Electrical discharge phenomena application for solid fossil fuels in-situ conversion

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Abstract. The application of high voltage to oil shale initiates partial discharges (PDs) with the following treeing like in insulating dielectrics. Critical PDs and treeing with a high propagation rate occur under the low electrical intensity ~10^2 V/cm due to oil shale's high porosity, heterogeneity and anisotropy. The completed discharge occurs as a result of these phenomena. Carbonization is initiated around a plasma channel at the treeing stage and extended during electromagnetic action time. Carbonized rock electrical resistance decreases by 8÷10 degrees to 10 ohm•cm, and shale and coal could be heated by Joule heat in carbonized volume and discharge plasma. A high-current supply is necessary for this heating stage. Also, a high-voltage supply with steep-grade characteristics can be used for PDs and treeing initiating and heating the carbonized rock with low resistance. Thus, these phenomena allow in-situ processing in order to produce a flammable gas and synthetic oil from inferior solid fossil fuels by pyrolytic conversion. Computations show that the ratio between energy derived from gas flaming and energy for shale conversion is more than fifty. Therefore, oil shale conversion with the help of electrical discharge phenomena application can be very efficient, as it needs little energy.

1. Introduction
Technologies of solid fuels underground conversion into liquid and gaseous energy feedstock have been attracting the attention of investigators and engineers for a long time. These technologies allow refusing mines and quarries building. This will decline solid fuels reserves development costs and give the possibility of effective inferior solid fossil fuels mining, which are unprofitable for developing by conventional methods. Many countries with poor conventional hydro carbons reserves, for example, China, are carrying out intensive investigations of underground oil shale processing after the successful experience of some USA companies in shale gas and oil extraction from oil shale through bed hydraulic fracturing [1]. Widespread in a significant amount oil shale deposits seem to be prospective energy feedstock. Hydrofrac application allows elaborating only 3÷5 % of a rock organic component. An extremely negative ecological impact calls into question this technology application, and the moratorium is imposed on fracturing in the majority of European countries. A highly efficient and ecological friendly technology of inferior solid fossil fuels underground pyrolytic conversion into liquid and gaseous energy feedstock can be made by using electrical discharge phenomena in a rock.

2. Partial discharge and treeing
Partial discharges (PDs) are incepted under the high voltage impact in oil shale and brown coal and induce treeing with the following breakdown. PDs are local surface discharges, foreign inclusions breakdowns, which are mainly presented by macro- and microscopic pores and cracks in material. PDs arise in high local electrical stress zones, which are created due to the difference between inclusions and enclosing material dielectric constant [2, 3]. As the size of the inclusion is less than the interelectrode space to several degrees, the electrical stress on inclusion can be found by the formula [3, 4]:

$$\frac{E_{\text{inc}}}{E_{\text{av}}} = \frac{\varepsilon_d}{\varepsilon_{\text{inc}}}$$

\( E_{\text{inc}} \) – electrical stress on the inclusion; \( E_{\text{av}} \) - average electrical stress; \( \varepsilon_d \) – enclosing material dielectric permittivity; \( \varepsilon_{\text{inc}} \) – inclusion dielectric permittivity.

Long-term PD activity induces treeing in some materials. Treeing is the growth of stochastically branching discharges structures, which are called dendrites [5]. PDs and treeing inception electrical intensity in oil shale does not exceeds 40 V/cm, when the interelectrode space is about 20 cm, however, for bigger interelectrode space PD inception the voltage from one to several tens kilovolts is needed. Under the discharges plasma impact rock thermal destruction occurs in the oil shale, like in some insulation materials [6]. Hence, the carbon concentration increases on dendrite sidewalls, so carbonization occurs. The carbonized volume electrical resistivity is about 10 Ohm•cm, what is less than the initial shale resistivity in 8÷10 degrees. The voltage in several tens kilovolt is needed for PD initiation and treeing propagation in oil shale with big interelectrode spaces. The current, flowing through the rock, includes displacement current and PD current, so it has small values. Therefore, the power of the supply may not be high.

