


Critical review of methods for intensifying the gas generation process in the reaction channel during underground coal gasification (UCG)

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Abstract

Purpose. The research purpose is to perform a critical analysis of methods for intensifying the gas generation process in the reaction channel to improve the efficiency and economic feasibility of coal seam gasification technology. The paper studies in detail the aspects of the chemical mechanism and technological parameters of this process in order to determine the possibilities for improving efficiency and productivity.

Methods. The review study is based on an approach that includes an analysis of the underground coal gasification development, the study of chemical reactions in the reaction channel, the study of the influence of factors such as temperature, pressure, blast and producer gas composition, etc. The experimental research data systematization is based on in-depth analysis of scientific papers published in peer-reviewed journals.

Findings. The systematized results of research into nine main methods for intensifying the gas generation process in the reaction channel during underground coal gasification are presented. The factors having the greatest influence on gas generation in the reaction channel have been identified.

Originality. Research results indicate the possibility of improving the process of underground coal gasification. The revealed relationships between different factors contribute to a deeper understanding of the chemical and physical processes in the reaction channel.

Practical implications. The results obtained can be used to optimize the underground coal gasification process, increase the productivity and quality of gas generation. The specified results can serve as a basis for further scientific research and innovative developments in obtaining an alternative type of fuel.

Keywords: *underground coal gasification, gas generation, intensification, chemical reactions, efficiency, optimization*

1. Introduction

Over the past centuries, humanity has met its energy needs through various means, spanning from harnessing solar energy to utilizing nuclear power [1], [2]. Among these, the combustion of fossil fuels has become a widely recognized method of energy release. Fossil fuels can include temporary sources like wood, but more commonly, they include coal, oil and gas [3]-[5]. These fuels can be burned directly or undergo indirect burning, wherein they are transformed into a more convenient form for use. For instance, coal can be converted into coal gas and coke, both serving as fuel sources [6]-[9].

Indirect burning of fossil fuels, such as the conversion of coal into coal gas and coke, offers certain advantages and applications. Coal gas, a gaseous product derived from coal, can be used as a fuel for heating, lighting, and even as a feedstock for chemical processes. By converting coal into coal gas and coke, the energy potential of coal can be harnessed more efficiently and conveniently. This allows for the utilization of different energy forms derived from fossil fuels, contributing to

the energy needs of society [10]-[12]. However, it is worth noting that the combustion of fossil fuels, including coal, oil, and gas, also raises concerns about environmental impact and climate change due to the release of greenhouse gases [13]-[15]. As the world seeks to transition to cleaner and more sustainable energy sources, alternative methods and technologies are being developed to minimize the reliance on fossil fuels and mitigate their negative effects on the environment [16]-[19].

The history of underground coal gasification (UCG) dates back to the 19th century when early concepts and ideas were conceived [20]. Siemens first conceived the idea of underground coal gasification as early as 1868. His objective was to utilize large quantities of coal that were economically impractical to mine for gas production. In 1914, Ramsay conducted small-scale experiments on underground gasification in Durham. However, there was no further development in Britain until 1950. In the 1930s, the USSR conducted large-scale trials, and similar trials were conducted in Europe and the United States in the late 1940s [21]-[25]. Key underground coal gasification projects worldwide are presented in Table 1.

Received: 7 April 2023. Accepted: 2 August 2023. Available online: 30 September 2023

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Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

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Table 1. Key underground coal gasification projects worldwide (revised from [26]-[37])

