

Environmental aspects of underground coal gasification

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1. Introduction

The concept of underground coal gasification involves direct obtaining of energy stored in coal beds that are difficult to mine using known and conventional methods, in a manner justified by economic, environmental and social benefits. Economic effect is shown by an improvement of coal use energy efficiency and its competitiveness by e.g. production of liquid and gaseous fuels from process gas. The sustainable development principle regarding exhaustion of non-renewable energy resource reserves leads to the conclusion it is necessary to seek possibility of obtaining energy from these resources in the most economic and effective manner, i.e. from coal beds for which open pit or underground mining are impossible due to technical or economical reasons. Moreover, global trends aiming to reduce greenhouse gas emissions, particularly CO₂, make it necessary to develop clean coal technologies including underground coal gasification [1]. In the social aspect, underground gasification eliminates hazards to health and life of people directly involved in the mining process.

This leads to the question: Why, despite unquestionable benefits, a technology – with foundations defined by such great scientists as William Siemens, Dmitri Mendeleev, William Ramsay more than 100 years ago – has not been implemented at large industrial scale? Putting aside unstable price ratios of fossil energy carriers (coal, oil, gas), this is due to the lack of possibility of clear determination – at investment preparation stage – of environmental risk related to construction, operation and decommissioning of the plant.

2. Nature of environmental hazards

Main social-economic costs related to underground coal gasification are identified as potential damage to the natural environment caused by the process, i.e. risk of polluting the natural environment and its consequences. Considering the entire life cycle of the plant, significant risks involve:

- risk of polluting underground water with drilling fluid from drilling processes conducted to make available subsequent parts of bed for gasification
- risk of polluting underground water with gaseous, liquid and solid substances produced in the process – both in the vicinity of the reactor and through bores for collecting the product
- risk of polluting atmospheric air with gases produced during gasification and product treatment and processing
- risk of polluting surface water and soil with waste water produced during product treatment and processing
- risk of personal health loss due to emission of pollutants to the natural environment
- risk of deformation of land surface due to the settling resulting from voids left after coal gasification.

Figure 1 presents processes related to underground coal gasification that may potentially have largest impact on individual environmental components.

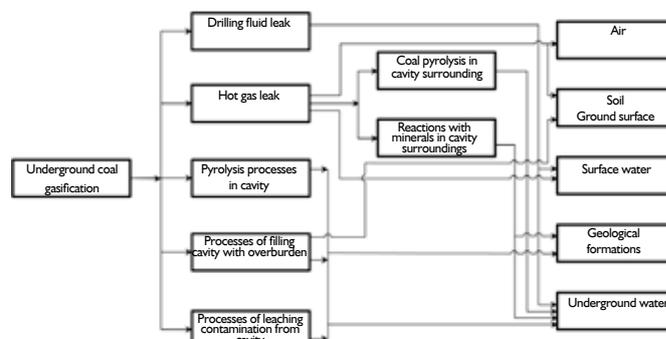


Fig. 1. Effect of underground coal gasification on environmental components (compiled based on [2])

Table 1
Environmental impact as a result of UCG in shallow beds

Country	Depth	Environmental Impact
Russia	Shallow beds, less than 200 m	Increase of groundwater temperature, phenol concentration was 0.17 mg/l in the georeactor and in range 0.0007 – 0.0042 mg/l in the georeactor surroundings
China	Shallow beds	Gas leaks, penetration of tar substances to rivers
Australia	Shallow beds, less than 130 m	No groundwater contamination or ground settling observed
USA 1982	Shallow beds, 70 m	Change in groundwater quality near the georeactor
USA 1972-1979	Very shallow beds, 40 m	Georeactor collapse, which lead to gas losses in the process and contamination of ground water, moreover land settling observed
USA 1979-1981	Shallow beds, inclined	Contamination of aquifer with benzene, contamination with phenol and benzene exceeding allowable concentrations, mainly in the coal itself
USA 1986-1988	Shallow beds	Gas leak, increased concentration of ammonium, sulphates and TDS and decrease in pH from 8.5 to 6.5 in the walls of bed aquifers

The presented dependencies (Fig. 1) are related to process using bore method that involves opening out the coal bed for injection of the gasification agent and collection of products using network of vertical or directional bore-holes from the surface. As the pressure in georeactor depends on its depth, it should be similar to hydrostatic pressure in its area as underground waters are most exposed to potential negative effects of the method involving bore method. This is especially unfavourable in case of shallow coal beds located near reservoirs of functional water. This is confirmed by results of experiments conducted in various countries. Table 1 presents the main environmental impacts of the process conducted in the shallow beds [3].

Gasification of shallow beds shows also an increased risk of uncontrolled, disorganised emission of gases to atmosphere. Table 2 presents data on gas losses from experimental and industrial plants operating in the first half of 20th century in the territory of former USSR [4]. Gas production volume of these plants was between 0.28 and 1.4 bln m³/year.

