N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 5, Number 437 (2019), 244 – 251 **https://doi.org/10.32014/2019.2518-170X.149**

UDC 537.9

B. T. Yermagambet[1], G. E. Remnev[2], S. M. Martemyanov[2], A. A. Bukharkin[2], Zh. M. Kassenova[1], N. U. Nurgaliyev[1]

[1]Institute of Coal Chemistry and Technology LLP, Astana, Kazakhstan,
[2]Tomsk polytechnic university, Tomsk, Russia.
E-mail: coaltech@bk.ru, remnev@tpu.ru, martemyanov@tpu.ru,
ater@tpu.ru, zhanar_k_68@mail.ru, nurgaliev_nao@mail.ru

PARTIAL DISCHARGES AND ELECTRIC BREAKDOWN IN COALS OF MAIKUBEN, EKIBASTUZ AND KORZHUNKOL BASINS

Abstract. The paper is devoted to the study of the possibility of underground pyrolytic conversion of coal from Kazakhstan into combustible gases and tar by heating with electric current. The purpose of this work is to study the patterns of electrical breakdown of coal as a result of long partial discharges action. The breakdown between the electrodes leads to the forming of a low-resistance channel which is supposed to be used as a resistive heating element for heating and pyrolysis of a part of the underground formation. The paper presents the dependences of the voltage of occurrence of partial discharges and the voltage of breakdown of coal. Coals of Maykubensky, Ekibastuzsky and Korzhunkolsky basins were used for research. Steel rods were used as electrodes, the interelectrode distance ranged from 5 to 30 cm. It was found that the average field of the occurrence of partial discharges and the average breakdown field decrease with increasing the electrode distance. It can be assumed that this tendency will be valid in the field conditions, which makes it possible to use electrothermal breakdown for underground heating and conversion of coal. Moreover, these dependences correlate with each other, which can be used to predict the breakdown voltage at a known voltage of the occurrence of partial discharges.

Key words: coal, partial discharges, electric breakdown, subterranean gasification, heating element, voltage, electric field.

Introduction. Recently, there has been a significant increase in attention to technologies for efficient processing of solid fossil fuels (black and brown coals, oil shale) and metamorphism research [1]. Underground conversion can claim to be one of the most efficient processing technologies. It does not require the extraction of rock to the surface, as well as the subsequent disposal of slag.

To date, a large number of different methods of underground conversion have been proposed. A number of them offer oxidative gasification by incomplete combustion of coal directly in the reservoir [2-4], heating of the reservoir with heat-transfer agent [5, 6], electromagnetic heating using radio frequency [7-9] or microwaves [10], heating with electric heaters [11, 12], heating with fuel cells [13], heating by electric current [14, 15].

The use of electric discharge technologies can give a new approach in the development of underground conversion methods. We have previously found that electric discharge processes, such as partial discharges and the electrical treeing caused by them, can lead to the breakdown of certain types of solid fuels at relatively low voltages. This effect can be used for electrical breakdown and subsequent heating of a part of a subterranean formation by using the breakdown channel as a resistive heating element [16].

In order to study the applicability of Kazakhstan coal for conversion in this way, we studied the characteristics of partial discharges and breakdowns in coal taken from the coal mines Maykuben (Maykuben basin), Bogatyr (Ekibastuz basin) and Saryadyr (Korzhunkol basin).

Partial discharges (PD) occur in dielectrics under the action of an applied external high voltage. PD is an incomplete breakdown of the dielectric, leading to the electric locking of the part of the interelectrode distance by discharge channel. The cause of partial discharges is the uneven distribution of the electric field inside the material. For an inhomogeneous substance having inclusions of different materials, the electric field in the interelectrode space will be distributed inversely proportional to the dielectric constant of materials [17]:

$$\frac{E_D}{E_I} = \frac{\varepsilon_I}{\varepsilon_D},$$

where E_D, E_I – electric field in main part of dielectric material and in inclusion correspondingly, ε_D, ε_I – permittivity of dielectric material and matter of inclusion correspondingly. Thus, the greatest field strength will be on elements with the lowest dielectric constant. As a rule, such are gas inclusions and pores. Moreover, the field on them will be the greater, the higher the dielectric constant of the rest of the dielectric.

