ High pressure hose
  - ✓ Jet nozzle

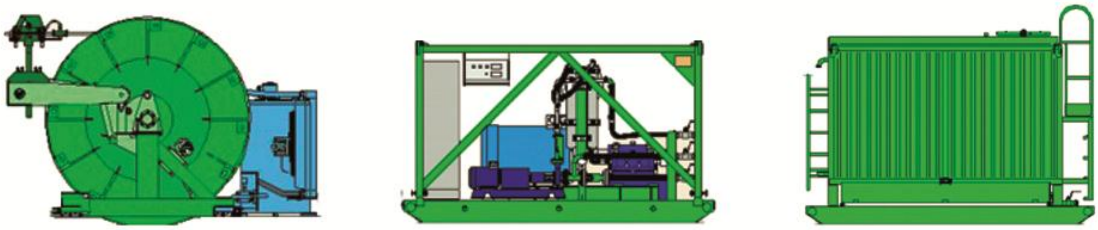


Figure 18 - Mini-coil tubing unit and hydrostation [86]

The content of the technology and equipment

This technology includes two parts: working method and equipment. Construction design for different wells may not be the same.

This technology includes the following equipment: complex equipment for the radial hydrojet drilling to increase the production efficiency that includes a ground complete device and system of downhole tools, which is the key part of the technology.

Ground equipment

1. **Special ground equipment**
    - Block of the high-pressure pump (the main part of the hydro drilling rig)
    - Instruments, tools, control machine
    - Wellhead equipment, ground-based instruments

2. **Bundled ground equipment**
    - Well repair device
    - Capacity of circulation or reservoir
    - Water Carrier

3. **The content of the technology and equipment**
    - The system for under-downhole tools
    - Under-downhole tools assembly

Main materials:

- ➢ Exploitative tubing (N80 or P110);
- ➢ Pumping rod, smooth rod

Anchor equipment
Control block
The drive unit
Swing-guide mechanism for branching
Jet tube
Jet head

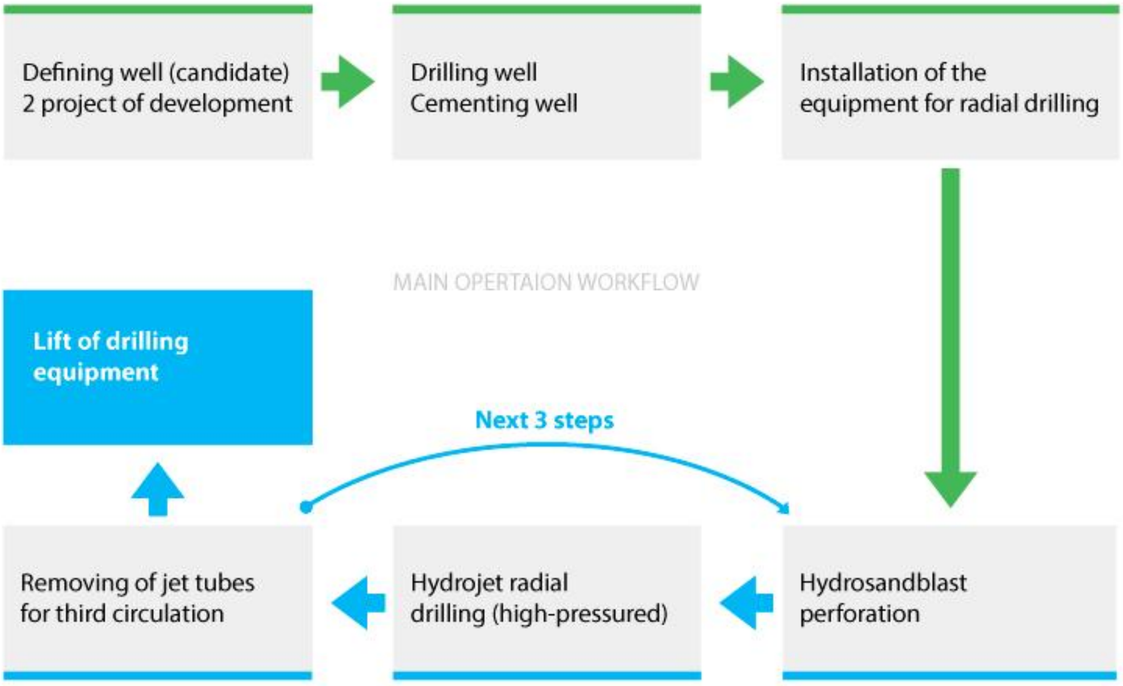


Figure 19 - The modeling of main operation workflow of hydrojet drilling [87]

The first step: the hydroimpact on casing string and cement sheath by abrasive jet (hydro-jet drilling of prepared holes). Second step: the impact on the formations by hydro-jet using a high pressure (hydro-jet drilling of radial holes).

Main technical characteristics

Main application conditions

- The depth of the working well: normally <3500 m, theoretically up to 6000 m;
- The temperature under the well: <145 ℃, currently there are still wells with abnormally high temperature and pressure;
- The main breeds of seams: sandstone and limestone, research of drilling in other breeds is being conducted.

Main technical characteristics

- Special ground equipment: with max operating pressure is 100 MPa, and max working feed of the equipment is 2.13 m^3/min;
- Hydraulic parameters:

Working pressure

for casing and cement sheath: 20-40 MPa;

for seam: 40-65MPa.

- The length of the radial channel > 10-100m;
- The diameter of the radial channel > 40-100mm;
- Number of hole formation at one time = 3 pcs;
- Increase in production rate: 1.5 - 4 times.

4.2.3 Calculating hydro-mechanical analysis of the hydrojet mechanism

Ground control device controls the flow rate of the under-well flexible jet pipe through the pumping rod, keeping it in a state of tension while it moves forward along the radial channel. Only in the state of tension the jet pipe can deeply and directly enter the formation in the vertical direction to the casing.

The mechanism of hydrojet drilling - the drive

- Fluid feeding from the backwards directed jet nozzle is greater than from the forward directed jet nozzle, so that there appears forward pushing force: Pushing force = F2-F1;
- The power of stretching within the jet pipe forces it to move forward.

