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CRITERIA OF VERIFICATION OF POTENTIAL LIGNITE RESOURCE BASE FOR UNDERGROUND GASIFICATION**

1. Introduction

Underground coal gasification is a technology classified as one of unconventional methods of mining exploitation. The technology has been developed for 100 years, counting from the first works over the experiment carried out by William Ramsey in Durham Coalfield. It was subsequently improved during numerous trials which were at first conducted in the former USSR, after World War II in European countries and later also in the USA in the 70s of 20th century. Recently we have been witnessing an increasing interest in underground coal gasification method. It is related to the progress made in the field of drilling technology, mainly directional drilling, allowing for decreasing costs of mining works and increasing safety of works as well as limiting the threat to the environment originating from the process of underground gasification. Continual growth of fuel prices in the world markets in the last few years is also meaningful. Underground gasification method is becoming competitive. Furthermore, it opens new possibilities in exploitation of deposits previously unavailable for conventional methods.

The results of hitherto conducted experiments and information exchange concerning the course of these experiments provide numerous conclusions which may be used for continual improvement in controlling of the underground gasification process and limiting environmental impact of this method. Recommendations and suggestions concerning the conditions of

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conducted experiments were broadly discussed inter alia after the research works ended in the USA, Spain or Australia. Certain information is also provided from analysis of gas production results from Soviet installations, then operated in former USSR republics.

In literature one may find numerous detailed information concerning the results of research studies concerning underground hard coal gasification. Many publications also provide information about successful trials of lignite gasification which is unfortunately misleading. Misunderstandings usually result from different ways of classification of lignites and hard coals in particular areas of the world. Coals matching UN-ECE classification of lignites (with heating value under 25 MJ/kg) used in the USA were gasified underground in former USSR countries, Australia (Chinchilla), Spain (El Tremedal installation) and in the USA (Hanna deposit).

2. Previous underground lignite gasification trials

In the research experiments and trials conducted on industrial scale in former USSR countries coal gasification concerned seams of coal matching ortho-lignite in the international classification. In Tula coalfield near Moscow (Podmoskownaja 1 and 2) exploitation was conducted until the reserves depleted. The heating value ranged between 8 and 21 MJ/kg with mean value of 11.8 MJ/kg. Coal moisture was 30% on average, ash content did not exceed 35% and volatile substance content reached 44.5% on average. In Podmoskownaja 2 installation in Tula the average annual gas yield reached 2 billion Nm³ [3, 4]. After the gasification ended, the exploitation was transferred to Szatsk deposit. In comparison to the previous deposit, the average heating value was lower and reached 11.1 MJ/kg. As little as 40 million m³ per year was extracted using the installation which does not allow for classifying this experiment as a success. It is worth underlining that other geological parameters of the deposit, namely moisture, ash content or volatile substance content were more favourable from the technological point of view than in Tula deposit.

Optimal gas production parameters were obtained from a lignite seam located in Angren in Uzbekistan. Average heating value of this coal reached 15.1 MJ/kg. The installation has allowed for producing as much as 1.4 billion Nm³ annually since 1965.

From the analysis of presented effects one may draw a conclusion that the factor determining the success of underground gasification trial is the quality of lignite described by the heating value (the heat of burning). As an example one may choose gasification trial in Sinelnikowski deposit. Heating value of lignite was only 8.0 MJ/kg and other parameters, like moisture and volatile substance content also were not favourable. The lack of detailed information concerning gas production parameters and production volume results from the failure of the trial conducted in Sinelnikowski deposit.

The remaining successful trials of underground coal gasification were carried out in installations operating in Lisiczansk (former USSR), Hanna (USA), El Tremedal (Spain) or Chinchilla (Australia) and based on lignite matching sub-bituminous coal in international

classification. These are lignites characterised by heating value exceeding 15.5 MJ/kg. They correspond to coals classified in Poland as low-quality hard coals. An overview of quality parameters of poor-quality coals subjected to underground gasification worldwide has been presented in Table 1. Graphical comparison of lignite heating value in particular trials of underground gasification has been presented in Figure 1.

