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JÓZEF DUBIŃSKI*, MARIAN TUREK*

BASIC ASPECTS OF PRODUCTIVITY OF UNDERGROUND COAL GASIFICATION PROCESS

PODSTAWOWE ASPEKTY PRODUKTYWNOŚCI PROCESU PODZIEMNEGO ZGAZOWANIA WĘGLA

An analysis of conditions which enable attaining possibly highest productivity of industrial scale underground coal gasification technology is presented. The analysis was prepared basing on results obtained during an experimental gasification process conducted in workings of an active hard coal mine. Basic aspects determining application and productivity of the technology concern both general conditions, referring to the hard coal seam being gasified, and practical issues, which need to be considered in coal mine conditions. To present them, the technology of underground coal gasification and still commonly used classical longwall method of mining coal seams are compared.

Keywords: productivity, underground coal gasification, technology of exploiting hard coal deposits

Przedstawiono analizę uwarunkowań pozwalających na uzyskanie możliwie jak największej produktywności technologii podziemnego zgazowania węgla, prowadzonego w skali przemysłowej. Analiza została wykonana w oparciu o rezultaty uzyskane w eksperymentalnym procesie zgazowania przeprowadzonym w wyrobiskach czynnej kopalni węgla kamiennego. Podstawowe aspekty determinujące zastosowanie i produktywność tej technologii dotyczą zarówno uwarunkowań ogólnych, odniesionych do zgazowywanego pokładu węgla kamiennego, jak i praktycznych, koniecznych do uwzględnienia w stosowaniu w warunkach kopalnianych. W celu ich lepszego zobrazowania, dokonywano porównań technologii podziemnego zgazowania węgla z powszechnie dotychczas stosowaną, klasyczną technologią ścianowej eksploatacji pokładów węgla.

Słowa kluczowe: produktywość, podziemne zgazowywanie węgla kamiennego, technologia eksploatacji złoża węgla kamniennego

* CENTRAL MINING INSTITUTE, PLAC GWARKÓW 1, 40-166 KATOWICE, POLAND

1. Introduction

Hitherto research into coal gasification were most often theoretical and they dealt with either realisation of the process itself or various aspects associated with general safety of its implementation (Janoszek et al., 2013; Kamińska-Pietrzak & Smoliński, 2013; Kapusta et al., 2014; Wachowicz et al., 2010). Whereas the research project titled "Developing coal gasification technology for highly effective production of fuels and electric energy", realized within the framework of National Centre for Research and Development titled "Advanced Technologies for Energy Generation", included, for the first time, a practical experiment of gasifying a section of coal seam 501 in active Wieczorek coal mine, which belongs to Katowicki Holding Węglowy S.A. (Strugała, 2014). The results obtained during the experiment are promising and in the future, hopefully, the technology of producing energy will be used on an industrial scale. Before it happens, numerous issues have to be specified: conditions , in which conducting underground coal gasification process is feasible; safety criteria both for the personnel and the environment (Burchart-Korol et al., 2014; Chećko et al., 2014a, b; Dubiński & Koteras, 2014; Kamińska-Pietrzak & Smoliński, 2013; Krzemień et al., 2014); technical issues associated with building an installation which enables commercial use of the process to produce a given amount of thermal power. Finally, another crucial issue will be cost-effectiveness of such a technology in a mining enterprise – the technology must be effective.

The following research paper is an attempt to analyse various aspects of obtaining satisfactory results of one of the effectiveness indicators , i.e. productivity. As in the future, once having dealt with the technical problems and issues associated with safe application of the technology, industrial scale underground coal gasification process may be treated as an alternative to the classical technology of mining hard coal deposits. Hence, in the considerations the two technologies are often compared.

2. Productivity as effectiveness indicator

Effectiveness of actions can be evaluated with various indicators (relative values), which describe relations between incurred costs and income or *vice versa*: effectiveness is a ratio of the effects to the investments in form of a numerical result, which shows what result is generated with the investments. The result is an indicator of effectiveness, also known as efficiency ratio. Depending on a purpose, efficiency ratios can be used by enterprises in different areas. The key indicator of effectiveness of an enterprise's functioning is productivity, which can be determined with different indicators. Most often it is a ratio of the amount of produced/sold products, or the value of products sold in a given period (so-called product flow), to the amount of applied or used up inputs of the production system:

- material:
  - physical – e.g. amount and/or value of used up materials, energy, tangible fixed assets,
  - financial – e.g. value of fixed capital or circulating capital involved in production,
- non-material – human – e.g. number of employees, time of work (number of work-days/working hours), costs of labour (so-called flow of factors of production).