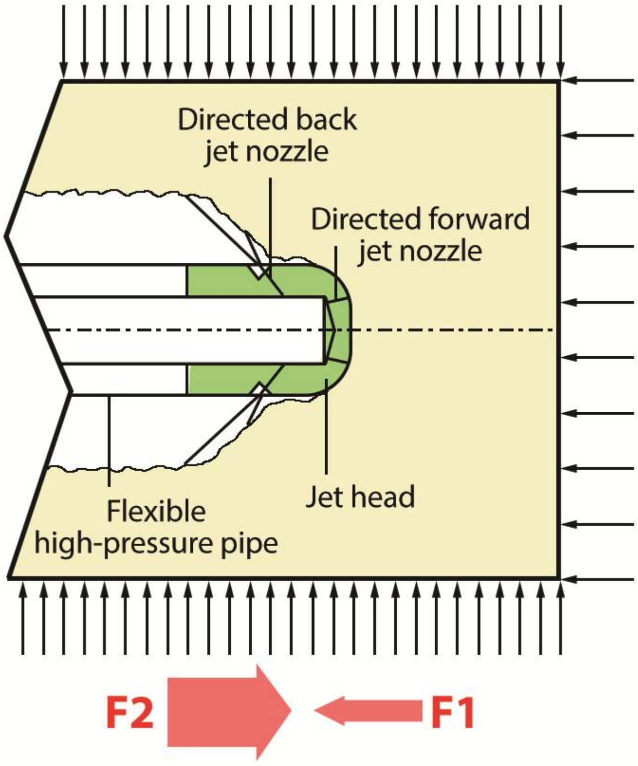


Figure 20 - The mechanism of hydrojet destruction/driiling [87]

According to this technology, the breed is destructed via breaking the breeds of seam by hydro jet of high pressure.

Forms of destruction of breed by hydro jet of high-pressure:

- Surface abrasion (hit)
- Hydraulic destruction
- The gap at elastic-stretching

- Cavitational destruction
- Shift

Mechanism of hydrojet drilling - hydro destruction

Jet head structure used by this technology has front and rear jet nozzle. While the front nozzle gives a small hole, the back one with a larger water capacity not only provides a translational thrust force, but also extends the radial bore. The size of the holes depends on the formation strength, the strength of host rocks, the load of rock pressure, tension of the bedrock, and the hydrojet penetration rate. According to the results of tests on the ground, the average diameter of the hole is about 5 cm for soft and medium-hard sandstone.

Mechanism of hydrojet drilling - the stability of the channel wall

The radial passage in the stability of a wall is similar to conventional uncased horizontal wells. The stability of the wall is mainly based on the tension of host rocks, i.e., on the county O_v, H_v, B_v, that influence the radial channel, which does not lead to the collapse of the walls of the channel.

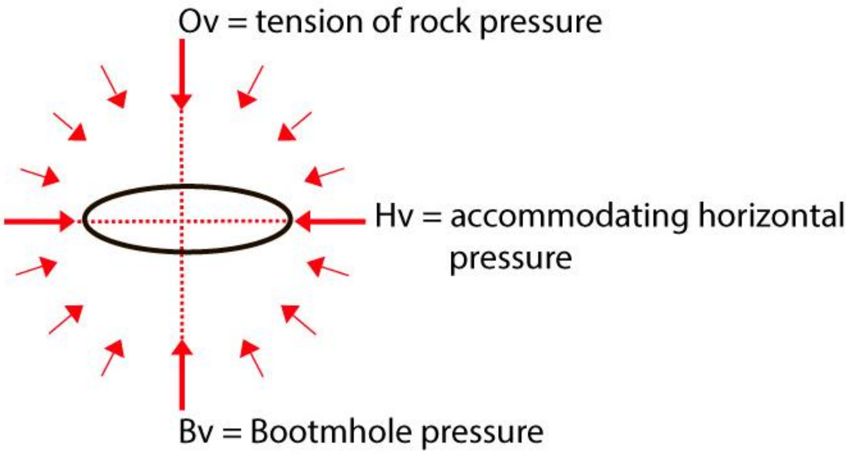


Figure 21- The stability of the channel wall [52]

Control of the trajectory of the radial channel

1. is carried out by the construction of jet head and by collecting the under-downhole tools;
2. is carried out by the rate of movement of the jet pipe;
3. is determined by selecting seams.

Rationale of the physical model of mechanical deformations of the gas-bearing coal seam at the hydrojet destruction of a seam

The processes of sorption and desorption of methane in the coal structure are accompanied by phenomena of swelling and shrinkage, respectively. Coal shrinkage occurs during the transition of methane from solid to gaseous state, which leads to emergence of space released by methane molecules in the desorbed carbon area. For this reason, under the influence of molecular forces, carbon microparticles and volume contraction are rearranged [22, 23, 87]. By a similar mechanism, the opposite phenomenon of coal swelling is implemented: when the methane is sorbed, the volume of coal is increased by means of disjoining action of adsorbed methane molecules. In the processes of coal shrinkage the stress-strained state changes, and consequently the permeability of the coal changes, too, which has a wide experimental confirmation. The impressive practical result is described in [88], where there was an effect of increase in permeability of the coal seam during degasification at the extraction of coalbed methane, which is of great economic interest.

For a theoretical description of the process, it is advised to use physical equations that reflect the patterns of the coal matrix deformations in combination with operating stresses of the rock pressure considering the sorption processes. For this purpose, we consider the following analytical model [41, 45]. Physical equations reflecting the connection between stresses and deformations at the joint display of mechanical and sorption deformations, using a simple principle of superposition, we can write as:

$$\begin{gathered}\sigma_x = \lambda(\theta + \theta_c) + 2G\left(\varepsilon_x + \frac{\theta_c}{3}\right);\ \tau_{xy} = G\gamma_{xy},\\ \sigma_y = \lambda(\theta + \theta_c) + 2G\left(\varepsilon_x + \frac{\theta_c}{3}\right);\ \tau_{yz} = G\gamma_{yz},\\ \sigma_z = \lambda(\theta + \theta_c) + 2G\left(\varepsilon_x + \frac{\theta_c}{3}\right);\ \tau_{zx} = G\gamma_{zx},\end{gathered} \tag{29}$$

where σ, ε, τ, γ – the components of the tensor of stresses and deformations;
θ- volume deformation under the influence of mechanical stresses;
θ_c - volume sorption deformation;
$G = E/2(1+\nu)$ – shear modulus;
$\lambda = \frac{E\upsilon}{(1+\upsilon)(1-2\upsilon)}$ - Lame constant;
E – deformation modulus;
ν- Poisson's ratio.

To describe the mechanism of inelastic deformation, that is, when after a cycle of change of mechanical load and sorption processes of shrinkage or swelling of coal particles do not return to their original state, there are residual deformations of hysteresis - in equations (29) it is recommended to use a variable quantity of deformation modulus, depending on the changing stresses.

At the present level of development of the method of finite elements, the computer modeling of tasks using nonlinear equations is quite available for applied calculations. At the same time the limiting factors are the lack of experience of computer modeling of this type and limited amount of basic experimental data in the processes of deformation hysteresis. The prospective figure of elastic-plastic deformations of the medium with the effect of geomechanical hysteresis (GH-model), in the form of the hypothesis - the model shows the following properties: with an increase in the compressive stress occurs nonlinear growth of relative deformations; with a decrease in compressive tension deformations decrease linearly, and then - at subsequent increase in tension they also increase linearly with deformation modulus of E_0. It should be noted that this mechanism reflects the famous Kaiser effect – the effect of remembering the previously existing stress [89], in which they appear only when a voltage value is equal to the prior maximum value; at the increase of voltage up to a previous maximum voltage occurs deformation in accordance with the original non-linear stress-strain curve; at subsequent cycles of increasing and decreasing voltages – the act of linear increase and decrease deformations is repeated.