PDs are characterized by a number of characteristics, the main of which are the voltage and field of occurrence, intensity, apparent charge. The voltage and field of occurrence reflect the threshold value of the applied field, at which the recorded partial discharges appear. This value characterizes the dielectric inhomogeneity of the material under study. The intensity of partial discharges is the number of PDs occurring in a dielectric per unit time. In the case of coal, the voltage of occurrence and the dependence of intensity on voltage reflect the dynamics of electric discharge processes in coals and can be used as indicators of the treeing beginning and the treeing breakdown. The apparent charge is the amount of charge that passed through the external electrical circuit at the moment of PD. Thus, this is the amount of charge that can be fixed by the measuring device, in contrast to the true charge, which passed inside the inclusion at the moment of PD. The name "apparent" is associated with the assumption that this characteristic is not equal to the true charge neutralized by a partial discharge. However, it is considered that this value indirectly reflects the value of the true charge.

In homogeneous insulating materials the apparent charge can be used as an indicator of critical PDs that lead to dielectric failure [18, 19]. To do this, calibration measurements for each specific material are carried out. In the case of coals, this approach is not applicable, as a large dispersion of the apparent charge of critical PDs can be expected because of a sharp material heterogeneity. So we have investigated the voltage of PDs occurrence and the breakdown voltage of the interelectrode gap in coals as a function of interelectrode distance.

Method of experiments. Measurement of the characteristics of partial discharges and voltage of the treeing breakdown is necessary to estimate the potential of applying these phenomena to develop underground pyrolysis technology. Thus, the low intensity of the PDs occurrence and the low voltage of the treeing breakdown indicate the possibility of producing a breakdown of a significant interelectrode distance at a technically realizable voltage value.

Samples for measuring of the PDs characteristics were made in the form of bars (figure 1) by cutting out from a solid fragment of coal on a stone-cutting machine with an abrasive-cutting disc with a diamond coating. The length of the bar was selected on the basis of the required interelectrode distance so that from the electrode to the edge of the bar remained at least 30 mm. Samples with an interelectrode distance from 5 cm to 30 cm were made from the target deposits coals. The width and height of the bar were selected in the range of 30-50% of the length.

Rod electrodes were used to supply voltage, since such an electrode configuration is a reduced model of the proposed technology for the breakdown and heating of an underground coal bed. The electrodes were rods of carbon steel with a 10 mm diameter, which are tightly inserted into the pre-drilled holes. The electrodes were deepened into the sample at 60–80% of the sample height.

The methods of measuring of the partial discharges characteristics are regulated by a number of normative documents [20, 21]. The measurement was carried out by applying a high voltage of industrial frequency to the sample and registering current pulses in an external circuit. Since the PD pulses have a higher frequency spectrum, in order to close PD current, a so-called coupling capacitor is switched on in parallel with the sample under test. Also in the circuit includes a recording device. The simplified electrical circuit diagram of the power and measuring parts of the equipment is shown in figure 2.

Figure 1 – A sample of coal for measuring of the characteristics of PD

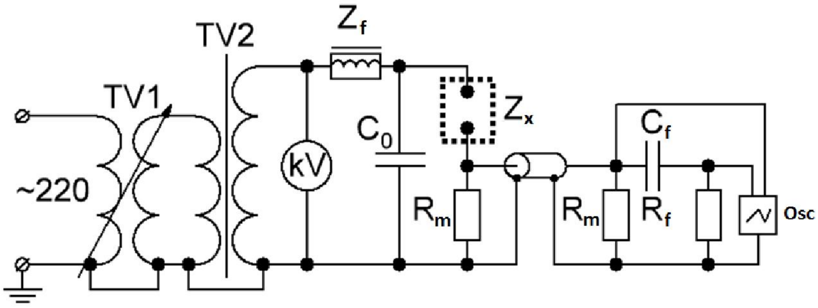


Figure 2 – The electrical circuit of the laboratory equipment for investigation of the characteristics of partial discharges

The equipment is supplied from an electrical network of alternating voltage of 220 V, which is fed to the regulating transformer TV1. This regulator with a rated power of 100 kW works as a variable magnetic coupling transformer. The voltage at its output can vary from 10 V to 220 V by moving the carriage placed inside the transformer. The voltage from the regulator output feed the step-up transformer TV2. This transformer with a rated power of 100 kW produces a voltage of 100 kV at an input voltage of 220 V. The voltage at the output of the TV2 transformer is monitored using a digital kilovoltmeter.