TABLE 1
Quality parameters of poor-quality coal in underground gasification trials [5]

Location / Name	Coal type	Coal moisture, %	Ash content, %	Volatile substances, %	Coal heating value, MJ/kg
Chinchilla	sub-bituminous	10	19.3	40	23
Hanna	sub-bituminous	no data	26.26	36.07	22.3
Lisiczansk	sub-bituminous	12–15	7–17	39–40	20–23
El Tremedal	sub-bituminous	22.2	14.3	27.5	18.1
Tashkent, (Angren)	Meta-lignite	35	12.2	33	15.1
Tula, Podmoskownaja 2	Ortho-lignite	30	34.3	44.5	11.8
Szatsk, Szatskaja 1*	Ortho-lignite	30	26	38.1	11.1
Sinelnikowski*	Ortho-lignite	55	23.8	65.5	8.0

* trial finished without success.

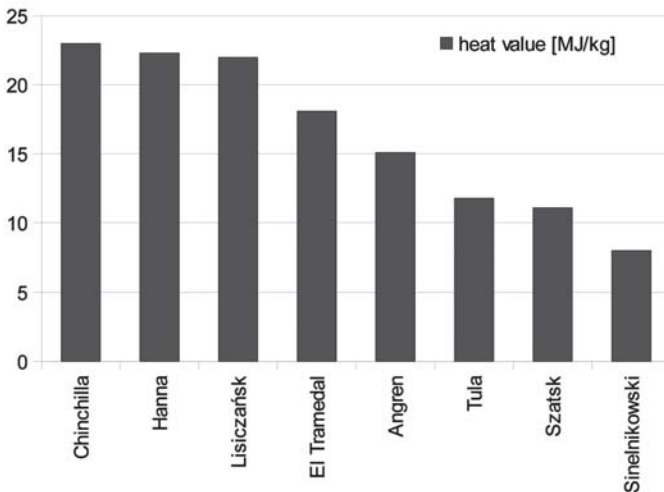


Fig. 1. Lignite heating value in underground gasification trials

It is also worth mentioning that some of the described trials were conducted in specific geological conditions. As an example, industrial scale of exploitation in Angren deposit was conducted on a seam isolated by a 25-meter-thick layer of kaolin. Hanna and Chinchilla deposit are characterised by relatively dry overburden and the areas surrounding the deposits are low-populated. Underground gasification trial in Spain was conducted on a lignite deposit located between 600 and 550 meters beneath the ground's surface. The experiment was terminated after circa 240 tonnes of lignite were gasified. The result of termination was an uncontrolled flow of water from sandstone overburden layers.

Conclusions from experiments conducted worldwide may be used as classification criteria for verification of potential resource base of lignite suitable for underground gasification. The proposed criteria may be divided into several groups: technological and deposit criteria, hydrogeological criteria and physiographic criteria.

3. Technological and deposit criteria

Results of analysis of previously conducted experiments with underground lignite gasification point out that fully successful trials of gasification were conducted when following conditions were met:

- seam depth must not exceed 250 meters,
- seams should be of relatively low thickness, from 0.5 to 24 m. Simultaneously the deepest seams had the highest thickness (Angren — seam located up to 250 m deep, thickness 24 m); exploitation of seams with thickness lower than 1 m caused technical problems.

Furthermore in the successful experiments:

- minimal heating value was not lower than 11.8 MJ/kg,
- the most favourable experiment results were obtained for meta-lignites and sub-bituminous lignites, meaning coals with heating value exceeding 15 MJ/kg and also bituminous coals with heating value reaching 25 MJ/kg.

The gasified coals were also usually characterised by:

- moisture under 35%,
- ash content under 35%,
- volatile substance content under 35%.

One may assume that heating value of coal may be the key parameter which decides about successful gasification. The research results published by Ściażko [11.] suggest that the increase in volatile matter cohesion over 35% causes reduction of coal burning heat.