Test site	Country	Year ↓	Coal type [*]	Coal seam thickness, m	Coal seam depth, m	Syngas calorific value, MJ/m ³	Well configuration**	Injected gas
Lysychansk	Ukraine	1934-1936	B	0.75	24	3-4	SDS	Air
Lysychansk	Ukraine	1943-1963	B	0.4	400	3.2	SDS	Air
Gorlovka	Ukraine	1935-1941	B	1.9	40	3.9-10.3	SDS	O ₂ /H ₂ O
Podmoskovna	USSR	1940-1962	L/SB	2-3	40-55	3.4-6	LVW	Air
Bois-la-Dame	Belgium	1948	A	1	–	2.5	–	–
Newman Spinney	UK	1949-1959	SB	1	75	1.4-2.6	–	Air
Yuzhno-Abinsk	USSR	1955-1989	B	2-3	100-138	4.1-12.1	LVW	Air
Shatska	USSR	1959	L	2	50	3.2	LVW	Air
Angren	Uzbekistan	1961-ongoing	L/SB	4-9	110-150	3.4-3.9	LVW	Air
Hanna 1	USA	1973-1974	HVB	9	120	3.4	LVW	Air
Hanna 2	USA	1975-1976	HVB	9	85	4.2-5.3	LVW	Air
Hanna 2	USA	1977	HVB	9	85	4.1	LVW	Air
Hoe Creek 1	USA	1976	HVB	7.5-8	40	3.6	LVW	Air
Hanna 3	USA	1977	HVB	9.1	84	4.1	–	Air
Hoe Creek 2A	USA	1977	HVB	7.5-8	40	3.4	LVW	Air
Hoe Creek 2B	USA	1977	HVB	7.5-8	40	9.0	LVW	O ₂ /H ₂ O
Hanna 4	USA	1977-1979	HVB	9.1	40	4.1	–	Air
Hoe Creek 3A	USA	1979	HVB	7.5-8	40	3.9	LVW	Air
Hoe Creek 3B	USA	1979	HVB	7.5-8	40	6.9	LVW	O ₂ /H ₂ O
Pricetown	USA	1979	B	1.8-2	270	6.1	LVW	Air
Rawlins 1A	USA	1979	SB	18	105	5.6	SDS	Air
Rawlins 1B	USA	1979	SB	18	105	8.1	SDS	O ₂ /H ₂ O
Rawlins 2	USA	1979	SB	18	130-180	11.8	–	O ₂ /H ₂ O
Brauy-en-Artois	France	1981	A	–	1200	–	–	–
Thulin	Belgium	1982-1984	SA	6	860	7.0	LVW	Air
Centralia A	USA	1984-1985	SB	6	75	9.7	CRIP	O ₂ /H ₂ O
Centralia B	USA	1984-1985	SB	6	75	8.4	LVW	O ₂ /H ₂ O
Haute-Duele	France	1985-1986	A	2	880	–	–	–
Thulin	Belgium	1986-1987	SA/A	6	860	7.0	LVW	Air
Rocky Mountain 1A	USA	1987-1988	SB	7	110	9.5	CRIP	O ₂ /H ₂ O
Rocky Mountain 1B	USA	1987-1988	SB	7	110	8.8	LVW	O ₂ /H ₂ O
Xinhe	China	1994	B	3.5	80	11.8	LT	Air/H ₂ O
Liuzhuang	China	1996	HVB	3	100	12.2	LT	Air/H ₂ O
El Tremedal	Spain	1997	SB	2	580-600	6.6-10.9	CRIP	O ₂ /H ₂ O
Xinwen	China	2000	HVB	1.8	100	10.4	LT	Air/H ₂ O
Chinchilla 1	Australia	2000	SB	10	132	4-5	LVW	Air
Feichang	China	2001	B	1.5	90	5.1	LT	Air
Xiyang	China	2001	A	6	190	11.9	LT	Air/H ₂ O
Suncan	China	2002	B	2	80	8.5	Tunnel	Air
Chinchilla 3	Australia	2007	SB	10	132	4-5	LVW	Air
Majuba	South Africa	2007	B	3.5-4.5	285	6.2	LVW	Air
Chinchilla 4	Australia	2009	SB	10	132	4-8	CRIP	Air
Bloodwood Panel 1	Australia	2009	SB	8-10	200	5-12	CRIP	O ₂ /H ₂ O
Chinchilla 5	Australia	2011	SB	5.5	132	4-11	CRIP	O ₂ /H ₂ O
Bloodwood Panel 2	Australia	2011	SB	8-10	200	5-6	CRIP	O ₂ /H ₂ O
SwanHills	Canada	2011	HVB	4.5	1400	16	CRIP	O ₂ /H ₂ O
Alaska SHR	USA	2012	L/SB	1-12	50-650	3.3-5	LVW	Air
Wieczorek	Poland	2014	SB	5.5	464	3.4	SM	Air, O ₂ , CO ₂