To describe the nonlinear deformations diagram with the effect of remembering the previously existing stress, it is necessary to consider the dynamics of stress changes over time. In the case of using the physical equations (29) as fundamental, it is necessary to introduce a function that takes into account the non-linear and temporal nature of the deformation modulus. For example, during the time $0 \ldots t_1$ stresses increase up to the first maximum. At the same time, the diagram of deformation implies that during this timeslot the nonlinear deformation modulus is $E_{(t)}$. Over time, the stress decreases and increases. According to deformation diagram, during the time $t_1 \ldots t_2$, deformation modulus is E_0. The acting tensions at the moments of time t_1 and t_2 are equal. During the time $t_2 \ldots t_3$ there is a growth of stress up to the next peak, while deformation modulus corresponds to the function $E_{(t)}$. According to the presented model hypothesis, the similar patterns of deformation are further repeated. The model reflects the well-known experimental data on residual deformations and the Kaiser effect. The acoustic emission is the result of change in the stress-strain state of the material. The acoustic emission memory effect (Kaiser effect) is observed under cyclic loading of solid state with increasing loading amplitude from cycle to cycle. In the rock salts manifestations of deformation memory effect is clearly observed during the uniaxial tests with constant longitudinal strain rate. In the coals under such mode of deformation, the memory effect on the curves of $\sigma(\varepsilon)$ is observed, so that the deformation memory effect is manifested more clearly in plastic rocks. As for the behavior of rocks in the areas of linear deformations, similar results have been observed in experiments on the salts, which also confirms the validity of the hypothetical model. Representative laboratory researches of the deformation and strength properties are presented in the Koshelev’s thesis. [89].

The logical condition for the choice of the function of deformation modulus performs the following requirements: "If the derivative of the current voltage versus time is greater than zero, a voltage is positive and greater than prior maximum, then it is necessary to use a non-linear function of deformation modulus, otherwise - to use a linear function. Fair for all areas - until the maximum strain state, upon the occurrence of which the deformation modulus tends to zero."

The mathematical description of condition in the Boolean operators is as follows:

$$E(t)=E_1(t)+E_2(t),$$

$$E_1(t) = E_0 \times F(t) \times \left[\frac{d\sigma(t)}{dt} > 0\right] \times [\sigma(t) > 0] \times \{\sigma(t) > max[\sigma(t)]\}, \qquad (30)$$

$$E_2(t) = E_0 \times \left[\sigma(t) < \sigma_{compr}\right] \times \{\sigma(t) \leq max[\sigma(t)]\} + E_{00} \times \left[\sigma(t) > \sigma_{compr}\right],$$

where $E(t)$ – complex deformation modulus, Pa;

$E_1(t)$ – module function on nonlinear sections of deformations, Pa;

$E_2(t)$ - module function on the linear sections of deformation hysteresis, Pa;

E_0 – linear elastic modulus (Young's modulus), Pa;

$F(t)$ – describing a nonlinear form of a diagram of stresses and deformations before a limiting condition, such as:

$$F(t) = \left[1 - \left(\frac{\sigma(t)}{n\sigma_{compr}}\right)^2\right] \times \left[\sigma(t) < \sigma_{compr}\right], \qquad (31)$$

where $\sigma(t)$- mechanical stress in time, Pa;

σ_{compr} – compressive strength limit, Pa;

n – approximation parameter;

$max[\sigma(t)]$- the maximum voltage in the previous sections, Pa;

E_{00}- deformation modulus in a transcendental section of deformation, Pa.

As for the behavior of the environment under the action of tensile stresses, the problem of describing the complex deformation modulus is complicated by the lack of experimental data on the behavior of rocks under uniaxial tensile stress. In the first approximation, we can hypothetically assume that the deformation diagram will be the same by quality, but with different values of elastic modulus in comparison to the compression conditions. We supplement the physical equations of the connection between stress and deformation with patterns of process of sorption shrinkage and swelling.

The volumetric deformation of the coal in the process of sorption shrinkage or swelling at full replacement of coal methane molecules by microparticles is:

$$\theta_c = \Delta G \times \rho_{CH4} \frac{\mu_{CH4}}{\mu_C}, \qquad (32)$$

$$\Delta G = G_0 - G,$$

where ΔG - относительная the magnitude of volumetric sorption or desorption of methane molecules in the coal structure, m^3/kg;

G_0 – the initial gas content of coal (volume of methane at T = 20 ^{0}C referred to the weight of the coal), m^3/kg;

G – current gas content of coal, m^3/kg;

$\rho_{сн4}$ – volumetric weight of methane at T= 20 ^{0}C, kg/m^3;

$\mu_{сн4}$ and μ_c - molar weight of coal and methane, respectively, kg/mol.

When deriving the formula (32) it is assumed that during the desorption of methane from coal, the initial volume of coal freed from methane, under the influence of molecular forces, is filled with carbon atoms and therefore there is a shrink of structural elements of coal. In fact, the full replacement of methane molecules by carbon atoms does not occur and, therefore, in the formula (32) it is more legitimate to use the multiplier that is less than 1, which should be determined by laboratory experiments. In the further assessments we assume this multiplier as equal to 1, supposing that performed calculations lead to the maximum possible influence of sorption shrinkage of a coal, and the real shrinkage will be less than the calculated one. In the formula (32) there is the following rule of signs: at the methane deformation desorption has a plus (shrinkage, $\Delta G > 0$), and, conversely, at the volumetric sorption it has minus (swelling, $\Delta G < 0$). With a known natural reservoir pressure, the initial gas content of coal is calculated using the Langmuir isotherm:

$$G_0 = \left(\frac{abP_{pl}}{1+bP_{pl}}\right)\frac{1}{\rho_C \rho_{CH4}}, \qquad (33)$$

where a – the maximum adsorption capacity in the equation of Langmuir, kg/m^3 (methane adsorbed mass in kgs divided by the coal volume in cubic meters);

b – Langmuir coefficient, Pa-1;

$\rho_{\text{с}}$ – volume mass of coal, kg/m^3.

For example, if a=60 kg/m^3; b=0,207·10-6 Па$^{-1}$; P_{pl}=14,43·105 Pa; $\rho_{\text{сн4}}$=0,67 kg/m^3; ρ_c=1300 kg/m^3 we get:

$$G_0 = \left(\frac{60*0{,}207*10^{-6}*14{,}43*10^{6}}{1+0{,}207*10^{-6}*14{,}43*10^{6}}\right)\frac{1}{1300*0{,}67} = 0{,}0158 \text{ m}^3/\text{kg}$$

(15,8 m^3 of methane, divided by 1 ton of coal).