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Table 2

Average gas losses from experimental and industrial plants "Podzem-gas"

Installation	(coal type) depth of deposition, m b.s.l.	(seam thickness, m) inclination angle, deg	average gas losses, %
Lisichanskaya	(hard coal) 60-250	(0.42-2.0) 38-60	23.7
Gorlovskaya	(hard coal) 80-200	(0.7-1.4) 38-55	22.5
South Abenskaya	(hard coal) 130-300	(2.0-9.0) 35-59	21.6
Angrenskaya	(lignite) 120-200	(8.0-15) 7	15.7
Podmoskovnaya	(lignite) 30-80	(2.0-2.5) 0	27.7
Shatskaya	(lignite) 30-60	(2.0-2.6) 0	29.6
Sinelnikovskaya	(lignite) 30-60	(3.5-6.0) 0	24.4

Gas from gasification has high volume of carbon dioxide as well as carbon monoxide that is hazardous to human life. Disorganised emission of just the latter poses a main direct threat for people employed for operation of the plant and people living in the vicinity. Volume of gas losses responsible for emission to atmosphere depends on hydro-geological structure surrounding the georeactor and georeactor pressure. The pressure is also an important factor in polluting surroundings (including underground water) with tar substances and liquids.

Different pattern of environmental impacts is found for the other underground gasification method, i.e. shaft method.

The shaft method can be used for gasification of coal remaining after mining bed using conventional mining methods, e.g. in legs of decommissioned shafts, remains that was unprofitable or impossible to mine due to economical or technical reasons. In this method, opening out involves drilling the headings, with gasification agent and product pipelines laid in both headings and shaft [5, 6]. The rock mass surrounding the georeactor is dried due to previous mining operations and the process may be conducted under pressure close to pressure in the underground mine. The process characteristics indicates that the shaft method involves much lower risk of underground water contamination. While contaminants may penetrate to surface waters (through mine draining system). Shaft process is also more hazardous to human due to potential emission of poisonous and explosive gas components to the mine atmosphere. The estimated risk is so high that it renders possibility of gasification in operating mine virtually impossible. Therefore, shaft method is considered possible for implementation only in case of mine or its part separated in terms of ventilation that is to be decommissioned.

3. Environmental impact of the experiment at pilot scale in KHW S.A. KWK Wieczorek

In the summer of 2014, multi-day long (1343 hours) trial of underground coal gasification using shaft method was conducted under real conditions of the coal bed as a part of Research Task "Development of coal gasification technology for highly efficient production of fuels and electricity" under the strategic research and development programme "Advanced technologies for energy generation". The georeactor was located in a bottom pillar of the Eastern Shaft of KWK Wieczorek in the bed 501, approx. 400 m b.g.l. The georeactor was connected to surface plant components that provided supply of technical gases

(air, oxygen, nitrogen, carbon dioxide) and collection of products, cooling, condensation of water and tar, gas purification and burning in the torch. Surface and underground part of the plant were connected with system of pipelines lined in the mine shaft and headings. The experiment resulted in gasification of approx. 250 Mg of coal obtaining approx. 1.033 mln m³ of average calorific value 3.55 MJ/m³. The detailed description of the plant, as well as process results are presented among others in [6 – 8].

Regarding the scope of preparatory works for construction and experiment performance, a number of actions required for execution in the view of legal regulations in the field of mining law and environmental protection were conducted.

The actions related to meeting requirements of mining law are not the subject of this study, whereas in terms of environmental protection, necessary arrangements were made, obtaining in result:

- the decision on environmental conditions for construction and operation of research UCG pilot installation, which qualifies it as an investment of potentially significant environmental impact. At the same time, based on the information submitted by the Central Mining Institute, the authority issuing the decision stated no need of conducting full environmental impact assessment, including preparation of report
- the water permit for introducing to drainage devices of "Przyjazn" Coke Plant sp. z o.o. of industrial waste water containing substances particularly harmful to the aquatic environment.

Moreover, the UCG research plant at KWK Wieczorek mine area was declared as plant introducing gases or dusts to the atmosphere.

Plant design and construction were preceded by risk assessment which included previous Central Mining Industry experiences from trials conducted at smaller scale in the coal bed 310 in the Experimental Mine Barbara in Mikołów as a part of the projects with acronyms HUGE and HUGE 2 funded by FWBiS. The identification of the most severe identified hazards to the environment and human health related to plant operation is presented in Figure 2 [9].