4. Isolation criteria

The process of underground coal gasification, like practically any other mining interference into a water-bearing rock-mass, is not indifferent to the environment. Among the most important negative influences one may mention the problem of subsidence occurring in the above-lying geological strata which are an effect of reduced volume of coal in the seam and the influence on the surrounding ground water environment. In the case of unsealing of the gasified seam surroundings exchange of fluids becomes possible. This way substances and chemical compounds typical for the georeactor's environment may be transported in the form of suspensions or solutions. The risk of contaminants migration may be reduced through proper choice of the seam for gasification when criteria of selection are clearly defined and the process is controlled both during its course and after it finishes.

When considering the character of isolating parameters of the seam chosen for gasification one should analyse the criteria directly defining the surrounding rocks, focusing particularly on the overburden characteristics. During these considerations parameters like the following usually appear: lithological formation, order of layers in the profile, hydrogeological parameters of the rock layers, including the distribution of filtration coefficients, distribution of pressure field and finally the thickness of the surrounding layer, most often assumed as a layer with low filtration capability and also indirectly the depth of the seam.

The general and most obvious condition broadly mentioned in the subject literature is the presence of rock layers characterised by low permeability in the coal seam overburden. Preferably, the rocks should be plastically deformed or consolidated with appropriately high strength and thickness. The first feature ensures tightness, preventing or inhibiting the layer's process products migration to the external environment and the other inhibits or eliminates the occurrence of subsidence in the area above the gas reactor. From the point of view of potential migration routes it is inadvisable to locate installations in areas characterised by tectonic involvement. Basing on the pioneer experiences of American researchers, R.L. Oliver and J.R. Covell [7] formulated criteria concerning the overburden rocks. The consolidated, poorly permeable overburden should reach thicknesses exceeding 15 m (> 50 ft), with total advisable thickness ranging between 90 and 460 m ($300\div 1500$ ft; in the authors' intentions introduction of maximal overburden thickness results from technical difficulties of conducting the underground gasification process on greater depths). The coal permeability coefficient should range between 50 and 150 mD ($4.8 \times 10^{-7} \div 1.4 \times 10^{-6}$ m/s) and the coefficient of overburden lying directly above the seam should be < 5 mD (4.8×10^{-8} m/s). It is assumed that rocks with filtration coefficients of $N \times 10^{-8}$ m/s (1 mD) and lower are classified as isolating.

However considering that impermeable rocks of mudstone type over the gasified coal deposit are thermally transformed, range of discontinuous deformations (collapse and fracture zone) over the seam, resource use indicator for the UCG method is about 0.6–0.75, reasonable seems to assume minimum thickness of isolating layer over the coal seam roof as 1.5 times of the coal seam thickness.

The indirect parameters that can be considered in the category of insulating power is the depth of the seam. The previously conducted underground coal gasification trials were limited to the depth range of 30 to 600 m. In the case of experiments conducted on greater depths, the undisputed advantage is the presence of significant thickness of overburden rocks, most often of variable formation. This guarantees that the risk of subsidence propagation towards the surface is minimised, limiting secondary clearing of the overburden that would allow for spatial mobility of the pyrolysis products. Together with depth, the probability of existence of drinking water in the seam surroundings decreases in favour of the saltish waters and brines, excluding the possibility of potential contamination and hazard to the water intakes. The possibility of using higher working pressures also increases, positively affecting the heating value of the obtained gas mixture. Increase in the working pressures results from the necessity to control the water filtration from the surrounding layers remaining under increased hydrostatic pressure in relation to the lower lying levels.

The advisable depths of designed coal seam gasification are variable. Starting from the minimal depth of 12 m [3] and preferred depth of over 150 m, through 15 m [8] and advisable [7] depth > 90 m to finally most often suggested 150 or 200 m. More detailed characteristics, dependable on the rock parameters have been presented in the work of Shafirovich et al. [9] who analysed the possibilities of an UCG installations in Indiana state. They have found that seam located over 200 m deep were most suitable for the gasification process and eliminated those lying closer than 60 m to the surface. The utility of the intermediate seams depended on the plasticity of the overburden rocks.