Similarly, we write the expression for the current gas content of coal at free gas pressure P = 10·10^5 Pa:

$$G = \left(\frac{abP}{1+bP}\right)\frac{1}{\rho_C \rho_{CH4}}, \qquad (34)$$

The result of the calculation:

$$G_0 = \left(\frac{60*0{,}207*10^{-6}*10{,}0*10^{5}}{1+0{,}207*10^{-6}*10{,}0*10^{5}}\right)\frac{1}{1300*0{,}67} = 0{,}0118 \quad \text{м}^3/\text{кг}$$

(11,8 m^3 of methane, divided by 1 ton of coal).

Thus, the physical equations that determine the process of coal deformations considering the combined action of mechanical stresses and the process of methane sorption under the influence of seam pressure, have the form of (29) considering the complex deformation modulus $E(t)$ (30) depending on stresses and time. Due to the complex structure, the heterogeneity of the coal seam, and the stochastic nature of its properties, the physical equations reflect the process in the first approximation. At that, the equations allow us to analyze and predict the basic patterns, considering the combined action of rock pressure and sorption deformations.

The use of alternating deformation modulus that reflects the hysteresis factor in the diagram of deformation and takes into account the effect of remembering the previously existing stresses, offers opportunities of modeling the processes of deformation under cyclic mechanical effects on the coal seam and the manifestation of volumetric sorption, which is important to justify the parameters of preliminary degassing of coal seams or choosing a method of influence on the coal seam in order to provide the required intensity of degassing. Let us estimate the equivalent stresses arising from sorption shrinkage of coal. The average coal deformation under the influence of a combination of factors of rock pressure and sorption is as follows:

$$\varepsilon_{av} = (\varepsilon_{av})_{rp} + \frac{\theta_C}{3}, \tag{35}$$

where $(\varepsilon_{av})_{rp}$ - average linear distortion depending on the average mechanical stress σ_{av}.

$$(\varepsilon_{av})_{rp} = \frac{1-2\mu}{E_0}\sigma_{av}, \tag{36}$$

The relative linear deformations of shrinkage or swelling of coal during methane sorption processes in the case an equal volume deformation are:

$$\Delta\varepsilon_1 = \Delta\varepsilon_2 = \Delta\varepsilon_3 = \frac{\theta_C}{3}, \tag{37}$$

The coefficient of sorption of coal shrinkage is expressed in terms of the derivative of the relative shrinkage deformation (swelling) of coal:

$$\alpha_{sorb} = \frac{d\theta_C}{dP} = -\frac{a*b}{(1+bP)^2} * \frac{1}{\rho_C} * \frac{\mu_{CH4}}{\mu_C}, \qquad \mathrm{Pa}^{-1} \tag{38}$$

Equation (38) reflects an important feature in the form of stabilization of sorption deformations at high gas pressures, when it is completely saturated with methane by coal and its swelling stops. In this case, as follows from (38), sorption shrinkage factor tends to zero.

At small changes in the methane pressure, the comprehensive magnitude of mechanical stress experienced by the coal during sorption is calculated from the approximate formula:

$$\sigma_{av} = \frac{E_0}{1-2\mu}\left[\frac{\alpha_{sorb}\Delta P}{3}\right], \tag{39}$$

Depending on the direction of pressure change, increased or decreased, the coal experiences hydrostatic compression or stretching [103]. From a practical point of view, when improving the permeability of coal there is great interest in tensile stresses, under the influence of which it is possible to implement growth and spread of the plurality of micro-cracks. Let us calculate the deformations and stresses under the following conditions:

1) under pressure P_1=14,43 bar, the gas content is G_0=15,8 m^3/t;
2) with P_2 = 13,43 bar, the gas content is G=15,0 m^3/t;
3) $\mu_{сн4}$ = 16 g/mol; μ_c= 12 g/mol; $\rho_{сн4}$ = 0,67 kg/m^3; E_0= 2·109 Pa; μ = 0,25.

Therefore, the decrease of gas content of coal by the formula (32) when the pressure changes by amount ΔP = 0.1 MPa (pressure 14,43 bar to 13,43 bar) is:

$$\Delta G=0{,}013203 - 0{,}012487=0{,}000716\ (m^3/kg)/bar.$$
$$(or\ 0{,}00716\ (m^3/kg)/MPa).$$

The coefficient of volume deformation due to the sorption shrinkage is:

$$\alpha_{sorb} = 0{,}00716 * 0{,}67 * \frac{16}{12} = 6{,}4 * 10^{-3}, \qquad MPa^{-1}$$

Consequently, the coefficient of linear strain increment is:

$$\alpha_{lin} = \frac{\alpha_{sorb}}{3} = \frac{6{,}4*10^{-3}}{3} = 2{,}13 * 10^{-3}, \qquad MPa^{-1}$$

The calculated theoretical value of the linear shrinkage coefficient of coal is in satisfactory agreement with the experimental results [1, 90], in which the values are measured in the range (1,5…2)·10-3 MPa^{-1}. Slightly overestimated magnitudes of the theoretical value are explained by the assumption of complete mutual substitution of volumes of methane and carbon molecules. Let us calculate the magnitude of comprehensive pressure, which occurs at reduction of the formation of methane pressure on one bar:

$$\sigma_{av} = \frac{2*10^9 Pa}{1-2*0{,}22}\left[\frac{6{,}4*10^{-3} MPa^{-1}(-0{,}1\ MPa)}{3}\right] = -8{,}53 * 10^5, \qquad Pa$$

Thus, as calculations demonstrate, the effect of shrinkage sorption coal, even with small depressions of formation pressure leads to a significant tensile stress, comparable to strength. It is also important to note that the reduction of formation pressure by 0.1 MPa leads to shrinkage stresses in absolute magnitude significantly more than the magnitude of the low gas pressure. To calculate the average stress at comprehensive deformation at the broader methane pressure variation, shown schematically in Figure 21, it is recommended to use a more accurate formula in the form of:

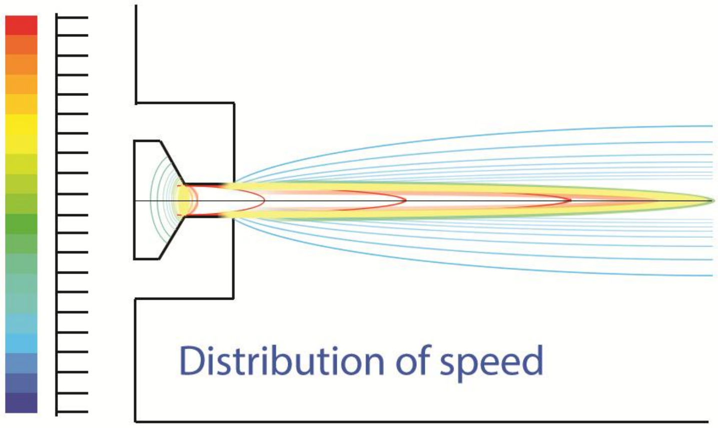
$$\sigma_{av} = \chi \frac{E_0}{3(1-2\mu)} \left(\frac{abP}{1+bP} - \frac{abP_{pl}}{1+bP_{pl}} \right) \frac{1}{\rho_C} * \frac{\mu_{CH4}}{\mu_C}, \qquad (40)$$