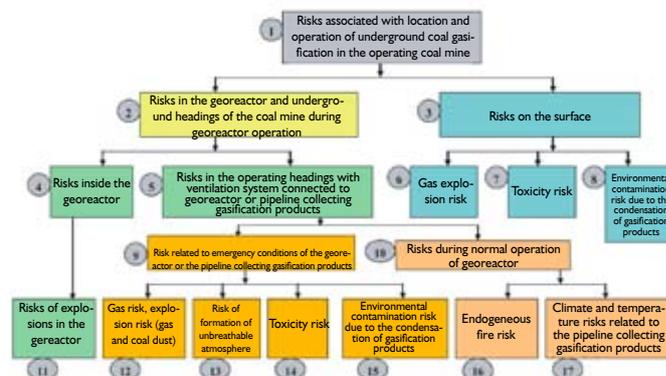


Fig. 2. Identification of hazards in the underground coal gasification process using shaft method

Surface plant could also pose a burden for the environment related to noise emission and emission of substances produced as a result of combustion of gas products in the torch.

In order to minimize or eliminate risk of hazards and burden, number of actions were undertaken and various methods were applied. As the experiment was conducted in the operational mine, the most important part included actions for elimination possibility of penetration of excessive hazardous gas amount to headings used for normal mine operation during conducted trial. To that end:

- at the stage of experiment concept development, the georeactor was placed in a ventilation network of the mine, thus ensuring as the smallest possible danger zone under conditions of normal georeactor operation and in case of emergency states as well as near the upcast shaft

- testing gallery, where georeactor inlet and outlet were located, was isolated from headings with explosion-proof stopping; the space behind the stopping was filled with inert gas (nitrogen), which prevented occurrence of explosive atmosphere in the separated area and produced overpressure in the testing gallery in relation to georeactor, which served as additional protection against drawing in the air
- hydraulic filling was laid and maintained in the area of the conducted experiment, which resulted in obtaining, for emergency cases, quick possibility of removal of testing gallery space by filling it with the filling material and filling the georeactor with filling mixture after the end of the experiment
- continuous flow control systems were used for air and oxygen, as well as for gas collection, controlled with pressure switches at georeactor inlet and outlet
- nitrogen feeding system to georeactor was executed with air/oxygen pipe and additional bore from heading located at the opposite side from the testing gallery. The systems allowed quick filling of the installation with inert gas in case of finding, during continuous measurement or chromatographic determination increase in oxygen concentration in process gas to the value posing a threat of formation of explosive mixture
- using fixed continuous measurement detectors, a ventilation-gas parameter monitoring system was constructed at the selected points of headings near the georeactor and installation outfeeding gas products; air conditions in heading were also controlled by periodical determination of samples using GC method
- monitoring bores were made in the rock mass surrounding the georeactor to control leak tightness of its walls (by analysing gas samples from bores).

A need to use the extended process monitoring and control systems, and safety systems was due to the process of instability in heterogeneous environment. Reaction space changes as gasification progresses, there are disturbances due to breaking down of coal lumps or roof collapse of the formed cavity.

In the experiment at KWK Wieczorek mine, pressure difference between georeactor inlet and outlet (measured at pipelines feeding in substrates and collecting products) was approx. 10 kPa with negative pressure at outlet of approx. 5 kPa. When the process was conducted under such conditions, no carbon monoxide was found in the air exhausted through air-shaft, nor in the surrounding headings. Sporadically, low concentrations of this compound were found in gas samples behind the stopping in the testing gallery (up to approx. 100 ppm). Each positive result was reflected in immediate response involving change in air/oxygen flow rate or product collection rate – in order to correct the pressures. It must be noted here that for the shaft method, gas safety is particularly important, therefore it is not always possible to control process only in order to obtain the best process results (e.g. optimum gas composition for a specific use).

In order to prevent risk of endogenous fire and climate arduousness caused by high temperature of gas product exhaust pipeline, it was thermally insulated. The insulation provides additional effect – the larger part of tar and water condensed on the surface installation and not in pre-separators in the headings.

Another important issue was a risk associated with possibility of contamination of underground and surface water. The main actions in that scope involved:

- periodic monitoring of mining water quality in the selected places in the headings surrounding the georeactor and mine main drainage system during the experiment and after its completion
- storing water-tar condensate from the surface part of the installation in the sealed containers and their transfer per water permit for introducing the industrial waste water containing substances

particularly harmful to the aquatic environment to drainage devices and agreement for industrial waste water treatment plant of the “Przyjazn” Coke Plant Sp. z o.o. in Dabrowa Gornicza.

There was no contamination associated with gasification process found in the samples taken at six sampling points. This particularly refers to phenols, BTEX and PAHs typical for this process and which were determined at level close to the level of quantification.

After completion of the experiment and georeactor quenching, cavities in the rock mass were filled with liquid filling. In the sample of eluate collected at this opportunity, phenols were determined to be of concentration 0.018 mg/l and PAHs of concentration 0.00144 mg/l, i.e. much lower than value acceptable in accordance with the Regulation of the Minister of Environment of 18 November 2014 on the conditions that must be met during disposal of waste into water or ground and on substances particularly harmful to aquatic environment (Journal of Laws of 16 December 2014, item 1800).