*A – anthracite; B – bituminous; L – lignite; SA – semi-anthracite; SBB – sub-bituminous; HVC – high-volatile bituminous

**CRIP – controlled retraction injection point; LT – long tunnel; LVW – linked vertical wells; SDS – steeply dipping seams; SM – shaft method

Despite initial expectations, the practical benefits of underground gasification have not been widely realized. However, recent continuous interest has led to a renewed focus on this technology [38]. Efforts to carry out underground coal gasification (in-situ coal gasification) have a long history, with significant activity occurring between 1945 and 1965. This activity was primarily concentrated in the USSR, the UK, and the USA, although projects were also reported in Belgium, Poland, Czechoslovakia, Italy, and Morocco.

In underground coal gasification, the reaction occurs in a combustion channel within the coal seam, where air is passed through. This process results in a mixture of various gases,

including coal-gas, water-gas, producer gas, flue gas, and sometimes free air. The coal in-situ is gasified, releasing the potential heat contained in the original coal as combustible gas, hot gas, and steam. However, some of the heat is lost through conduction underground into the surrounding strata [39], [40].

To enable the passage of air through a coal seam and recover the generated gas, a pathway must be established from the surface to the coal. Conventional methods such as drilling wells are commonly employed to create access points from the surface to the coal seam. There are various techniques available for forming a pathway for air and gas through a coal seam [41].

Until 1952, most international trials relied on the construction of underground galleries, where gasification reactions occurred either within these galleries or in wells drilled from them into the coal seam. These trials were primarily conducted in steeply sloping seams. In the middle of the 1950s, two alternative techniques were developed to create channels through the coal seam without the need for manual labor or extensive underground preparation. In one method, the seam was fractured and the channel was formed by burning it with high-pressure air. In the other method, a strong electric current was applied to ignite the coal, resulting in the formation of fissures through which air could be passed. In the UK, trials were conducted on creating the channel in the coal seam using a technique called directional drilling. The USSR made the most prolonged and extensive effort in underground coal gasification, which started in the early 1930s and continued until the 1990s. Their endeavors advanced to a commercial stage when the gas produced was utilized for power generation. From 1946 to 1958, the US Bureau of Mines conducted comprehensive field studies on underground gasification in Gorgas, Alabama. Similar studies were also carried out at Chesterfield in the UK. However, both programs were discontinued as the collected data indicated that the process was economically unviable at that time. Nevertheless, since those early experiments, the technology associated with underground coal gasification has significantly improved [42]-[45].

Recently, there has been a notable concentration of UCG initiatives in countries like China, Australia, and South Africa, where operational power or chemical plants are supplied with UCG syngas. Additionally, UCG projects are at the planning stages in Canada and the U.S. China, in particular, has emerged as a global leader in UCG endeavors, having undertaken 16 UCG pilot projects since 1991. Presently, the Xin Wen coal mining group in Shandong Province boasts six UCG reactors that are actively generating syngas for cooking and heating purposes. Another project in the Shanxi Province employs the producer gas for the production of ammonia and hydrogen. Beyond the boundaries of the former Soviet Union, the Australian Chincilla site in Queensland stands as one of the most substantial undertakings. This project, operating from 1997 to 2003, successfully gasified approximately 30 thousand tons of brown coal [46]-[52].

Nowadays numerous researchers hailing from diverse countries such as China, the US, India, Australia, Ukraine, Poland, Brazil, Canada, Bangladesh, and the UK, are actively immersed in significant advancements within the domain of underground coal gasification technology [53]-[57].

If current underground coal gasification programs are successful, it could unlock significant coal reserves that are currently considered economically unfeasible to mine [58]. The direct utilization of the low-calorific-value gas generated from underground gasification for power generation or in-plant requirements would eliminate the need for the methanation step typically required to upgrade the gas to synthetic natural gas (SNG) or even Hydrogen production [59]-[62]. Furthermore, the use of oxygen in the gasification process would remove nitrogen as a diluent from the producer gas, simplifying subsequent processing. Hence, there is the potential for producing SNG and hydrogen directly from the in-situ producer gas. The ongoing field, small-scale and large-scale experiments are going to provide valuable insights into the

economic and environmental advantages of different processes and assess the feasibility of in-situ gasification compared to conventional coal energy recovery techniques. These results will help determine the viability and potential benefits of underground coal gasification.