Numerous authors introduce minimum limits of depth or advises limitations in locating installations on great depths. Justified concerns are related to technical and economic aspects of the exploitation. Depths exceeding 300 m require using more sophisticated and therefore more expensive drilling technologies [6, 9].

5. Physiographic and environmental criteria

Fulfilling the geological and technological criteria when choosing the location of the seam for underground coal gasification greatly contributes to limiting the harmfulness of this process to the environment. Despite this, the hazard of potentially negative effects related to migration of reaction and technological gases, solid and soluble products of the reaction, heat emission and also the possibility of continuous and discontinuous deformations of the above-lying rock layers, forces to use additional protection of the most exposed elements of the natural environment through introduction of environmental criteria of choice.

When one analyses worldwide publications, he may encounter a few opinions which support the fact that the surface infrastructure location criteria for underground coal gasification installations should meet the assumptions defined for mines extracting minerals using conventional methods while the transport infrastructure should be a subject of limitations similar to the ones created for gas transport infrastructure [1, 3, 6]. Additionally, the group

of components defining the environmental conditions will impose significant limitations associated with the location of the future georeactor in environmentally, naturally or landscape valuable areas. Special protection should be put on the most endangered elements of the environment, namely the groundwaters which are the potential agent of transport of the contaminants, but also on the ground surface with valuable natural habitats, river network, industrial, infrastructural or other significant objects with special meaning that require protection.

The most often advised distance from the gasified seam to the water-bearing rock layers is a distance equal to at least twenty five times the thickness of the gasified layer [10], although values from 30 m [6] to even 2000 m [2] appear in the literature. The minimal distance from the surface waters (including reservoirs, rivers and watercourses) is 1600 m [3], although the environmental risk at a moderate level is acceptable when the minimal distance is 1000 m [2].

A conflict with the natural environment (inter alia through possible surface deformations) or the need for protecting the surface because of the existing infrastructure, automatically limits the possibility to mine the deposit. This considerations in the worldwide literature are not broadly discussed, although some important criteria taking physiographic factors of the georeactor location do appear. An overview of these has been presented by Białeczka [2]. With regard to the protection of existing surface infrastructure (including power lines, roads and railroads) the preferred distance from the underground georeactor is over 1600 m, although there are opinions that the lower limit is 200 (400) m [2, 3].

Implementation of underground coal gasification should take place in areas characterised by the lack of any human activity and if it is not possible, the population density and human activity in the area should be limited to the minimum. Some authors even suggest these terrains should be undeveloped [3]. According to others the minimal distance from urban developments or residential areas should exceed 1600 m [2]. In case of particularly valuable natural areas protected by the law it seems obvious that locating installations becomes impossible.

The area occupied by the surface installation (while taking environmental aspects into account, but also considering economic and technological factors) should not exceed 20 ha. The relief of such terrain in the location guidelines is limited to its morphologic features, but it seems that the terrain's inclination and location with regard to the surface water level draining the entire area should be the leading element. It is assumed that the higher this parameter's value, the worse are the conditions for locating surface infrastructure for underground coal gasification. Therefore the arbitrariness of location is the greatest on areas with low inclinations, not exceeding 6° (10%). However, the location should be situated a few meters above the groundwater level ordinate. It is favourable because of minimising drainage cost of the areas subjected to flooding because of ground surface subsidence. Higher values of inclination do not limit the investment, although they may increase the investment costs. Additionally the terrains should be characterised with favourable climate conditions, meaning there should not exist a hazard of contaminants accumulation in the lower parts of atmosphere.

6. Summary

The conducted analysis can become a basis for verification of resource base in Poland of lignites potentially viable for underground gasification. The presented criteria of verification have not been verified by experiments in comparable Polish conditions and as a whole and in some points are burdened with a degree of uncertainty when it comes to suitability of deposits for gasification. However, even when these reservations are taken into account, the results of previously conducted experiments may be useful for preliminary assessment of resource potential and perspectives of UCG development in Poland. The results of preliminary selection may give weaker or stronger stimulus for conducting preparatory works and pilot-scale research and trials on chosen deposit fragments.

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