The element Z_f is used as a blocking impedance, which does not allow to high-frequency interference from the supplying network and transformers to flow into the measuring circuit. It also helps to ensure that the PD current pulses are closed in the circuit between the sample and the coupling capacitor. A highly inductive wire-wound resistor with a nominal resistance of 1 kΩ is used as Z_f. The resistor has the shape of a tube, and a set of ferrite washers was placed inside of them to increase its inductance.

Capacity C_0 performs the function of a coupling capacitor in the circuit. The high-frequency current pulse of partial discharges closes through this capacitance. C_0 was made from 5 220 pF ceramic capacitors connected in series. The total rated battery capacity is 44 pF, the maximum allowable voltage is 112 kV. According to international standard IEC 60270, the capacitance of the coupling capacitor was chosen close to the interelectrode capacitance of the sample under study.

The element Z_x is a test sample. Two resistors, designated in the circuit as R_m, work as current sensors, which are used for registration of partial discharge pulses. Physically measuring device (oscilloscope) removed a few meters from the sample under high voltage. The signal source is connected to the receiver by a shielded cable. To prevent interference, the cable line is matched by connecting resistors at both ends with a resistance equal to the cable impedance. In this case, these resistors simultaneously work as a shunt. Resistance of each R_m is 150 Ohms.

The signal from the output of the measuring shunt passes through a high-pass filter, in order to separate the low-frequency volume conductivity current from the current of partial discharges, whose frequency spectrum lies in the range of tens to hundreds of megahertz. Two signals come to the measuring device - directly from the shunt and from the output of the filter. The kilovoltmeter kV is a high-voltage resistive frequency-compensated divider, which is also connected to the oscilloscope.

The voltage applied to the sample during the experiment was gradually increased from zero to the moment of sample breakdown at a rate of 100 V/min. Using an oscilloscope, the presence of partial discharges was recorded and the voltage applied to the sample was measured.

Results and discussion. Samples of coal under the action of high voltage exhibit a capacitive-resistive reaction with a predominance of the resistive component (figure 3). The phase shift between current and voltage is 15-20 degrees. The phase of the PD at the moment of their appearance corresponds to the amplitude of the flowing current. As the voltage increases, the PD phase range expands.

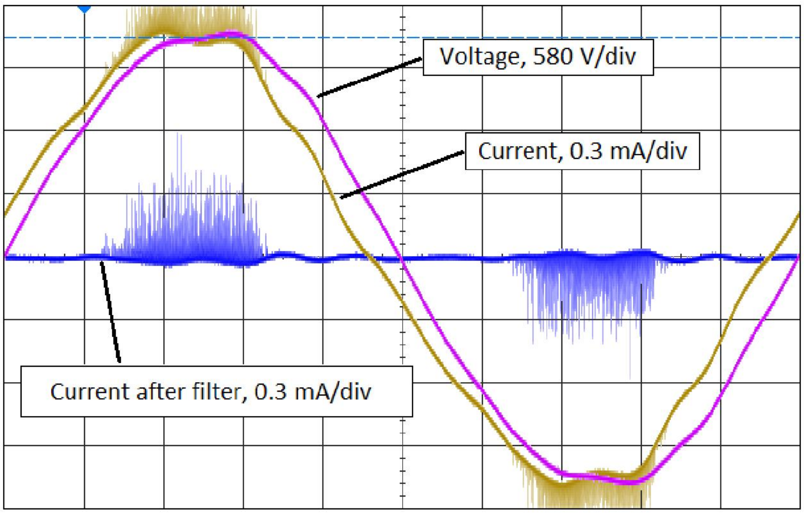


Figure 3 – Diagrams of voltage and current through the sample (horizontal scale 2 ms / div)

The pulses of partial discharges current have a front duration of 5-10 ns (figure 4). This is the time of discharge plasma action in the gas pore. Then the pulse has an exponential decay, indicating the process of recharging pore capacity.

