Analysis of criteria for UCG siting and operation

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Long-standing investigations into coal have enabled the identification of essential features of the course of the underground coal gasification (UCG) process as well the role and significance of some factors. The qualitative and quantitative characteristics of the most essential factors from the viewpoint of UCG process realisation constitutes the subject of this article. The analysis takes into consideration the results of investigations into the UCG process conducted by Polish scientists within the period 1950-2008.

Key words: *underground coal gasification, coal reserves, natural factors, technical factors*

Introduction

In recent years, the global economy has shown a tendency to return to fossil fuels as a primary source of energy. The intrinsically economic coal resources in Europe, which constitute about 25 % of world resources of this mineral (Burton, 2007).

The largest coal producers in Europe include: the Czech Republic, Germany, Great Britain, Poland, Russia and Ukraine. A substantial part of the solid fossil fuel resources of the European Union, including the ones that are unrecoverable, are located in Poland. This implies that these Polish resources may be important for strengthening the continent's energy security (Białecka, 2008; Collectivework, 2002; PARGWK, 2007).

Being a relatively cheap fuel, coal is a viable option to ensure energy security. Its future, however, largely depends on the application of appropriate technologies that reduce the negative impact of coal combustion on the environment.

Underground coal gasification (UCG) is an appropriate technology to economically access the energy resources in deep or unmineable coal seam and potentially to extract these reserves through production of gas for power generation, production of liquid fuels or chemicals.

Poland is a potentially good area for underground coal gasification. Coal gasification remains in line with the development strategies of the Polish energy sector, including the policies concerning activities in the field of mining and heavy industry restructuring.

Coal gasification in the seam is a complicated process, influenced apart from technological factors by natural factors.

The natural factors play a decisive role among the criteria of seam selection for UCG (Blindermam, 2005; Jaskulski, 1982). These factors include the coal type and physicochemical properties, depth of occurrence, thickness and angle of inclination of the coal bed, type and tightness of the rock mass, hydro-geological conditions, deposit tectonics, quantity of resources, presence of methane in the deposit and the conditions of the infrastructure on the surface.

From among technological factors that influence the gasification process the following should be mentioned: type of the oxidising agent used, velocity of its flow, and pressure in the generator.

An analysis and classification of mentioned criteria constitutes the subject of this paper.

UCG process description

Coal gasification consists in coal partial combustion and entire conversion into gas fuel composed of combustible components as CO, H_2, hydrocarbons, and a quantity of inert gases. Tab. 1 summarizes the important overall reactions participating in the coal gasification process.

Depending on the gasifying agent used (oxygen, air, water vapour) and process parameters we obtain gas fuels of different composition and various calorific values. There can be: weak gases, as the air gas, semi-water gas and water gas, or high calorific strong gases with high methane content. As this has been mentioned above, the UCG process is conducted in underground generators, which constitute separated coal seam parties opened up from the surface; they are connected through a borehole system in the seam with the surface (fig. 1). Coal gasification in the underground generator starts from coal seam ignition

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at the beginning of the borehole. After the creation of a fire front follows the real gasification process with fire front displacement along the channel. The remaining space after the gasified coal gets filled up with roof rock, slag and ash.

Tab. 1. Fundamental reactions for coal gasification.

Reaction	Enthalpy Δ*H* [kJ/mol]					
	T=298K	T=498K	T=698K	T=898K	T=1098K	T=1298K
$C + O_2 = CO_2$	–393,50	–393,62	–393,92	–394,39	–394,86	–395,29
$2C + O_2 = 2CO$	–221,15	–220,14	–221,14	–223,17	–225,62	–228,05
$C + H_2O = CO + H_2$	131,20	133,75	135,12	135,691	135,73	135,40
$C + 2H_2O = CO_2 + 2H_2$	90,05	94,02	97,47	100,16	102,22	103,57
$C + CO_2 = 2CO$	172,35	173,48	172,78	171,22	169,25	167,23
$C + 2H_2 = CH_4$	–74,71	–80,55	–85,19	–88,59	–90,78	–91,93
$CO + H_2O = CO_2 + H_2$	–41,15	–39,73	–37,65	–35,53	–33,51	–31,83
$2CO + 2H_2 = CH_4 + CO_2$	–247,07	–254,02	–257,97	–259,80	–260,02	–259,17
$CO + 3H_2 = CH_4 + H_2O$	–205,92	–214,29	–220,31	–224,28	–226,51	–227,34