Indicators defined in such a way describe so-called partial productivities of: materials, energy, tangible fixed assets, capital, labour.

In general, productivity of a production process run in a given enterprise can be expressed as (Kowalczyk, 2007):

$$\textbf{Productivity "P"} = \frac{\textbf{Effects "E"}}{\textbf{Investments "N"}}$$

When the whole volume of the product produced/sold in a given period and the total amount of used up or applied assets are considered, it is referred to as total productivity. Most often total productivity can be expressed:

- in terms of money – as a ratio of the income to the costs of given used up or applied resources,
- as a ratio of volume of product made/sold to the costs of given used up or applied resources.

In the classical longwall system of mining coal seams, commonly used in mining enterprises of hard coal mining industry, an effect is expressed either as the amount [Mg] or calorific value [GJ] of the processed coal (and possibly accompanying methane) produced. In hard coal gasification the production effect can be expressed as either the volume [m^3] or calorific value [GJ] of the produced syngas. Thus, both technologies share a "common unit" of product flow. Knowing the amount of investments incurred to produce them, we can compare productivity attained when the technologies are used. Once the technical problems associated with industrial scale application of underground coal gasification have been solved, it will be easier to take a decision whether to apply the technology in coal mines.

3. Productivity of mining enterprise – applying two different exploitation technologies

It is a general rule, referring to all enterprises, that productivity depends on the costs of operating. Low productivity results in higher consumption of resources, especially materials and energy, which, in turn, results in high price of the final product. On the other hand, high productivity results in lowering costs of production and increasing generated profit, which is usually one of fundamental prerequisites of the very existence of a company. An example of such an association, referring to a mining enterprise, is presented in Figure 1.

All enterprises, including the mining ones, during both their operating activities and investing activities, have to take into consideration their external conditions (closer and farther) where it is located, which have an influence on their functioning. Surely, it may be assumed that both for a mining enterprise exploiting hard coal deposits with the classical mining method and the one which applies underground gasification process, the farther environment, consisting of a set of macroeconomic conditions of operating, is more or less the same. However there are differences in the close environment, involving all the systems with which an enterprise enters into direct relations i.e. suppliers (of capital, raw materials, work) of the enterprise and consumers (of final products). It is presented in Figure 2.

From the economic point of view, comparison of a production system employing classical mining technology and the other employing underground coal gasification, shows significant advantages of the latter one in the aspect of: costs associated with the flow of factors of production,

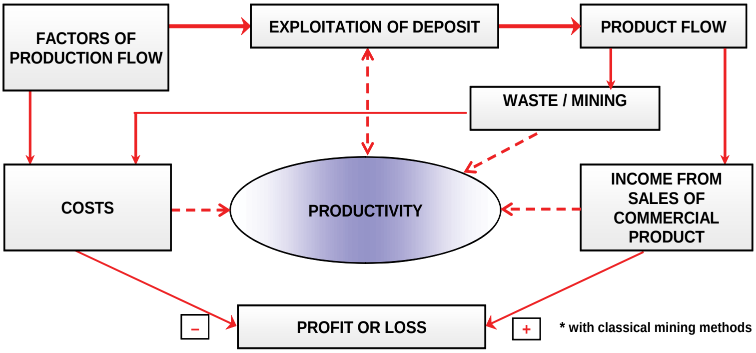

Fig. 1. Productivity in a mining enterprise.
Source: own elaboration, basing on Czechowski et al., 1999)

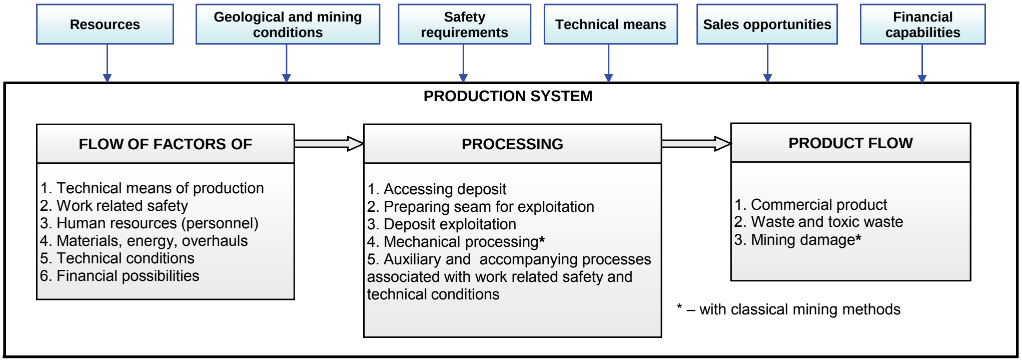

Fig. 2. Production system of mining enterprise and influence of its close environment conditions.
Source: own elaboration

processing them and negative effects of the exploitation. It refers both to investment costs and operating costs. The ranges where there are the biggest differences between the two technologies, are collected and presented in Table 1.