The research purpose is to perform a critical analysis of methods for intensifying the gas generation process in the reaction channel during underground coal gasification to identify opportunities for improving the efficiency and productivity of this process. To achieve the purpose set, the following research objectives are formulated:

- study scientific publications in peer-reviewed journals to understand the main aspects and trends in the field of underground coal gasification;
- identify the main reactions occurring in the reaction channel during coal gasification, in particular, diffusion, adsorption, oxygen-carbon film formation and other processes;
- analyze the influence of temperature, pressure, composition of the blast and producer gas on the gas generation process efficiency;
- analyze the available approaches and methods, such as the use of catalysts, magnetic fields, and other technical innovations that can improve the productivity and quality of gas generation;
- evaluate the potential benefit from the implementation of gas generation intensification methods in the reaction channel during underground coal gasification.

2. Chemical mechanism of the underground coal gasification process

When heating coal to a temperature of 300-900°C, its organic mass decomposes intensively with the release of gases and tar vapors from volatile substances. As a result, up to 40-50% of coal thermal energy can be converted into gaseous and vaporous products [63]-[65]. The amount of thermal energy that can be converted depends on the method of thermal decomposition of coal and the content of volatile substances in it. After evaporation of volatile substances there remains a coke residue, which mainly consists of carbon and ash.

Gasification is a complex heterogeneous physical-chemical process occurring at high temperatures. Its main element is an interaction between the solid phase, represented by carbon, and the gas phase, which can be air, air-oxygen, steam-air, steam-oxygen, and other combinations of blast gases [66], [67]. The course of the chemical process of underground coal gasification is influenced by coal grade, its moisture and ash content, the composition of the blast, the thermal mode of gasification, the pressure in the gasifier, mining-geological and hydrogeological conditions, as well as technological schemes for preparing the gasifier [68]. When carbon (coal) interacts with blast, including oxygen and a small amount of steam, primary reactions occur with the corresponding energy values in kilojoules per mole of substance. Reactions accompanying the interaction of the carbon part of the fuel with the blast (air, oxygen, steam) can be divided into primary and secondary [69] (Fig. 1).

In accordance with [69], reactions (A1) and (A2) are the main sources of heat, which is consumed during carbon-water vapour interaction in reactions (A3) and (A4). Secondary reactions (A5-A6) proceed when gaseous products of primary reactions (A1-A4) interact with fuel carbon, oxygen, water vapor and with each other.