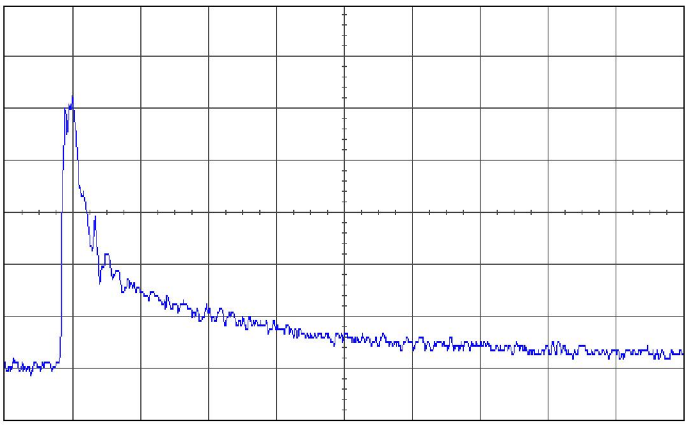
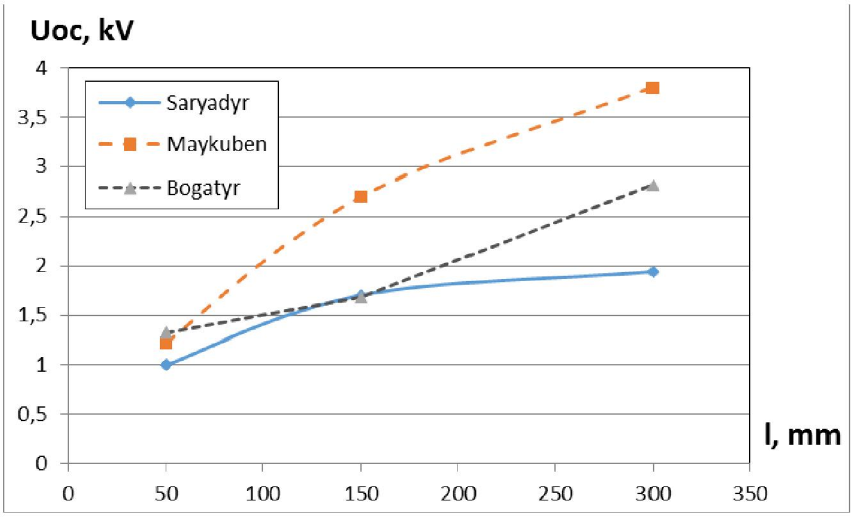


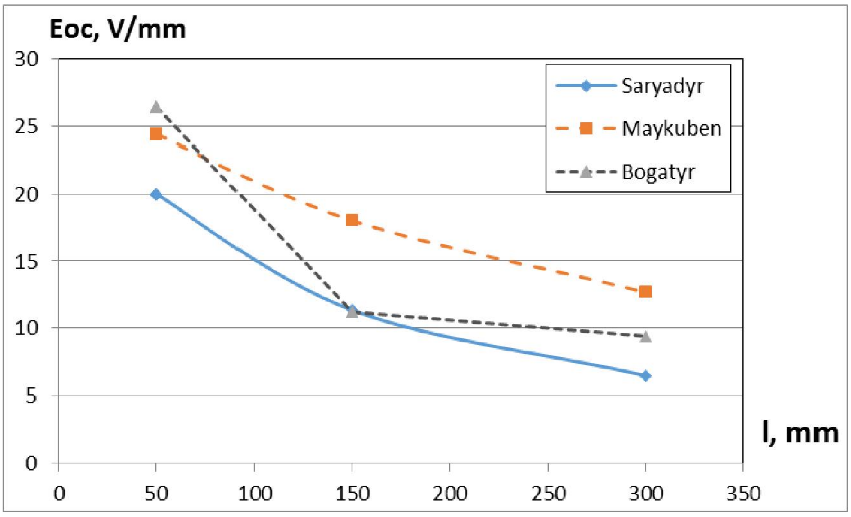
Figure 4 – Diagrams of a single PD current. The scale of the horizontal axis is 100 ns / div, the vertical axis is 27 μA/div

The voltage of occurrence of partial discharges U_{oc} is the smallest voltage at which the partial discharges appear. It can be assumed that the lower the voltage required for the occurrence of PDs, the lower the voltage cause the treeing and breakdown. Therefore, the voltage of PDs occurrence can be used as indirect indicator of the breakdown voltage. When a voltage is applied to a real subterranean formation, knowledge of such a correlation may be highly helpful.