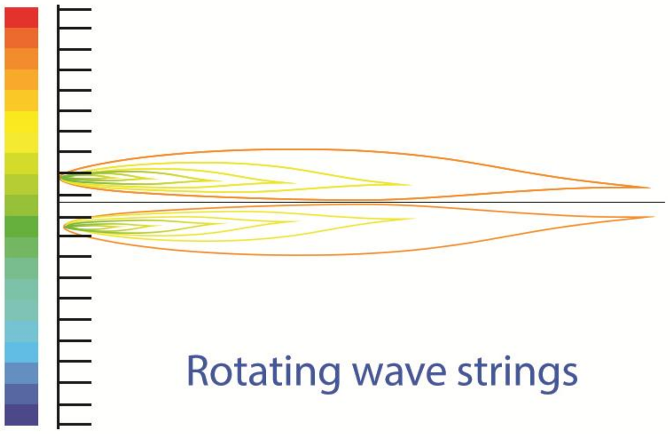
where χ- a correction coefficient, less than 1, which is determined in laboratory tests; In addition, in the formula (40) it is more accurately described how methane and carbon microparticles replace one another along the curve of sorption isotherms of Langmuir.

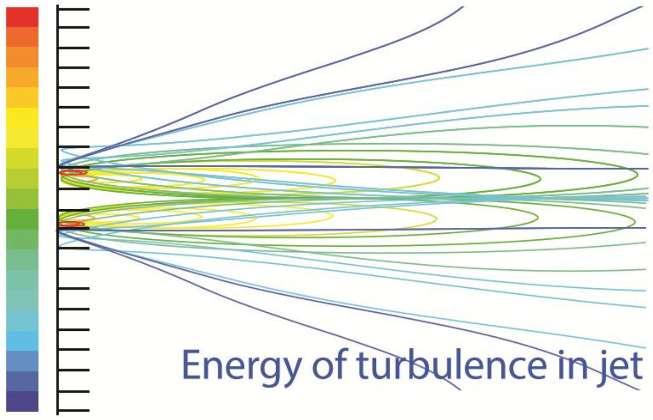
The performed assessment calculations offer the prospect of using the physical effect of shrinkage stresses in the technical solutions in increasing the permeability of the coal, increasing the microcracks, reducing the total deformation modulus, relaxation of stress and unloading of high rock pressure at degassing of coal. This is especially relevant in the production of cleaning works in dangerous areas and the prevention of manifestations of dangerous geological phenomena.

Thus, with the reduction of formation pressure of methane by 0.5 Mpa, there are tensile stresses in carbon structure, with absolute magnitude five times higher. In our assumption, these tensions can increase the permeability of the coal. This effect of changes in the properties should be used for engineering objectives aimed at improving the efficiency of methane extracting.

By modeling the processes of hydrojet destruction of the coal seam on the basis of conducted finite element calculations, we obtained the following interpretation:







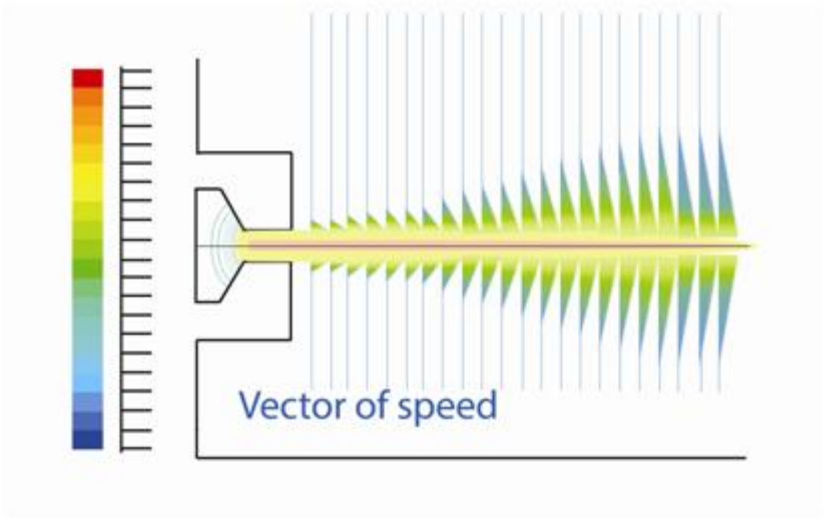


Figure 22 - Simulation of physical processes of the hydrojet destruction of the coal rocks

The main field of application of radial drilling are relatively soft, hard coal deposits fractured wherein the fracturing method cannot be performed either due to plasticity of breeds, or inability to provide the necessary fracture pressure (250 atm or higher) [104].The radial drilling includes the modified technology of flexible tubing (coiled tubing) for drilling shanks with a diameter of 50 mm and length up to 100 m away from the main shank.

The main purpose of this method is to improve the performance of the main well by drilling radial shanks beyond the damaged bottom zone and to provide access to non-draining areas of the coal seam. Currently, this technology is used only in a vertical or almost vertical wells, although there are still researches on refining of the technology for use in inclined and horizontal wells. Decisions on the selection of candidate wells, are made jointly by the operator and the contractor of radial drilling, generally depending on the mechanical state of the well and its production capacity.

The analysis of the new technology of "radial hydrojet drilling", has shown that it has an effect on the destruction of soft rocks of the coal seam, since this is a horizontal drilling technology with low cost and sufficient hole to enhance the production of methane (up to 50 mm).

This method allows to achieve precise placement of sidetracks and extended opening of reservoir breeds in comparison to other methods of increasing the production rate of methane.

- Application in high-producing wells, as well as in low-producing wells;
- For reducing the pressure drop, increasing the operational radius of the gas well, improving the flow profile of the fluid in the reservoir around the sidetrack and increasing the productivity of most sediments collector;
- For penetration of the irregular collector and the vertical fractures without the influence of the tilt angle of the formation;
- For the production of unused reserves in the inter-well space;
- For increasing the flow rate of methane from the thin and bad border seams;
- For increasing the flow rate of gas from single well when used for opening of vertical cracks and penetration of limestone karst, karst cavities and cracks;
- The application of this technology for gas production in the coal seam and other minerals.

4.2.4 Experimental research of horizontal hydrojet drilling on the facilities of Dolin suite

The most coal-bearing and industrially valuable seams are seams of Karaganda and Dolin suites.