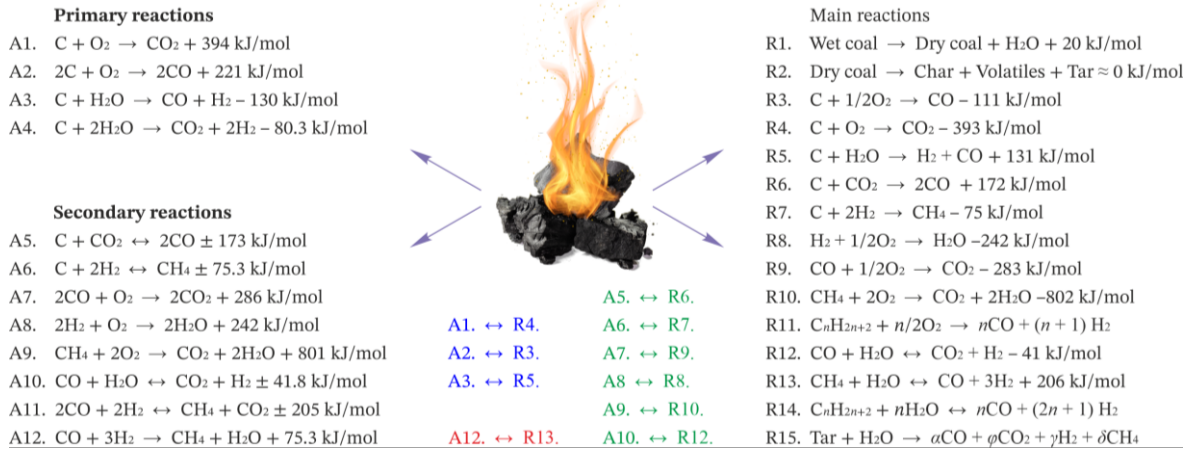


Figure 1. Main reactions involved in coal gasification processes: A1-A12 according to [69]; R1-R15 according to [70]

According to other data, only reactions (A1) and (A2) are referred to as primary, while reactions (A5) and (A7) are referred to as secondary. During high-temperature carbon combustion, in addition to the indicated primary and secondary reactions, final reactions (A3), (A4) and (A12) proceed on the outer coal surface and on the surface of pores. Under conditions of counter-diffusion of incomplete combustion products from the coal seam surface to the blast flow, processes (A7-A10) occur.

Figure 1 (R1-R15) summarizes the key chemical reactions occurring in an underground coal gasifier, as outlined by [70]. The chemical reactions involved in underground coal gasification encompass various processes. These include moisture evaporation (R1), pyrolysis (R2), char combustion reactions (R3, R4), char gasification reactions with steam (R5), carbon dioxide (R6) and hydrogen (R7). Additionally, gas-phase combustion reactions (R8-R11), water-gas shift reaction (R12) and steam-methane reforming reaction (R13) take place. Other reactions involve the reforming of higher hydrocarbons (R14) and the cracking/reforming of tar (R15).

As mentioned in [70], reactions involving other higher molecular weight hydrocarbons released during pyrolysis may be significant [71], and reactions involving nitrogen and sulphur are important for determining the minor species and contaminants present in the syngas [72]. Schematically, the processes occurring in the reaction channel can be represented as follows (Fig. 2). It has been experimentally proven that, depending on the temperature, hydrodynamic conditions and partial pressures of individual gas phase components (blast), the ratio of CO and CO₂ in the resulting gas varies over a wide range.

At the first stage, oxygen diffuses from the gas volume to the reaction coal surface, after which oxygen is adsorbed by the coal surface (the second stage). At the third stage, an intermediate oxygen-carbon film (chemical process) is formed. At the fourth stage, the intermediate oxygen-carbon film is decomposed under the action of high temperature or oxygen molecules from the gas volume. At the fifth stage, reaction products are desorbed from the coal surface.

The heat generated by combustion, according to reactions (A1) and (A2), is consumed during fuel carbon-water vapor interaction (A3) and (A4). At elevated temperatures, an increase in the yield of products formed by reactions (A3), (A6), (A10), (A11), and a decrease in others is expected. The reaction of water vapor-fuel carbon interaction (A3) is the primary reaction and has a significant influence on the gas generation process during steam-air or steam-oxygen blast. Water vapor decomposition is the main process in the production of gas using a steam-air blast.