Figure 5,a shows the dependence of the voltage of the PDs occurrence U_{oc} on the distance between the electrodes l. For the coals under study, the U_{oc} varies up to 2 times, which is due to the different porosity and different composition of the mineral component of the coal.



a)



b)

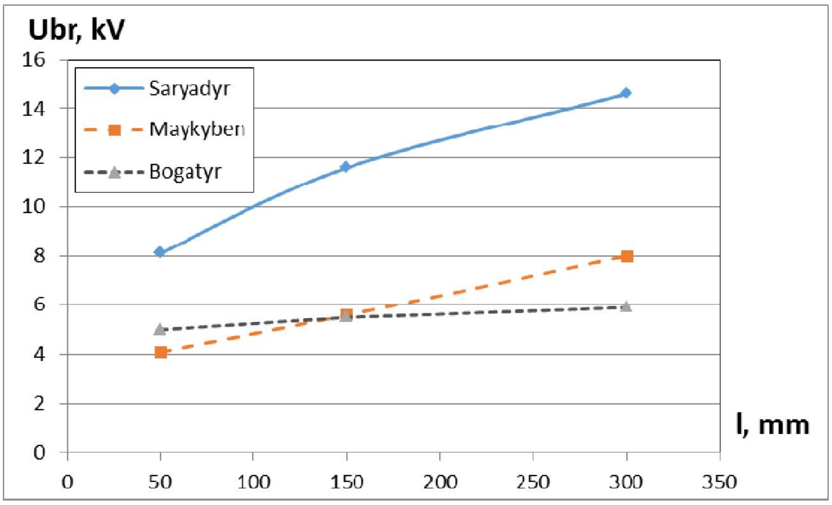
Figure 5 – Voltage (a) and field intensity (b) of the occurrence of the PD in coals depending on the distance

Curves show that increasing of interelectrode distance leads to increasing of the occurrence voltage. This is due to the fact that with the same voltage, but a greater interelectrode distance, the average field strength will be lower. However, it is also of interest how the average intensity of the occurrence of E_{oc} (figure 5,b), which was determined as follows, depends on the interelectrode distance:

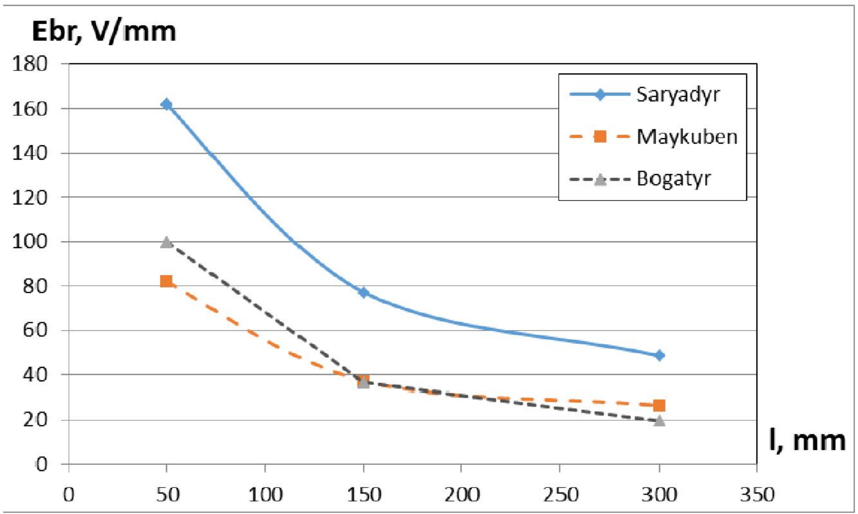
$$E_{oc} = \frac{U_{oc}}{l}.$$

It can be seen that the average intensity of partial discharges occurrence decreases with an increasing of the interelectrode distance. This suggests that the voltage of occurrence depends on the distance nonlinearly. Extrapolating the graphs to large distances, it can be assumed that E_{oc} will continue to decline further, that is, U_{oc} will increase more slowly with increasing of interelectrode distance.