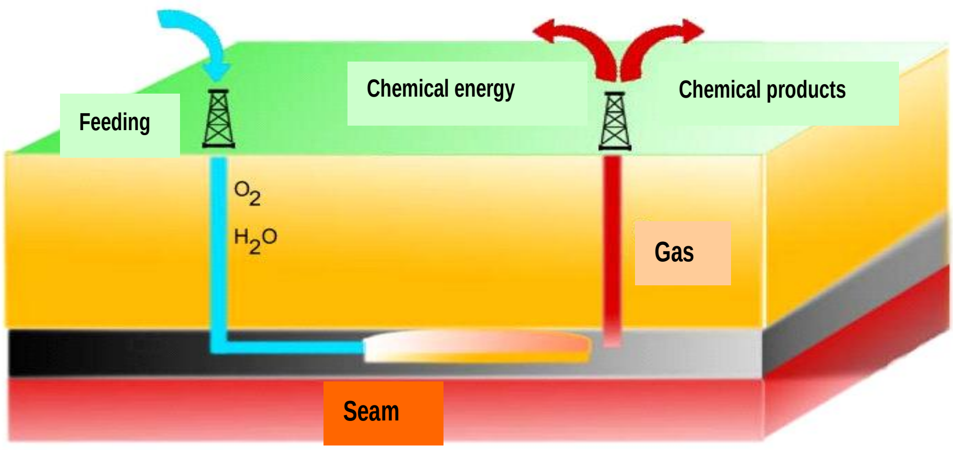

Fig. 1. Scheme of the UCG process.

The conditions of underground gasification are difficult, because coal subject to gasification occurs not in the form of crushed peaces, but as a compact mass, with which oxygen can react on a limited and one-sidedly opened surface. Acting on the incandescent coal surface the oxidising agent reacts with coal comprised in the deposit (one-stage or two-stage reaction). In the coal gasification process we can distinguish three basic zones: oxidation, reduction and pyrolysis.

Because the gasifying material contains oxygen, in the first oxidation zone arise carbon dioxide and carbon monoxide according to the reactions:

$$C + O_2 \rightarrow CO_2$$
$$2C + O_2 \rightarrow 2CO$$
$$2CO + O_2 \rightarrow 2CO_2$$

The thermal energy emitted during these exothermic reactions maintains the necessary temperature that conditions the gasification process course. These reactions are also the source of heat utilised with respect to the course of exothermic reactions, including moisture evaporation, coal heating up and gasification as well as heat emitted to the environment (heat losses).

In the zone of carbon dioxide reduction arises carbon monoxide according to the following reaction:

$$C + CO_2 \rightarrow 2CO$$

From the water vapour comprised in the gasifying material arise hydrogen and carbon monoxide according to the reaction:

$$C + H_2O_{(g)} \rightarrow CO + H_2$$

and in the case of pressure increase from the conveyed or forming there hydrogen arises methane according to the reaction:

$$C + 2H_2 \rightarrow CH_4$$

The coal content in the reaction zone decreases constantly.

During the pyrolisis stage carbonisate, moderately calorific gas and liquid hydrocarbons are obtained. This stage takes place in a very short time, frequently of the order of fractions of seconds, and its capacity is directly influenced by the type of coal used, final temperature and reaction time.

Analysis of natural factors influencing ucg realization

Coal gasification in the bed is a complicated process which, apart from technological factors, is influenced by several natural factors (tab. 2).

Tab. 2. Classification criteria for underground gasification.

Criterion	Characteristics/remarks
coal type	any
physicochemical properties of coal	recommended: high content of volatile matter, low agglomerating capacity or its lack, ash content < 50% by weight
occurrence depth	profitability criterion
bed thickness	more than 1 m
angle of inclination of coal bed	any
type and tightness of rock mass	recommended: firmness and tightness of rock mass, thickness and lithology of rock mass – overburden in slightly permeable layers (clays, silts, shale clays)
hydrogeological conditions	recommended: lack of fissures, faults, aquiferous layers, water reservoirs causing water inflow
deposit tectonics	recommended homogeneity of deposit (lack of fissure, faults)
quantity of resources	profitability criterion
methane presence in the bed	causes gas hazard
conditions of infrastructure	recommended lack of building development

1. For underground coal gasification, coals of different type, including brown coals through hard coals and anthracite can be utilized. Because of the simplicity of creating underground gas generators, most operations in the world (Blinderman, 2005; Rauk, 1982) were carried out in more gas permeable conditions of brown coal beds and younger formations of hard coals. Generally, these deposits occurred at shallower depths, down to 300 m, and ignited relatively easily. Strongly swelling and coking coals have the tendency to block gas flow through the coal bed, thus hindering the course of the reaction. Anthracites have low permeability, they usually occur at great depths, and are non-flammable; however, they are also suitable for gasification.