As the above collection shows, underground gasification method has a significant "edge" over the classical mining method – in each of the aspects the costs which have to be incurred to start and conduct the operations, are much lower. It definitely favours increasing productivity. The costs can be even lower if e.g. gasification is conducted only with technological boreholes drilled from the surface – then it is not necessary to drive any underground workings. More detailed analyses of the issue shall be accompanied with a complex evaluation of the costs of underground coal gasification process in various geological, mining and technical conditions (Magda, 2012).

Lower investment costs and operating costs mean high probability of attaining a satisfactory level of productivity of the underground coal gasification technology. Yet to make it happen, it is necessary to have satisfactory parameters of the commercial product , i.e. syngas.

TABLE 1

Comparison of factors generating investment costs and operating costs

No.	Specification	Classical method of mining hard coal deposit	Underground gasification of hard coal deposit
1.	Technical means of production		Much lower costs of technical equipment
2.	Work-related safety		Much lower costs, due to much smaller scope of works and personnel
3.	Human resources (personnel)		Even several dozen times smaller
4.	Accessing a deposit	Necessary to drive vertical or inclined workings from the surface (shafts and declines) and horizontal workings in the rock mass	Necessary to drill technological boreholes from the surface and possibly horizontal preparatory workings – incomparably lower costs
5.	Preparing seam for exploitation	Necessary to drive transport and ventilation workings in seams	Necessary to drive much smaller number of workings
6.	Mechanical processing		None
7.	Waste and toxic by-products	Most often necessary to dump waste rock Costs of fees for discharging saline water and gas emission (methane)	Gasification by-products which can be utilised in specialist plants
8.	Mining damage		None or of incomparably smaller scope

Source: own elaboration.

4. Factors which influence productivity of underground coal gasification process

Considerations included in the chapter were basing on experience gathered during the experimental underground gasification process conducted in a coal seam in Wieczorek coal mine. Once the gasification process was initiated, under normal operation, between 600 and 800 m^3/hour of syngas was produced, of net calorific value of between approx. 3.0 and 4.5 MJ/m^3. To illustrate how it refers to net calorific value of coal, Table 2 compares amounts of coal and gas, of various net calorific values, necessary to produce 1 GJ of energy.

TABLE 2

Comparison of amounts of coal and gas of differentiated net calorific values necessary to produce 1 GJ of energy

net calorific value of coal	19 GJ/Mg	20 GJ/Mg	21 GJ/Mg	22 GJ/Mg
Amount of coal necessary to produce 1 GJ of energy [kg]	52.63	50.00	47.62	45.45
net calorific value of gas	3.0 MJ/m^3	3.5 MJ/m^3	4.0 MJ/m^3	4.5 MJ/m^3
Amount of gas necessary to produce 1 GJ of energy [m^3]	333.33	285.71	250.00	222.22

Source: own elaboration.

This time the comparison shows more beneficial use of the final product – to produce the same amount of energy much less coal, produced in a traditional way, is required. In the experiment 600-800 m^3 of gas was produced per hour, which would enable production of approx. 1.8-2.4 GJ of energy (gas of net calorific value of 3.0 MJ/m^3). With coal of net calorific value of 4.5 MJ/m^3 approx. 2.7-3.6 GJ of energy would be produced. Assuming that an average longwall produces 3,000 ton of coal per day, it can be estimated that the amount of coal produced in one hour (approx. 125,000 kg) is enough to produce between approx. 2,375 GJ (coal of net calorific value of 19 GJ/Mg) and approx. 2,750 GJ of energy (coal of net calorific value of 22 GJ/Mg).

However it is worth mentioning that, according to theoretical calculations, only approximately 245 ton of coal was gasified during the experiment, producing over 1,000,000 m^3 of syngas. It means that although net calorific value of the gas produced in underground coal gasification process is approximately one tenth of the commonly used methane-rich natural gas, it can be produced in large quantities. It is extremely important to use all the capabilities of producing large amounts of gas of possibly highest net calorific value in the georeactor, and thus significantly increase productivity. Producing large amounts of gas can be also accomplished through multiplying georeactors, where it is produced.