The voltage U_{br} and the field E_{br} (figure 6) of the breakdown characterize the magnitude of the electromagnetic action at which the electrical resistance of the inter-electrode gap of the sample abruptly decreases in several hundred or thousand times. The reason for this is the forming of a through-channel breakdown between the electrodes, consisting of discharge plasma. The high temperature of this plasma causes thermal destruction and carbonization of the coal substance, so the resistance of the interelectrode gap retains its low value even after the voltage is turned off.



a)



b)

Figure 6 – Voltage (a) and field intensity (b) of coal breakdown versus distance

The behavior of the curves $U_{br} = f(l)$ and $E_{br} = f(l)$ is very similar to the dependencies $U_{oc} = f(l)$ and $E_{oc} = f(l)$, respectively, however, the breakdown occurs at voltages several times higher than the partial discharge voltage. It also shows that, in contrast to homogeneous dielectrics, in coals, the average breakdown voltage significantly decreases with an increasing of the interelectrode distance. The behavior of the curves suggests that a further increasing of the interelectrode distance will lead to slight increasing of the breakdown voltage. As a result, the breakdown of interelectrode distances of tens of meters in the conditions of a real underground reservoir may require technically realizable in field conditions voltage.

The correlation between the voltage of PD occurrence and the breakdown voltage may also be useful in the field. Knowing how many times the breakdown voltage exceeds the PD occurrence voltage for these coals, by fixing Uoc, we can predict Ubr at a given interelectrode distance.

Findings. The use of electric heating of underground coal beds may make it possible to create a new highly efficient technology for the processing of coal. Studies have shown the possibility of coal breakdown for using the breakdown channel as a heating element. The behavior of the dependence of the breakdown voltage on the interelectrode distance suggests that in field conditions the technically achievable voltage will allow to breakdown the interelectrode distance of tens of meters.

Acknowledgenents. The work was carried out as part of the scientific and technical program № IRN BR05236359 "Scientific and technological support for coal processing and the production of high conversion coal chemistry products" and project № IRN AP05131004 on the topic "Development of underground gasification technology for Ekibastuz and Maykuben coal and the creation of an experimental industrial plant", funded by the Committee of Science of Ministry of Science and Education of the Republic of Kazakhstan.

Б. Т. Ермағамбет[1], Г. Е. Ремнев[2], С. М. Мартемьянов[2], А. А. Бухаркин[2], Ж. М. Касенова[1], Н. У. Нургалиев[1]

[1]«Көмір химиясы және технология институты» ЖШС, Астана, Қазақстан,
[2]Томск Ұлттық Зерттеу және Политехникалық Институты, Томск, Ресей

МАЙКӨБЕН, ЕКІБАСТҰЗ ЖӘНЕ ҚОРЖЫНКӨЛ КӨМІРЛЕРІНДЕГІ ІШІНАРА РАЗРЯДТТАР МЕН ЭЛЕКТРЛІК БҰЗЫЛУЛАР

Аннотация. Мақала Қазақстан көмірін электр тогымен қыздыру арқылы жанғыш газдар мен шайырларды жерасты пиролиттік әдіспен қайта өңдеудеуін зерттеуге арналады. Бұл жұмыстың мақсаты ұзартылған ішінара шығарындылар нәтижесінде көмірдің электрлік бөліктерінің үлгілерін зерттеу болып табылады. Электродтар арасындағы бұзылудың нәтижесінде төменомды арна пайда болады, бұл жер асты түзілімін қыздыруға, пиролизге арналған резистивті қыздыру элементі ретінде қолданылады. Бұл мақалада ішінара разрядтардың пайда болу кернеуінің және көмірдің бұзылу кернеуінің тәуелділігі келтірілген. Зерттеулер үшін Майкөбен, Екібастұз және Қоржынкөл бассейндерінің көмірлері пайдаланылады. Электродтар ретінде болат құбырлар пайдаланылды және электрөткізуқашықтықаралығы 5-тен 30 см-ге дейін болды. Ішінара разрядтардың қашықтығы үлкендеуінен орташа қарқындылығы және электродтың аралық кеңеюімен, орташа сыну қарқындылығының төмендеуі анықталды. Бұл үрдіс жерасты жылыту мен көмірді қайта өңдеу үшін электротермальды бұзылуды қолдануға мүмкіндік беретін өріс үшін жарамды деп болжауға болады. Сонымен қатар, бұл тәуелділіктердің бір-бірімен байланысуы, ішінара зарядтардың пайда болу қарқындылығында бұзылу кернеуін болжау үшін пайдаланылады.