2. There is a tendency to consider UCG in deeper beds. This is connected with the simultaneous increase in the unit cost of derived gas. Until now, practical realisation of UCG was accomplished mainly in coal beds that occur at depths from 300 to 700 m. Trials at considerable depths, though not numerous, took place mainly in Europe, including Belgium (Creedy, 2001; Kowol, 1997). Analysis of the literature suggests that coal gasification in areas not disturbed by mining activities at depths exceeding 700 m will provide a tight underground generator owing to the plastic behaviour of carboniferous shales in these conditions (Creedy, 2001; Jaskulski, 1982). Conditions are different in areas disturbed by mining activities where the implementation of UCG requires many preparatory operations, including the sealing of gas generators as is the case for the Upper Silesian Coal Basin.

3. For UCG technology, highly inclined coal beds do not impose additional problems. The gasification of steeply occurring beds will be characterised by fewer drilling operations compared to those for horizontal beds.

4. The gasification of beds 1 m thick or more improves economics (Burton, 2007; Jaskulski, 1982). Beds that are thinner than 0.5 m. are not considered suitable for UCG.

5. European and Polish investigations suggest that beds with ash content exceeding 50 % by weight decreases the calorific value of the gas and hinders the process control (Dziunikowski, 1954; Jaskulski, 1982). In case of moderate ash quantities in coal, however, the ash oxides of some metals influence catalytically the course of the gasification reaction and increase the calorific value of the produced gas.

6. The UCG process may be influenced by the presence of water. The natural water inflow has a considerably greater impact on UCG than the bed moisture itself. The occurrence of aquiferous zones in the direct vicinity of the gasified bed or a strong natural water inflow can cause great difficulties, and even the stoppage of the gasification process. The UCG process can also exert a negative impact on the water level and purity. The maximum content of water for the production of usable low-calorific gas amounts to somewhat more than 0.5 kg of water per 1 kg of coal designed for gasification. Thus, excess water must be pumped out of the system (Burton, 2007; Rauk, 1982).

7. A considerable impact on UCG has the natural water inflow. The occurrence of aquiferous layers in the direct vicinity of the gasified seam or strong natural water inflow can cause great difficulties, and even stoppage of the gasification process. In an extreme case an inrush of considerable water quantities to the generator can follow, and in consequence the extinction of reaction. If conducting of the UCG process is planned in an area, from which water is drawn, then the problem requires particular attention and care. The quantity of toxic substances penetrating into aquiferous layers can be considerable, therefore permanent monitoring of the water quality will be needed.

Hard coal resources for UCG in Poland

The potential hard coal reserves (Collective work, 2002; Hankus, 2005; Kaziuk, 2001) in Poland concern developed resources in operating mines as well as coal resources and beds that are located in regions with no mining activities, in regions of planned mining activities, as well as coal beds in the regions of existing mines which are not extracted (Tab. 3-4). Hard coal deposits occur in the Upper and Lower Silesian and Lublin Coal Basins. The richest coal seams occur in the Upper Silesian sandstone series, particularly on the main saddle, within the Bytom trough and on the Jastrzębie saddle. In the deposits of the Upper Silesian Coal Basin, steam coals constitute 2/3 of the total intrinsically economic reserves, while much of the balance are coking coals.

Tab. 3. Reserves in developed and undeveloped deposits in Poland as on 31 December 2005.

No.	Area	Resources, million Mg		
		Intrinsically economic resources	Potentially economic resources	Economic resources
1	**Poland**	15,713	11,143	6,001
2	**USC (GZW)***	15,123	10,716	5,681
3	**LCB (LZW)***	590	427	320
4	**LSCB (DZW)***	-	-	-

USC (GZW) - Upper Silesian Coal Basin
LCB (LZW) - Lublin Coal Basin
LSCB (DZW) - Lower Silesian Coal Basin

Tab. 4. Hard coal resources in Poland in developed and undeveloped deposits in the aspect of mining.