When radial drilling, the filtered water (<10 microns) is circulating along flexible tubing, and the perforation is achieved by the ejection of water through nozzles under high pressure corresponding to the strength of compression of formation breeds. Control of the jet flexible tubing and the control surface allows to maintain a constant tension of the flexible hose in the radial bore. This tension, along with the column exit point allows the formation of only a straight line at the exit of the column while maintaining this tension. Based on the experience of CBM production in the United States, Canada and Australia [85,106], it was decided to use a surfactant as a cleaning agent and a method for increasing the rate of penetration. On average, each 100m drilling sidetrack took less than 2 hours on the sites Dolin suite.

Table 10 - Depth of occurrence and power of coal seams of Dolin suite

The well number (project depth)	Seam indexes	Depth of occurrence, m	Normal power of a seam, m
№016 (560 m)	∂_{10}	432	0,99
	∂_{9}	438	1,84
	∂_{8}	449	2,34
	∂_{7}	455	1,98
	∂_{6}	468	3,2
	∂_{5}	481	1,29

	$д_{4}$	498	4,7
	$д_{3}$	512	0,82
	$д_{2}$	518	2,00
	$д_{1}$	558	1,20
№014 (510 m)	$д_{10}$	432	0,99
	$д_{9}$	438	1,84
	$д_{8}$	449	2,34
	$д_{7}$	455	1,98
	$д_{6}$	468	3,2
	$д_{5}$	481	1,29
	$д_{4}$	498	4,7
№012 (580 m)	$д_{10}$	442	0,99
	$д_{9}$	458	1,84
	$д_{8}$	479	2,34
	$д_{7}$	505	1,98
	$д_{6}$	568	3,2
№021 (600 m)	$д_{8}$	417	2,02
	$д_{7}$	440	3,44
	$д_{6}$	456	2,9
	$д_{5}$	462	4,55
	$д_{4}$	485	2,81
	$д_{3}$	500	2,01
	$д_{1}$	576	1,21
	$к_{13}$	589	5,86
№028 (565 m)	$д_{10}$	389	3,24
	$д_{9}$	414	0,98
	$д_{8}$	420	1,7
	$д_{6}$	438	4,17
	$д_{5}$	460	3,01
	$д_{4}$	472	2,56
	$д_{3}$	521	1,14
	$д_{2}$	553	3,82
№034 (660 m)	$д_{10}$	412	1,17
	$д_{8}$	434	2,59
	$д_{7}$	460	1,44
	$д_{6}$	478	2,9
	$д_{5}$	492	3,86
	$д_{3}$	535	1,24
	$д_{1}$	583	2,97
	$к_{13}$	612	4,21
	$к_{12}$	669	3,14

During radial drilling in the areas of Dolin suite we chose six wells located in different parts of the deposit. All the wells were vertical or almost vertical. On four candidate wells there were attempts to drill four sidetracks at one level, and on the *well № 016* - four sidetracks on two levels. Except for the *well № 014*, where it was possible to drill only two sidetracks, on the rest of wells the drilling has been successful, sidetracks with the length of about 100 m were drilled on all planned levels. All sidetracks were treated with 10% solution of hydrochloric acid right after the drilling.

The results of tests in the areas of Dolin suites indicate the expediency and need for the method of radial drilling. For example, in the *well № 012*, located just south of the deposit center, four radial tracks were drilled at a depth of 550.9 m, with 98 meters in length of each. The intensity of gas release in this area gradually increased to 2.0 - 4.7 times, and the overall coefficient of intensification reached the value of 5.2 - the amount of extracted methane reached 8-10 m^3/t instead of 1.2-1.9 m^3/t.

The *well № 021*, located just north of the center of the deposit, is the only cased well, where the radial drilling was carried out. In all there were 4 drilled sidetracks, each of 100 m long. Due to with the arisen difficulties during the drilling of these sidetracks, two of them were drilled at a depth of 536.7 m, and the other two at a depth of 586 m. It is assumed that these difficulties were due to poor quality of cementing between the casing and the formation. The effective radius of the impact increased and was about 52-98 m. The volume of methane removed through the wellbore to the surface of the downhole to a ton of reserves varied from 3.14 to 7.25 m^3/t. The flow rate of methane varied from 3 to 5 m^3/min.

The *well № 028* with sliced sidetracks in the east side of the deposit. In all there were 4 drilled sidetracks at the depth of 557 meters, each of 100 m long. The flow rate of oil after radial drilling has increased from 2.1 to 7.2 m^3/min, which is represented in the increase of productivity by 3.4 times.

The *well №034* with sliced sidetrack in the northwest of the deposit. When drilling the radial sidetracks we faced serious difficulties, presumably caused by the fact that the well was previously subjected to acid treatment. This acid treatment and the subsequent increase of the sidetrack diameter probably caused the impossibility and centering of the whipstock in the well. Nevertheless, it was possible to cut two sidetracks in the well (one of them of 94 m long, and the second one of 23 m) at the depth of 651.3 m. Despite the fact that it was possible to drill only two sidetracks, the production rate of the well has increased from 2.2 to 4.9 m^3/min, i.e. almost by 2.2 times.

Full-scale tests in areas Dolin suites demonstrate the need for and feasibility of the method of radial drilling with the addition of surfactants, based on the German production and sulfonol stabilizer – “POLOFIXHV” company CMC. The test objects were selected №№ wells were 012, 021, 028, where each sidetrack is drilled with an incremental increase in the surfactant concentration in sequence: 0.01%, 0.05%, 0.1%, 0.5%. During the test, the speed of shaft sinking was measured. In order to determine the effectiveness of the method chosen for the comparative analysis of the two lateral wellbore 014, drilled in a water-based have been chosen, which also measure the speed of shaft sinking. The proposed comparative analysis is justified, since wellbores test length is relatively close. The test results are shown in Table 11.