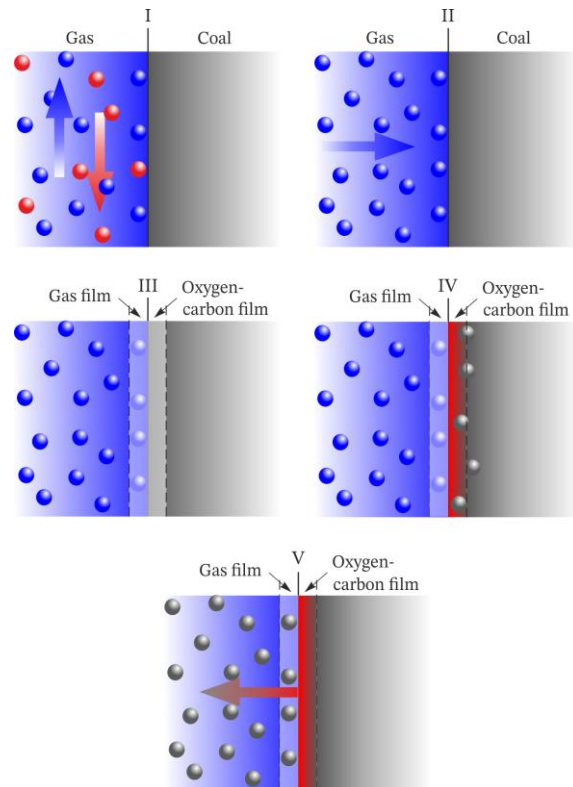


Figure 2. Schematic representation of processes in the reaction channel: I – diffusion; II – adsorption; III – oxygen-carbon film formation; IV – created film decomposition; V – desorption

Gasification of high-ash coal seams using steam-air blast produces gas with a higher CO₂ content than gasification of low-ash coal seams. Obviously, during coal gasification, the CO conversion reaction (A10) proceeds simultaneously with the process of water vapor-carbon interaction, significantly accelerated by the ash parts of the fuel. It should be noted that some brown coal types and their ash at 600-1000°C are strong catalysts for the reaction (A10).

An analysis of reactions suggests that with an increase in pressure, according to (A6), (A11), (A12), the yield of CH₄ should increase, and according to reactions (A7) – CO₂, since they all proceed with a decrease in volume. Consider the equilibrium conditions for reactions (A5), (A6) and (A10) that determine the composition of gaseous fuel, which is formed in the reaction channel of the gasifier.

Among the secondary reactions, the most important is the heterogeneous reaction (A5) that occurs when CO₂ is reduced

to CO. During the solid fuel gasification, the heterogeneous reaction of CO₂ reduction to CO has a decisive influence on the quality of the gas produced and proceeds at a significant rate at high temperatures, in particular at temperatures above 800°C. The endothermic reaction (A5) proceeds mainly in the reduction zone of the reaction channel. In this zone, there is an intensive reduction of carbon oxides using heat, which is an important element in the gas mixture formation.

Within a temperature range of 940-1000°C, the equilibrium of reactions (A5) shifts to the right. Under these conditions, the concentration of CO in the gas produced by gasification increases, since the amount of CO generated from CO₂ reduction increases. At the same time, the CO₂ content in the gas decreases, as it is consumed in the reaction to form CO. Thus, within the specified temperature range, the reaction proceeds towards an increase in the CO concentration and towards a decrease in the CO₂ content of in the resulting gas.

At a temperature in the range of 400-500°C, the reaction equilibrium (A5) shifts to the left, which means that the inverse reaction becomes more significant than in the straight direction. Gasification at these temperatures increases the amount of CO₂, because the inverse reaction prevails over the direct reaction, and some of the CO formed is converted back to CO₂. Therefore, the CO₂ concentration in the gas increases. On the other hand, the CO concentration decreases as part of the CO is converted to CO₂ during the inverse reaction. Accordingly, in the temperature range of 400-500°C, the reaction progresses in the opposite direction, leading to an increase in the CO₂ content and a decrease in the CO content in the resulting gas.

Processes (A6) and (A10) are exothermic, that is, release heat during the course of the process. As the gasification temperature increases due to these exothermic reactions, the yield of the resulting gases decreases. When the temperature increases, the reactions proceed faster, but due to their exothermic nature, they release more heat, which can influence on the equilibrium concentrations of the gases formed. A decrease in the initial gas amount can occur due to an increased rate of inverse reactions or due to the influence of the thermal effect. Consequently, with an increase in the gasification temperature of exothermic reactions, the total yield of the resulting gases may decrease.

Reactions (A6) and (A10) are exothermic, therefore, as the gasification temperature increases, the yield of the resulting gases decreases. At the same time, the reactions (A4) and (A5) occurring during gasification are highly non-isothermal, that is, they proceed with heat radiation or absorption, which affects their rate and completeness. The main problem is that during underground coal gasification, when the main thermal effect comes from the oxidation zone, the reactions do not have time to complete due to the limited size of the reduction zone with the corresponding temperature. This results in an insufficient conversion of CO₂ and H₂O to CO and H₂, as well as reduced energy efficiency of the process. These limitations have an impact on the gasification efficiency, so there is a need to develop new technologies and methods that will help improve coal gasification process and energy efficiency. Research and development of innovative approaches can help overcome the shortcomings of conventional UCG technology and ensure more efficient use of coal resources.