Түйін сөздер: көмір, ішінара разряд, электр тогының бұзылуы, жерасты газдандыру, қыздыру элементі, кернеу, қарқындылық.

Б. Т. Ермагамбет[1], Г. Е. Ремнев[2], С. М. Мартемьянов[2], А. А. Бухаркин[2], Ж. М. Касенова[1], Н. У. Нургалиев[1]

[1]ТОО «Институт химии угля и технологии», Астана, Казахстан,
[2] Национальный исследовательский Томский политехнический университет, Томск, Россия

ЧАСТИЧНЫЕ РАЗРЯДЫ И ЭЛЕКТРИЧЕСКИЙ ПРОБОЙ В УГЛЯХ МАЙКУБЕНСКОГО, ЭКИБАСТУЗСКОГО И КОРЖУНКОЛЬСКОГО БАССЕЙНОВ

Аннотация. Статья посвящена исследованию возможности подземной пиролитической конверсии углей Казахстана в горючие газы и смолы путем нагрева электрическим током. Цель проведенной работы состоит в исследовании закономерностей электрического пробоя углей в результате продолжительного действия частичных разрядов. В результате пробоя между электродами образуется низкоомный канал, который предполагается использовать в качестве резистивного нагревательного элемента для нагрева и пиролиза участка подземного пласта. В статье приведены зависимости напряжения возникновения частичных разрядов и напряжения пробоя углей. Для исследований были использованы угли Майкубенского, Экибастузского и Коржункольского бассейнов. В качестве электродов использовались стальные стержни, межэлектродное расстояние составляло от 5 до 30 см. Обнаружено, что средняя напряженность возникновения частичных разрядов и средняя напряженность пробоя снижаются при увеличении межэлектродного расстояния. Можно предположить, что эта тенденция будет справедлива и в полевых условиях, что дает возможность использовать электротепловой пробой для подземного нагрева и конверсии углей. При этом данные зависимости

коррелируют между собой, что может быть использовано для прогнозирования напряжения пробоя при известной напряженности возникновения частичных разрядов.

Ключевые слова: уголь, частичные разряды, электрический пробой, подземная газификация, нагревательный элемент, напряжение, электрическое поле.

Information about the authors:

Yermagambet Bolat Toleukhanuly, Doctor of Chemical Science, Professor, Director of LLP "Institute of Coal Chemistry and Technology", Astana, Kazakhstan; bake.yer@mail.ru; https://orcid.org/0000-0003-1556-9526

Remnev Gennadiy Efimovich, Doctor of Technical Science, Professor, Tomsk polytechnic university, Tomsk, Russia; remnev@tpu.ru; https://orcid.org/0000-0002-1654-3179

Martemyanov Sergey Mikhaylovich, Candidate of Technical Science, Associate professor, Tomsk polytechnic university, Tomsk, Russia; martemyanov@tpu.ru; https://orcid.org/0000-0001-5372-6276

Bukharkin Andrey Andreevich, Master of Technic and Technology, engineer, Tomsk polytechnic university, Tomsk, Russia; ater@tpu.ru; https://orcid.org/0000-0002-6877-1595

Kassenova Zhanar Muratbekovna, Master of Chemical Sciences and Technology, Deputy Director of LLP "Institute of Coal Chemistry and Technology", Astana, Kazakhstan; zhanar_k_68@mail.ru; https://orcid.org/0000-0002-9497-7319

Nurgaliyev Nurken Uteuovich, Candidate of Chemical Science, Leading Researcher of LLP "Institute of Coal Chemistry and Technology", Astana, Kazakhstan; nurgaliev_nao@mail.ru; https://orcid.org/0000-0001-9171-2238

REFERENCES

[1] Baybatsha A.B., Supin Pen, Satibekova S.B. Evaluation of the physical and mechanical properties of rocks by the degree of coal metamorphism // News of the National academy of sciences of Kazakhstan, Series of geological and technical sciences. 2019, 1(433), 187-194. DOI: 10.32014/2019.2518-170X.23 (in Russ.).