Table 11 - Weighted mean change rate of the mechanical radial drilling hydrojet

		Rate of sinking, m/h									
№	SAA concentration, %	10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m
1.	-	33,5	31,8	35,1	31,5	31,5	30,4	26,5	28	28,1	28,1
2.	0,01	32,5	34,1	34,2	27,8	30,5	36,1	36,1	37,8	37,8	37,1
3.	0,05	34,8	35,6	37,0	35,1	35,6	37,8	29,3	31,8	35,6	37,8
4.	0,1	44,1	44,0	46,2	38,1	47,8	49,1	44,1	45,6	45,6	45,6
5.	0,5	43,9	44,1	44,5	43,2	46,5	46,5	44,2	49,1	49,5	44,1

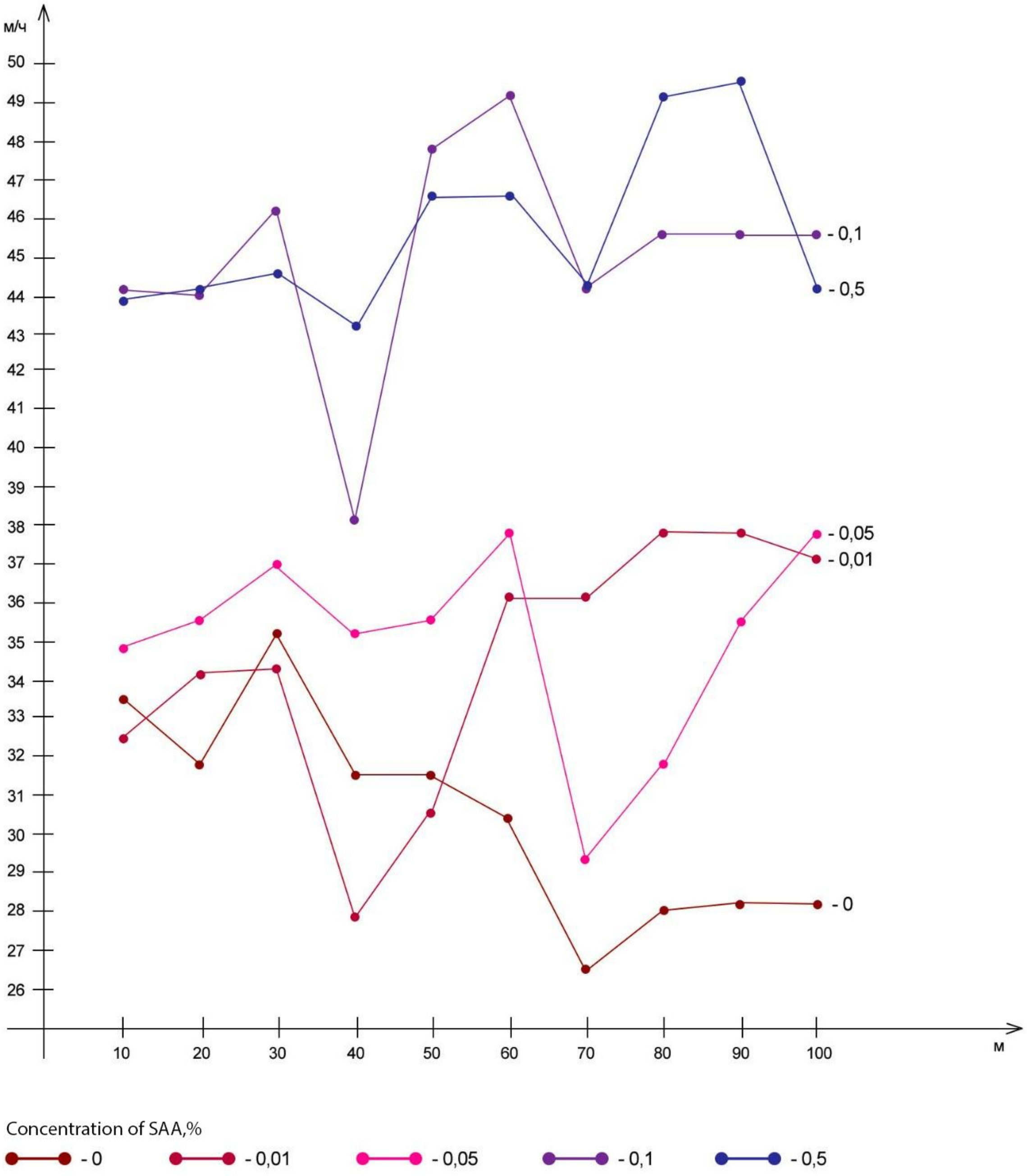


Figure 23 - Change rate diagram of the mechanical radial drilling hydrojet due to the SAA concentration

As it can be seen from Fig. 23 weighted average change rate of penetration speed of the lateral hole with SAS concentration of 0.1% and 0.5% are close. With the SAF concentration of 0.1% is recognized as the most effective and economic viability.

In general, radial drilling in the areas of Dolin suite may be considered quite successful. Almost all the wells, subjected to these experimental tests have shown a significant increase in productivity in the result of radial drilling.

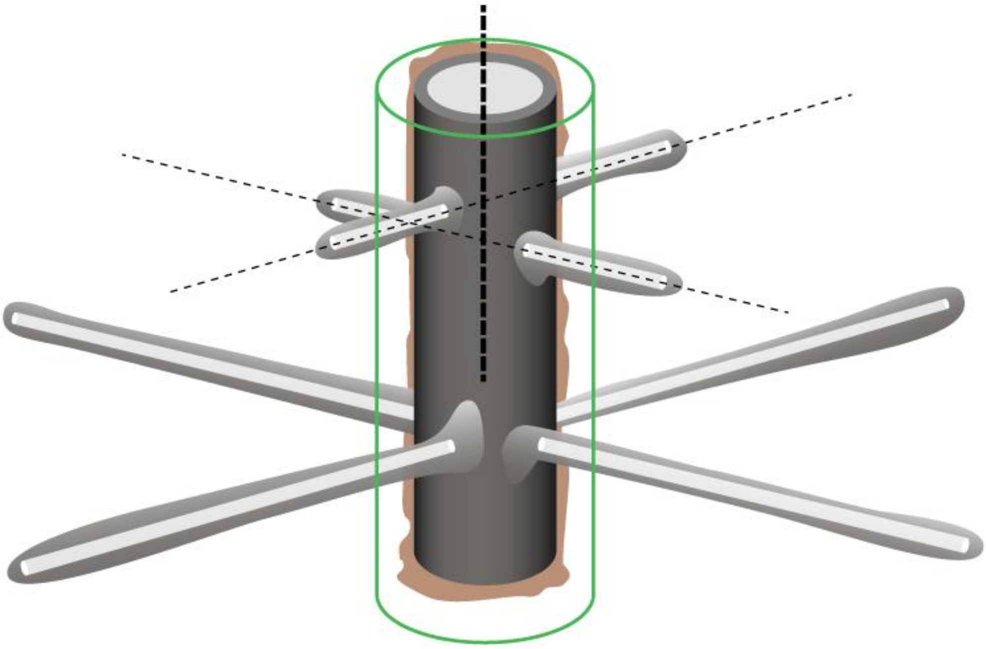


Figure 24 - Radial hydrojet drilling - extended dissection of reservoir rocks in comparison with traditional methods [author's interpretation]

The most important conclusion of the experimental testing of radial drilling in the areas of Dolin suite is the fact that the key to successful implementation of the works on the radial drilling is the right choice of wells and deposits. When radial drilling of sidetracks we have faced problems only in those wells with an enlarged diameter of the sidetrack as a result of previously conducted acidizing, which led to the impossibility of centering of the whipstock in the well. We have also faced problems while cutting radial sidetracks in the well № 021, due to the poor quality of the cementing between the casing and the formation. It underlines the importance of accurate planning and selection of the wells before the beginning of radial drilling.