Reaction (A5) that reduces CO₂ to CO, proceeds with an increase in volume and pressure. With an increase in pressure in the underground gasifier, the reaction (A5) equilibrium

shifts towards the initial CO₂ product. This means that more CO₂ remains in the resulting gas, and the amount of CO produced can decrease. Reaction (A6) refers to hydrocarbon fuel gasification, in which methane (CH₄) is formed. This reaction proceeds with a decrease in volume, that is, with a decrease in the amount of gas (for example, by forming methane molecules). Higher pressure increases the equilibrium methane yield, which means that increasing the pressure helps the reaction proceed more completely and increases methane formation. Reaction (A10) corresponds to water gas (H₂O) – carbon dioxide (CO₂) reaction to form carbon monoxide (CO) and hydrogen (H₂). In this reaction, the volume of reacting substances does not change, so the composition of the equilibrium components does not depend on pressure. It is important to consider the effect of pressure on reactions when planning and optimizing gasification processes to achieve desired results and maximize the formation of combustible gases such as CH₄ and CO.

Reaction (A3) is the interconnectedness of reactions (A5) and (A10). This reaction includes the formation of CO from CO₂ (A5) and the formation of CO₂ and H₂ from H₂O (A10). Reaction (A11) is also the interconnectedness of reactions (A6) and (A5). This reaction includes the formation of CH₄ and CO₂ from 2CO and 2H₂. As pressure increases, the yield of methane (CH₄) in reactions (A6), (A11) and (A12) increases, that is, more methane is formed under these conditions. In addition, the yield of CO₂ (carbon dioxide) increases according to reaction (A7) with increasing pressure. It is important to note that all these reactions proceed with a decrease in volume, which means that the formation of reaction products is accompanied by a decrease in the volume of gases. In addition, the content of CO and H₂ is determined in the formed gases by the reactions (A2), (A3) and (A5), which proceed with an increase in volume.

The information provided and specified in this section supplements our understanding of the interconnectedness of solid fuel gasification reactions and their influence on the resulting gases and process conditions.

3. Intensification of the underground coal gasification process

The scope of experimental research on the UCG process, which has been carried out over the past decades, confirms the course of gasification described in the previous section. At the same time, it should be noted that under natural conditions, the general pattern of coal gasification process is influenced by a number of very important factors, such as various physical conditions, temperature, pressure, coal properties, the composition of the bottom and roof, the quantity and quality of blast reagents, etc. These factors can interact and have an additional influence on the reactions and the overall course of gasification [73]-[76].

Coal combustion consists of a sequence of stages, such as drying, sublimation of volatile substances, ignition and combustion of solid coke residue, which interact with each other [77]. The main stage of the combustion process is the burning of coking coal residue, namely carbon. Primary chemical reactions, the interaction of carbon with oxygen, result in the formation of carbon monoxide and carbon dioxide. This process is accompanied by secondary reduction reactions. The coal gasification process is very complex, as it combines chemical and physical processes such as gas genera-

tion, mixing and heat exchange. These processes characterize hydrodynamic, gas-dynamic and thermodynamic phenomena affecting the solid fuel gasification process [78]-[80].

When heated, some part of the coal mass organic products decomposes and is released in the form of steam and gases, which is the volatile part. Some of these volatile substances are released and burned with carbon. It should be noted that with slow heating, a successive release of volatile substances and their ignition is observed, and then combustion of the coke residue containing organic and mineral parts of the fuel, as well as ash.

Two approaches can be implemented to increase the yield of carbon monoxide. Firstly, it is possible to reduce the role of the reaction of its interaction with oxygen by increasing the blowing of the combustion face surface. This contributes to an increase in the carbon monoxide concentration in the gasification products. Secondly, it is possible to add a small amount of inhibitory additives (inhibitors) to the blast, which will reduce the activity of carbon monoxide combustion. This will lead to an increase in the rate of carbon combustion, and thus increase in the yield of carbon monoxide in gas products. Both approaches can be used to optimize the coal gasification process and increase the yield of desired gas products such as carbon monoxide.