Among the factors which influence whether a satisfactory level of productivity is attained, the following groups can be identified:

- geological factors,
- technological factors,
- environmental protection factors.

In mining activities it is fundamental to investigate carefully geological and mining conditions prior to any mining activities, which ought to be aimed at attaining satisfactory economic results and minimizing their negative effects. To maximise probability of attaining high production effectiveness, both with the classical mining method and with underground coal gasification, it is necessary, most of all, to have sufficient data concerning occurrence of a deposit. In case of a deposit or a seam planned for exploitation with underground gasification, the data ought to include:

- location (area and depth of occurrence),
- prospecting deposits i.e. thickness of the seams and amount of deposited coal,
- determining deposition – identifying occurrence of possible geological disturbances, which may affect the course of the gasification process,
- determining occurrence and scale of natural hazards.

Collecting the necessary data, at the stage of designing exploitation, enables initial estimation of effectiveness of the operation, together with its key indicator – productivity. It will be also a basis for taking right decisions of accessing and mining a deposit, which in turn are associated with another group of factors, called technological ones.

The most important one of them, determining the way a georeactor (a selected section of a seam to be gasified) is accessed and equipped, is determining the method of gasification (Magda, 2012):

- with a shaft,
- without a shaft:
  - with CRIP or εUCG method,
  - with or without access to the georeactor from an underground working.

In each of the methods a deposit is accessed in a different way (different number of technological boreholes drilled from the surface) and the underground part of the technological installation is prepared in a different way too. Obviously, it means radical differences in the volume of necessary investments. In each of the cases it requires conducting a detailed technical and economic analysis of various options to access and prepare the deposit for exploitation. For instance, it may seem that applying the method without a shaft, assuming that no underground roadway is driven to access the area of a georeactor, ought to result with better productivity indicators due to lower financial investments. Yet, it needs to be said, that in the light of experience gathered during the experiment in Wieczorek coal mine, conducting the process without any access to the area of a georeactor from underground workings is a solution of rather distant future. It is so because without the access it is virtually impossible to solve potential technical problems or make repairs , which is unacceptable if the technology is to be used commercially.

Less important for the attained productivity are the necessary investments into technical equipment of gasification installation. Its above the surface part, which receives the produced gas, is independent on the method the deposit is accessed and on the gasification technology i.e. in all cases it is similar. The underground part is much more differentiated – it may differ in the number, length and type of main pipelines (feeding the gasification agent and receiving gasification products), as well as the equipment of the pipelines (e.g. separators collecting contaminants). Yet one fact needs emphasising here again: costs of technical equipment, whichever underground gasification technology is applied, are incomparably lower than the costs of applying classical mining method.

A similar conclusion refers to the last group of factors associated with environmental protection and eliminating negative influence on the surface. The aspect has to undergo detailed research, yet even now it may be concluded, with a large dose of certainty, that exploitation of deposits with underground gasification:

- does not lead to significant subsidence of the surface, especially when compared with longwall mining with cave-in,
- does not produce large amounts of mining waste (waste rock) of marginal economic use, which is most often stored in dumps. Tar and tar water produced during the gasification process can be utilised in chemical plants (in the experiment it was a coking plant) or they may be used as intermediates,
- does not make it necessary to:
  - discharge often large amounts of saline water into watercourses,
  - emit greenhouse gases (methane) into the atmosphere,
- generates a much more environmentally friendly commercial product than coal; gas combustion emits much less pollution into the atmosphere.

As far as the environmental aspect is concerned it has to be emphasised that the technology still requires detailed geochemical analyses of the products and waste generated in the core of a georeactor and their impact on the environment , e.g. concerning possible pollution of groundwater.

5. Conditions to attain satisfactory productivity in practical use of underground coal gasification technology

Once the decision of applying the underground coal gasification technology is taken, a place to conduct it is found, the deposit is accessed and the necessary technical infrastructure is built, there are also conditions in the practical application which concern attaining satisfactory indicators of productivity.

As it has already been mentioned, the produced syngas has relatively low net calorific value. That is why its commercial use depends on the capability of producing it in large quantities. The experiment carried out in Wieczorek coal mine showed that there are technical possibilities to influence the volume and parameters of the produced gas. However they still have to undergo numerous tests and analyses. The tests and analyses will show in detail technological and technical solutions that will enable cost-efficient application of industrial scale gasification.