Table 3 presents summary of analysis of waste water sample from the condensation system of the plant during the experiment [10]. A vast range of concentrations of individual contaminants in different batches of waste water is particularly noteworthy. Such differences can be explained with changes of conditions and parameters in the georeactor during the gasification process.

Table 3
Parameter range of waste water collected from the plant

No.	Parameter	Unit	Parameter range		
			average	max	min
1.					
2.	conductivity	μS/cm	10,108	11,900	8,180
3.	pH	pH	8.8	9.0	8.7
4.	s - COD(Cr)	mg/l O ₂	8,042	16,200	4,530
5.	n - COD(Cr)	mg/l O ₂	26,050	59,200	13,200
6.	ammonium nitrogen	mg/l NH ₄	2,067	2,700	1,300
7.	total slurry	mg/l	2,892	10,000	460
8.	chlorides	mg/l Cl	1,122	2,400	730
9.	sulphates	mg/l SO ₄	77.3	240.0	20.0
10.	total cyanides	mg/l CN	0.70	0.89	0.37
11.	rhodanates	mg/l CNC	33.2	49	30
12.	volatile phenols	mg/l	1,717	2,300	1,000
s - COD(Cr)	- in non-filtered sample				
n - COD(Cr)	- in filtered sample				

For the pilot plant, burden for the atmospheric air could be associated with the following phenomena:

- emission of components of process gas from mine ventilation system in case of failure in underground part of the plant
- emission of combustion gases from the torch.

Regular monitoring of ventilation air composition from the Eastern Shaft has shown no special increase in methane, carbon dioxide, carbon monoxide concentrations. The content of these gases did not exceed 7500 ppm for methane and 3500 ppm for CO₂. Carbon monoxide was not found in any sample.

During the entire experiment, 1,033 thousand m³ of gas of average calorific value of 3.55 MJ/m³ and 2,760 kg of liquid propane-butane gas were burned in the torch. Indicator calculations of emission of main contaminants gave the following results:

- sulphur dioxide – 3,843 kg
- dust from burning fuel – 246 kg
- nitrogen oxides (expressed as NO₂) – 656 kg
- carbon dioxide – 523.7 Mg.

The conducted model computation of contaminant propagation in atmospheric air showed no exceedances of allowable values.

The main source of noise were air compressor and process gas fan located in the industrial area of the Eastern Shaft. Taking into the account noise from operation of main mine fans installed in the shaft, the additional sound sources did not cause deterioration of acoustic conditions in the surroundings.

Results of pilot trial were also used to conduct LCA for power generation plant from gas obtained from the UCG [11]. The analysis was conducted using ReCiPe 2008 H/A method with SimaPro 8 software. Three impact categories were considered with respective percentage:

- impact on human health – 49.9%
- impact on ecosystem – 31.3%
- impact on natural resources – 18.8%

The largest contribution to unfavourable process impact was associated with CO₂ emission.

4. Summary and conclusions

The nature of the underground coal gasification involving namely:

- its progress in not fully known environment in terms of hydro-geological structure and physicochemical properties
- varying parameters resulting from instantaneous conditions in the underground reactor
- limited possibilities of precise control of the process
- formation of liquid and gaseous substances harmful to environment and health or explosive (hydrogen, carbon dioxide and monoxide, hydrogen sulphide, phenols, BTEX, PAHs and others) under the process conditions

makes it necessary to apply many organisational and engineering measures to minimise potential risks. Pilot experiment conducted in particularly difficult conditions, thanks to adopted comprehensive approach was completed successfully. Comprehensive approach involved conducting initial study of coal bed and its surroundings in the area of planned georeactor location, as well as analysis of ventilation system for headings, preparing risk assessment, compiling documentation necessary for obtaining permits required by the applicable regulations. The results of these works were used at the stage of detailed designing and plant construction, as well as during its operation and closure.

Such comprehensive approach involving state-of-the-art test and analysis methods, mathematical models and procedures is a key to reaching the goal – safe operation of the UCG plant in all stages of its existence (construction, gas production, decommissioning). It shall be noted that it is necessary to apply individual solutions adapted for local conditions of the planned undertaking. Therefore, one should not expect too far reaching standardisation of installations or applying universal solutions.

Undoubtedly, the time of industrial implementation of technology is getting closer due to the technical progress in collected shale gas and methane from coal. Using increasingly powerful and more precise equipment for directional drilling, rock fracturing starts to be applied in preparatory works for construction of georeactor of defined overall dimensions, and in strictly defined limits.

To summarise, despite increasing importance of environmental issues that must be considered in every human activity, development for underground coal gasification in terms of avoiding environmental hazards allows today to decide to construct completely safe industrial plant at large scale.

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