3. Breakdown

Electrothermal breakdown with the formation of a plasma channel surrounded by a low-resistance carbonized area occurs, when the dendrite straps the interelectrode space. This channel resistance is significantly lower than the original rock resistance. However, it remains high due to a small dendrite diameter (about 200 micrometers). The current, flowing through the channel, grows sharply under the high voltage impact, and it heats the rock due to joule heat. The volume subjected to carbonization increases and the low resistance zone widens radially from the dendrite. The power supply, which provides the voltage to several kilovolts and the current up to several amperes, is appropriate to use for reaching low resistance due to channel widening. The resistance decreases to 0.1÷1 ohm, when the carbonization zone reaches a specified cross-section. A low voltage and high current power supply is necessary for the purpose of oil shale further heating.

4. Conversion

The conductive channel temperature influences on the ratio between gaseous and liquid conversion products and depends on the power that is input in the bed. The channel resistance decreases as a result of carbonization volume widening due to heating. Hence, the control on the power that is input in the bed is needed for specified conversion products obtaining. The regulation has to be carried out in a wide range because of the significant resistance decrease.

5. Experiment

A step-up transformer with the maximum root-mean square voltage up to 10 kV and the power-to-size ratio 2 kW is used in experiments for PD and treeing initiation with the following electrothermal breakdown. The breakdown electrical stress is about 45 V/cm, when the interelectrode space is about 50 cm. The rod electrodes with a 6 mm diameter inserted in shale on the 50 mm depth are used for electromagnetic energy input in the rock. The transformer with the maximum root-mean square voltage up to 1 kV and power-to-size ratio 2 kW is used at the channel formation stage. Voltage regulation is carried out by a transformer with variable magnetic coupling, which simultaneously performs the function of a high-current supply for pyrolytic conversion. This transformer power-to-
size ratio is 100 kW with the regulation possibility from 0 V to input voltage and the maximum current about 264 A. The experimental functional circuit is shown in Figure 1. A three-stage power supply scheme is realized by high-voltage high-current contactors. This voltage-current characteristic has a sectionally approximate hyperbolic form (Figure 2). It allows providing constant input power up to 2 kW in a wide load resistance range. Contactors are rated at the maximum voltage of 10 kV and current 400 A. A pressure tight chamber with a 60 L volume is used to imitate fluid pressure in the underground conditions. Liquid and gaseous conversion products are sampled from the chamber. Nitrogen is used as the inert environment.

Figure 1. Experimental scheme. TV1 – the transformer with variable magnetic coupling; TV2 – the step-up transformer 1 kV; TV3 – the step-up transformer 10 kV; K1, K2, K3 – high voltage contactors; TA1 – the current transformer; Cx – a rock specimen.

Figure 2. Power supply voltage-current characteristics for providing about 2 kW in load resistance wide range. A dotted line – theoretically calculated characteristics, a solid line – realized in experiment characteristics.
Pyrolytic conversion products composition depends on a temperature and heating rate. The resistance of the conductive channel, which is simultaneously a heating element, decreases because of the channel cross-section increase. Therefore, the power input in the rock should be regulated for specified conversion products obtaining. This task is necessary to solve for a very wide load resistance range. A three-stage power supply is used in the implemented experiments. The supply voltage-current parameter is a sectionally approximate hyperbolic function. Theoretically calculated for 2 kW and realized power supply characteristics are shown in Figure 2.

6. Conclusion
The highly efficient technology of oil shale organic component pyrolytic conversion into liquid and gaseous energy feedstock can be created due to electrical discharge phenomena in the rock. A power supply for the implementation of this conversion method has to provide high voltage and high current at different stages. Conventionally, the power source characteristics can be divided into three ranges: before the breakdown, immediately after the breakdown, and heating. Therefore, ranges discrete switching with fine control into each of the range is advisable for weight and size parameters of the power supply and its cost-efficiency.

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