Assuming that the parameters and deposition of a seam (or its part) to be gasified, justify use of the technology, the tests carried out during the experiment showed that there are technical possibilities of improving productivity of the process, especially through using the right gasification agent. The experiment was carried out with:

- mixture of oxygen and air of various proportions,
- air flow of between 230 and even 350 m^3/hour,
- air and water flow of between 50 and 75 l/hour,
- air and carbon dioxide flow of approx. 60-75 m^3/hour.

Without going into detailed technical considerations concerning the results obtained during different attempts, it can be concluded that it is possible to influence changes in temperature, volume and calorific value of the produced gas – the process was controllable. Changes in the parameters of the gasification medium supplied to the area of a georeactor influenced parameters of the produced gas in a foreseeable way. However, there was a problem as rather large fluctuations in parameters of the gas, especially its volume and calorific value, were observed (temperature was more stable). To some extent it was a result of carrying out different tests, yet, surely, it was also largely influenced by "local" parameters of the gasified coal and technical problems. For instance, a drop in temperature of gas caused an increase in precipitation of contaminants, which slowed flow of gas in the return pipeline and, in turn, decreased the volume of gas and its calorific value. In an extreme case in the last days of July, the full tanks of waste separators virtually stopped the whole process.

Figures 3-5 present graphs which show mean daily values of temperature, amount and net calorific value of the produced gas during the experiment (only days of normal operation are considered).

Further works to be realised within the framework of the research project, concerning development of a technological project and an initial feasibility study of so-called demo UCG installation, as well as determining priority directions of development of the UCG technology, shall focus mainly on the production of large amounts of gas, of possibly invariable parameters. From the technical point of view it is an extremely important requirement when the technology of obtaining gas on industrial scale is applied. When commercially used the feed of gas shall have steady parameters. From the economic point of view it is a prerequisite to attain adequately high productivity.

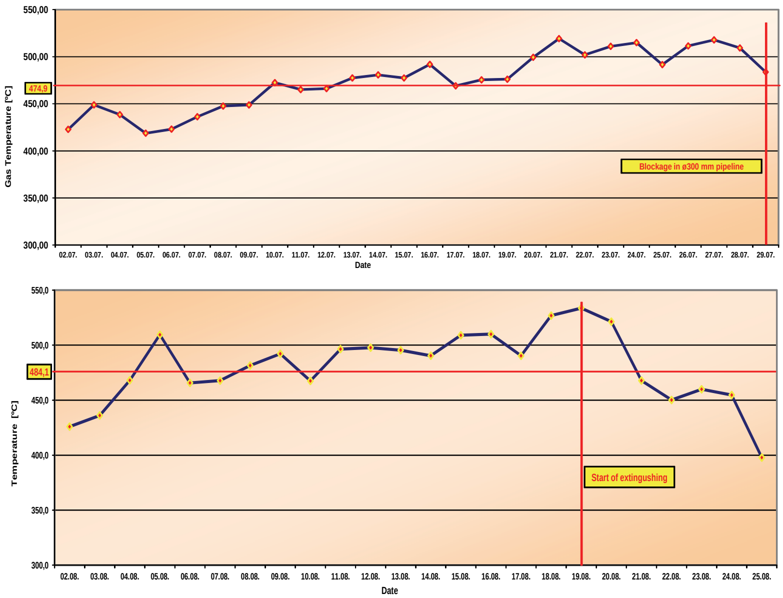

Fig. 3. Mean daily temperature of syngas at the nozzle of the georeactor in July and August, normal operation.
Source: own elaboration

Fig. 4. Mean daily amount of syngas produced in the georeactor in July and August, normal operation.
Source: own elaboration

Fig. 5. Mean daily calorific value of syngas produced in the georeactor in July and August, normal operation.
Source: own elaboration

6. Summary

1. Results of research and tests obtained during the experimental underground coal gasification process, which was carried out in workings of an active coal mine, are the basis for further works on solving technical problems associated with industrial scale application of the technology.
2. Much lower investment costs and operating costs, comparing with commonly used classical technologies of mining hard coal deposits; which have to be incurred to run underground coal gasification, are a significant reason to consider the conditions which have to be met to attain high level of productivity for the type of exploitation.
3. Assuming that the problems concerning industrial scale application of underground coal gasification (both the technical and work-related safety aspects) are solved in a satisfactory way, the first aspect of the ability to attain high productivity to be determined is a set of requirements concerning the proper recognition of geological and mining conditions of a deposit (a seam or its part) to be gasified. It will be also extremely important to develop criteria of selecting the right method of gasifying.
4. Relatively low net calorific value of gas produced in underground coal gasification is a factor which hinders attaining high productivity of the process. The risk can be minimised through technical means of producing safely large amounts of gas of possibly stable calorific value.

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