[2] Bell D.A., Towler B.F., Fan M. (**2010**) William Andrew is an imprint of Elsevier. 411 p.

[3] Bhutto A.W., Bazmi A.A., Zahedi G. (**2013**) Underground coal gasification: From fundamentals to applications // Progress in Energy and Combustion Science. 39(1): 189-214. DOI: 10.1016/j.pecs.2012.09.004 (in Eng.).

[4] Kreinin E.V. (**2016**) Unconventional hydrocarbon sources. New technologies for their development: Monograph. M.: Prospekt. 208 p. (in Russ.).

[5] Sandberg C.L., Fowler T.D., Vinegar H.J., Schoeber W.J. **(2009)** In situ conversion process utilizing a closed loop heating system. United States Patent 7575052.

[6] Pelofsky A.H. (**1973**) In situ production of bitumen from oil shale. United States Patent 3882941.

[7] Kinzer D.E. (**2007**) Processing hydrocarbons and Debye frequencies. United States Patent 7312428.

[8] Kinzer D.E. (**2004**) In situ processing of hydrocarbon-bearing formations with variable frequency dielectric heating. United States Patent 7115847.

[9] Kinzer D.E. (**2004)** In situ processing of hydrocarbon-bearing formations with automatic impedance matching radio frequency dielectric heating. United States Patent 7109457.

[10] Kiamanesh A.I. (**1990**) In-situ tuned microwave oil extraction process. United States Patent 5082054.

[11] Sandberg C.L., Vinegar H.J., Harris C.K., Son J.S., Carl, Jr. F.G. (**2012**) High voltage temperature limited heaters. United States Patent 8238730.

[12] Sandberg C.L., Vinegar H.J., Harris C.K., Son J.S., Carl, Jr. F.G. (**2012**) Insulated conductor temperature limited heaters. United States Patent 8224164.

[13] Savage M.T. (**2004**) Apparatus and method for heating subterranean formations using fuel cells. United States Patent 6684948.

[14] Symington W.A., Thomas M.M., Passey Q.R., M. El-Rabaa A.W., Moss J.H., Kaminsky R.D. (**2008**) Methods of treating a subterranean formation to convert organic matter into producible hydrocarbons. United States Patent 7331385.

[15] Lopatin V.V., Martemyanov S.M., Bukharkin A.A. (**2014**) Method of underground gasification. Patent of the Russian Federation 2521255 (in Russ.).

[16] Bukharkin A.A., Lopatin V.V., Martemyanov S.M., Koryashov I.A. (**2014**) Electrical discharge phenomena application for solid fossil fuels in-situ conversion // Journal of Physics: Conference Series. 552: 1-4. DOI:10.1088/1742-6596/552/1/012012 (in Eng.).

[17] Kuchinskij G.S. (**1979**) Partial discharges in high-voltage structure. L.: Energy. 224 p.

[18] Champion J.V., Dodd S.J., Alison J.M. (**1996**) The correlation between the partial discharge behaviour and the spatial and temporal development of electrical trees grown in an epoxy resin // Journal of Physics D: Applied Physics. 29(10): 2689-2695. DOI: 10.1088/0022-3727/29/10/023 (in Eng.).

[19] Vogelsang R., Fruth B., Farr T. (**2005**) Detection of electrical tree propagation by partial discharge measurements // European transactions on electrical power. 15(3): 271. DOI: https://doi.org/10.1002/etep.60 (in Eng.).

[20] ГОСТ 20074-83. Electrical equipment and electrical installations. Method of measuring the characteristics of partial discharges. M., 1983 (in Russ.).

[21] International standard IEC 60270. High Voltage Test Methods - Partial Discharge Measurement. 2000 (in Eng.).