The tests in the areas of Dolinskaya suite have undoubtedly proved that the radial drilling is not only a cost-effective method to increase productivity and to provide access to "clamped" hydrocarbons, but also is the shortest way to achieve these goals.

Summary of Chapter 4

1. We have described the physical equations that reflect the patterns of deformation of coal matrixes in combination with operating voltages of rock pressure, in view of the sorption processes and a rough calculation of deformations and stresses.
2. Our calculations have demonstrated that the action of adsorption of coal shrinkage, even with small depressions of formation pressure, leads to a significant tensile mechanical stress. In our assumption, these stresses may increase the permeability of the coal, and this effect is expedient to use in the technical solutions aimed at improving the degassing rate.
3. We have considered one of the most common methods of treatment of bottomhole areas – the gradual hydraulic fracturing - with the aim of stimulation

or injectivity in hard coal deposits (due to the great power of productive horizon - more than 10 meters).

4. Based on the results of modeling and natural research of the wells № X-5; X-6; X-7; X-8, we have performed commercial inflow of methane in which the removal of extracted methane reached 9,2-14.1 m^3/t.
5. During industrial testing of radial hydrojet drilling in Dolin suite, especially in soft rock layers ∂_6 and ∂_{10}, all six wells have shown the ability to increase the production rate of methane to the average values. The application of SAA, as a cleaning agent, showed an increase in penetration rate under ceteris paribus, and similar nature of the effect of regime parameters.

5. Technical and economic efficiency of investigated technology of coalbed methane industrial production

The data of performed gas sampling allows us to determine the position of the border areas of methane and to predict the change in the gas content in area and at the depth of the investigated territory.

We have produced inflow intensification of productive horizons on 4 wells by technology of multi-stage fracturing on a flexible tube.

Despite the fact that the layers exposed to industrial tests were "dry", the development and exploitation of CBM wells, due to their specific features, require a forced evacuation of associated formation water. Only under the condition of complete drainage of concurrently developed group of productive coal seams, it is possible to achieve the maximum production rates of wells.

Table 11 - Capital expenditure on exploitation of the equipment for hydraulic fracturing

The cost of equipment for hydraulic fracturing			
	Manufacturer of the equipment for hydraulic fracturing, US $	Service company	General capital cost, US $
Equipment for hydraulic fracturing	1 100 000		1 100 000
Engineering designing and support	150 000		150 000
Special metal material	125 000 [1, 4]		125 000
Spare parts and consumable supplies	45 000		45 000
Training	15 000		15 000
Delivery	15 000		15 000
Training [2]		250 000	250 000
The technical expertise of assembly and efficiency		20 000	20 000
Other costs[3, 4]			
General capital cost	1 450 000	305 000	1 755 000
[1] The price info is given for the material N [2] Provided by ARI and recognized provider of hydraulic fracturing services [3] Other additional components [4] FOB Houston			
The cost of exploitation of the equipment for hydraulic fracturing (per one procedure [5])			
Staff			3020

Transport fuel	4 l/km		
Operating fuel	384 l/km		2180
Repair and service	2000 per one procedure		2000
Materials:	Cost /Item		
Gel	6,50 /lb.	1 320 lb.	8 580
Surface-active substance	15,00 /gal.	44 gal.	660
Crusher	100,00 /gal.	0,67 gal.	67
Sand	100 00 /m.t.	40 m.t.	4 000
[5] Assuming three processing on each well, at 4 wells, general exploitation costs is $ 100 000 approx.			

The average cost of gradual (multiple) fracturing in the conditions of Karaganda suite at depths of 780-830 meters is approximately estimated at 56,000 US dollars.

Estimation of economic efficiency of the radial hydrojet drilling in the conditions of Dolin suite is quite a difficult task due to numerically small tests aiming at coal-bed methane production.

In general, the economic efficiency of the investigated technologies cannot be estimated by "Methodology for determining the economic efficiency of the coal industry of new technology, inventions and innovations" [53], which is used in the coal industry, since in this context the coalbed methane is considered as an independent product.

The additional economic benefit can be estimated at a combined generation of energy from methane, which can be estimated at the cost of replaced coal (1000 m^3 of methane is equivalent to 1.8 tons of coal). [93]

It should be noted that the proposed technology of coal-bed methane extraction does not affect the future shaft development of coal-bed and stability of rocks during mining, and has no negative impact on the environment and the territory near the gas field.

Production of methane, which can be carried out in parallel with coal mining, will significantly reduce the high gas content of the Karaganda coal basin and minimize the risk of underground explosions.

Conclusion

The thesis is a scientific qualification work containing new research and practical results with justification of technology of industrial production of coalbed methane, based on gradual hydraulic fracturing technology and radial hydrojet drilling.

The main scientific results and practical conclusions and recommendations, received personally by the author are as follows:

1. Methane recovery in wells intensifies degassing of mining coal seam that leads to safety benefits with a high load on the working face.
2. Mining and geological conditions of the development of the coal seam of hard rocks of Karaganda suite and geometry of underground excavation were determined on the basis of theoretical study of the gas permeability of the coal seam, volume deformation of coal in the process of its sorption or desorption in the range of methane formation pressure, the mass transfer coalbed methane mechanisms.
3. Interval hydraulic fracturing has provided the conditions for anhydrous methane production by blocking the underground fluid entering the well by the gas pressure in coal deposits exceeding the value of the hydrostatic pressure of water in the surrounding rocks.
4. Basing on the calculations, we determined the parameters of gradual hydraulic fracturing, which resulted in the removal of methane up to 9,2-14.1 m^3/t. At large application of this method the flow rate of methane can reach up to 20-25 000 m^3/day on well with the additional equipping by high-performance pumping stations and durable binding of wells.
5. Conducted calculation of deformations and pressures of soft rocks in Dolin suite enabled to determine the most effective method of coalbed methane production - the radial hydrojet drilling using SAS with a concentration of up to 0.1%.
6. The economic efficiency of commercial production of coalbed methane should be determined by combination of cost reduction on emissions into the atmosphere, the use of methane as a fuel and raw material for the petrochemical industry, as an independent commercial product (in the future).
7. The prospects of further development hydraulic fracturing, as the technology of extraction of coalbed methane are connected with large-scale use of proppant fracking, which implies the fact that a thick gel is used as a proppant (LPG fracturing gel).

Moreover, the organization of commercial methane production in the Karaganda coal basin as a secondary positive effect provides:

- protection of air basin and improvement of ecological situation in the region by reducing emissions of methane and coal combustion products into the atmosphere;
- reducing the gas danger of future underground mining of coal seams as a result of advance degassing;

- absence of negative consequences of commercial methane production on the future shaft development of coal-bed and stability of rocks during mining.

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