Years	Deposits	Resources, million Mg			
		geological	intrinsically economic	potentially economic	economic
2001	developed	29,184	16,045	13,139	7,496
	undeveloped	46,681	29,855	16,826	7
2002	developed	28,868	15,888	12,980	7,376
	undeveloped	44,698	28,197	16,503	4
2003	developed	27,402	15,971	11,431	7,088
	undeveloped	43,397	27,151	16,246	14
2004	developed	35,842	16,041	19,801	6,928
	undeveloped	43,107	26,538	16,569	0
2005	developed	26,682	15,921	10,760	6,012
	undeveloped	44,541	28,030	16,511	2

It is of interest to consider the resources suitable for new techniques of energy production, including UCG. Apart from resources developed for coal mining in operating mines, in the total quantity of coal resources in Poland there exist undeveloped geological resources (Table 4), composed of:

- the resources of prospective deposits,
- the resources of reserve deposits,
- the resources of deposits where mining has been ceased because of mine closure.

Undeveloped resources as well as resources remaining in closed mines can also constitute the basis for underground energy generation processes from hard coal.

Thus, Polish coal resources for UCG may be considered to be among the largest in the Europe.

Characteristic parameters of Polish hard coal seams

Generally the reserves of Polish coals are characterised by good quality parameters (Collective work 2002). About 73 % of them constitute coals with calorific value exceeding 25 MJ/kg. A very small quantity amounting to 6 % points out a calorific value below 22 MJ/kg. Almost all reserves mentioned above, i.e. about 9 %, include ash amounting to 20 %, of which 50 % constitute coals with ash content not exceeding 10 %. Most of these reserves, as many as 77,4 %, have low sulphur content not exceeding 0,9 %. The reserves containing more than 1.5 % constitute only 5 % of the general reserve quantity and occur mainly in mines that extract seams of the highest part of the Carboniferous profile.

Because of the seam inclination angle, the reserves are relatively easy for mining operations, because they occur mainly in seams with low inclination. 76,7 % of reserves occur in seams with inclination up to 12^0, 22 % in seams with the angle of inclination from 13^0 to 30^0, and only 1.3 % of reserves in seams, where the angle of inclination is higher that 30^0.

About 53 % of coal reserves occur in seams of medium thickness, i.e. from 1.5 to 3.5 m. Only 25% occur in seams of thickness exceeding 3.5 m, and 22 % in thin seams of thickness below 1.5 m.

Power coals constitute about 64 % of reserves, high-rank coking coals about 24 %, while coking coals constitute only about 12 %.

High-rank coals occur generally in mines situated in the south-western part of the Upper Silesian Coal Basin.

The analysis of hard coal reserves according to such parameters as seam thickness or the angle of inclination of seams as well as quality parameters allows to state that in the majority those are reserves occurring in seams of medium thickness and small inclination, characterised by coals with very advantageous quality parameters, i.e. low ash and sulphur content and high calorific value.

Discussion on technological factors influencing the course of the ucg process

The analysis of main factors influencing the realisation of the UCG process allows to state the following factors:

1. For coal gasification in the deposit as the gasifying agent we can use oxygen, air, oxygen with water vapour etc., and the selection of the proper agent should result from the intended quality of produced gas, seam moisture and angle of inclination of the seam. Table 5 presents gas compositions dependent on the gasifying agent used (Dziunikowski, 1960; Rauk, 1964; Rauk, 1982).

Tab. 5. Composition of gas from the UCG process as a function of gasifying agent used.

Gasifying agent	Average calorific value, [MJ/m^3]	Gas composition [%]						
		CO_2	CO	H_2	CH_4	CnHm	N_2	O_2
Oxygen	8,3	24.6	21.9	31.6	5.4	-	14.8	1.7
oxygen + water vapour*	9,4	24.5	31.4	41.2	2.8	-	0.1	-
Air	3,3	9.9	14.6	10.9	1.6	-	62.0	1.0
heated air**	3.8	11.6	14.7	13.3	1.6	-	58.3	0.5
Air upgraded with oxygen***	5,4	30.0	11.9	13.2	1.8	0.6	47.0	1.8

Explanations:

** - The use of a oxygen-water vapour mixture is justified in the case of very low water quantities in the seam. In the considerable part of existing conditions the water quantity in the seam and surrounding environment is sufficiently high and there is no need to supply water vapour from the surface. Investigations have pointed out that the optimum relation of water vapour to oxygen is 1.1:1.*

*** - In the table are given data for air heated up to the temperature of 770 K. The air flowed counter-current to hot process gases.*

**** - In the table are given data for air upgraded with oxygen by 15 %.*

When using oxygen or heated air, the coal gasification process runs in conditions of a high thermal state of the generator. In connection with the above the process stabilisation follows very quickly, and the width of the burned out space becomes settled already at the distance of several metres from the generator beginning.

The dimension of the space in this case will be higher than when using other gasifying agents, because the width of the gasified space is conditioned by the quantity of reacted oxygen per coal unit of the channel surface in a time unit. We obtain in this case gas of high calorific value exceeding 8,3 MJ/m^3.

Leading of water vapour to the generator causes water decomposition, and the simultaneously occurring reactions delay roof rock melting. This process enables coal gasification at a considerable seam depth and obtainment of gas of high calorific value amounting to about 9,4 MJ/m^3.

When using cold air in the coal gasification process, the thermal state of the generator is relatively low. In spite of the above, the gasification process in the reaction zone runs at temperatures from 1270 to 1570 K according to the conditions, in which gasification takes place. In this case we obtain gas of industrial value equal to about 3,3 MJ/m^3.

1. The flow velocity of gasifying agents has essential influence on the course of the gasification process and direction of fire advance in the generator channel (Burton 2007, Wasilewski 1966).
   According to the velocity of blast flow of the gesifying agent one of two directions of fire advance in the generator channel is determined: consistent or reverse towards the blast direction. In the case of use of the coal gasification method based on fire advance in the opposite direction to the flow of the gasifying agent flux, its velocity ranges from several to several dozen cm/sec and this movement has a laminar character. The velocity of fire advance in the reverse direction will increase, when the velocity of the gasifying agent flow will approach the critical velocity. After its exceeding the fire advance in the reverse direction decreases and the direction arises which is consistent with the blast flux flow. Inversely in the case of decrease of the gasifying agent flow velocity follows an increase of fire advance velocity in the radial direction, and decrease in the reverse direction. In the case of coal gasification by means of fire advance in the direction consistent with the gasifying agent flow, its velocity must be higher than the critical velocity, i.e. from 1 m/sec, when the change of fire advance from the reverse to the consistent one follows. From British experience results that in the case of the Reynolds number amounting to 300 000-350 000 and blast flux velocity to 1.5 - 2 m/sec we obtain optimum coal gasification indices and a high width of burned out deposit. Along with a further increase of the flux velocity follows worseening of the coal gasification process and decrease of the width of burned out deposit.

2. Essential is permanent control and gas pressure regulation in the generator.
   Increased pressure is apart from the temperature an essential factor influencing the chemical reaction course of the gasification process, and thus its result. Pressure influences in an advantageous way the multiphase methanation reaction.
   Essential is also the pressure equilibrium in the gas generator, what does not cause the displacement of underground waters in the gas generator but facilitates their slow migration towards the reaction front, ensuring the necessary vapour quantity for the reaction and simultaneously preventing gas escapes. Water infiltration influences decidedly the UCG process result (Burton, 2007; Rauk, 1976).

Table 6 shows the essential factors for UCG process conducting.

Tab. 6. Specification of factors essential for UCG process conducting.

Factor	Characteristics/remarks
Gasifying agent	Oxygen, oxygen + water vapour, air
Type of blast	conditioned by the intended quality of produced gas
Blast flux velocity	1.5 – 2.5 m/sec
Gas generator dimensions	
Length	dependent on the angle of seam inclination and temperature in the reaction zone
Diameter	Dependent on drill diameter
Optimum process parameters	
Oxygen-water vapour blast	1:1.1
Blast velocity	1.8 m/sec
Obtained gas of calorific value	8,3-10,4 MJ/m^3
Gas generator temperature	< 2000 K
Pressure	Preventing water inflow to the generator

Summary

Long-standing investigations into underground coal gasification have allowed to a great extent to recognise the role and significance of some parameters of this process. The main factor influencing the process course and conducting are natural determinants.

The technological factors, though dependent on natural factors, can be shaped with respect to the use of deposit development technologies and conducting of the underground gasification process. The article presents a brief discussion on natural and technological factors, which influence the UCG course.

The analysis of the hard coal resources in Poland indicates the possibility to use part of its reserves for UCG.

- In the structure of geological resource of all mines, there exist currently economically unrecoverable deposits. It is expected, however, that they could be mined in the future. The quantity of these resources as of 31st December, 2005 amounted to *27,271 million Mg* on a country scale, of which *10,760 million Mg* occur in developed deposits.
- The analysis of the mean of coefficients relating to the use of resources, which for balance reserves amounts to 0.47 and for potentially economic reserves to 0.39, indicates a high potential of coal resources that can be considered as the basis for coal gasification projects.
- The potentially economic resources, losses and reserves of deposits where mining activities were ceased because of mine closure form the basis for non-traditional energy generation technologies.

It should be stressed that the analysis carried out on the basis of mineable resources does not reflect the total quantity of resources available for future development of considering different techniques, including gasification technologies.

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