The coal gasification process intensification requires some important conditions. To achieve the gasification efficiency, first of all, it is important to have a sufficiently developed coal mass surface, on which chemical reactions occur. In addition, a continuous supply of oxygen (blast) to the combustion face surface from blast injection well is required [29], [81], [82]. This provides the required amount of oxygen for the gasification chemical reactions. The availability of sufficient oxygen and its constant supply to the coal mass active surface are often key factors for ensuring the gasification process efficiency and intensity. These conditions help to maximize the coal mass potential for the maximum yield of gas products and ensure the efficient flow of the gas generation process.

Determining the degree of coal substance conversion during gasification is a very difficult task, since it depends on many factors and parameters. Among these parameters, the blast flow composition, the contact duration between the blast and fuel, pressure, temperature, elemental composition of coal, its pore structure, hydrogeological conditions, etc. are important. In addition, the rate of solid fuel decomposition under the influence of heat treatment is of great importance. This process also affects the degree of coal conversion and the composition of gas products formed during gasification. Given the specified factors and parameters, it is possible to obtain a more accurate and complete picture of the coal gasification process and understand which factors have the greatest influence on the degree of fuel conversion and how to achieve a more efficient and optimal result [83], [84].

The main direction of the underground gasification intensification is associated with an increase in the intensity of heterogeneous processes occurring on interface between the solid and gaseous phases. When intensifying these processes, it is necessary to carefully consider and change certain factors that have a significant impact on the rate of the process and the yield of gas generation products.



The rate of chemical reactions depends on a variety of factors, such as the nature of the interacting molecules and the process conditions. These conditions may include variations in blast flows, temperature, pressure, hydrodynamics of the process (blast pulsation and turbulence parameters), the phase interface state (coal porosity and ash content, presence of water-unrush, moisture), stability of side rocks and rock pressure, as well as peculiarities of backfilling (pressurization) of the mined-out space.

In the next subsection, possible technical methods are studied to intensify the processes of obtaining combustible gases during underground coal gasification.

3.1. Temperature increase in the reaction channel

The gasification intensity is determined by the activity of chemical reactions and directly depends on the rate of oxygen supply to the coal mass and removal of gasification products. The oxygen-coal interaction occurs rather slowly, through the diffusion process. At elevated temperatures that occur during gasification (1100-1300°C), the combustion rate is determined mainly by the oxygen diffusion intensity to the coal mass surface involved in the reactions [85]-[88]. If the rate of air movement on the combustion face surface is increased to tens of meters per second, the gasification process will occur with significant intensity. In this case, the combustion rate will also increase with increasing temperature, pressure and oxygen concentration.

It is known that an increase in the temperature of the coal seam outer surface contributes to an increase in the rate of heterogeneous processes [89]. In this case, the influence of temperature on the reaction rate is determined by the thermal effect value (q) of these reactions. The temperature in the reaction channel most strongly influences on endothermic reactions, in which, according to Le Chatelier's principle, the reaction rate increases and the time required to reach equilibrium decreases [90], [91]. However, achieving this is a difficult task, since traditional methods of underground coal gasification are based on compensation of the endothermic effect of carbon reactions with carbon dioxide, water vapor and carbon dioxide dissociation only due to the physical heat of the gas flow coming from the oxidation zone to the reduction zone.

Experience shows that under such conditions, endothermic reactions do not have time to complete due to the low coal mass temperature in the reduction zone. This results in low degree of CO₂ and H₂O conversion and, consequently, to low energy efficiency of the process. In this case, the energy efficiency is determined as the ratio of the difference in the matter flows at the inlet and outlet of the gasifier to the flow value at the inlet. In addition, CO carbon monoxide, located in the combustion face, strongly inhibits CO₂ and H₂O interaction with the coal seam, thereby complicating the gasification process.

Figure 3 shows the dependence of CO and CO₂ content in gasification products on temperature increase. In the gasification process, endothermic and endothermic reactions are non-thermal. The non-thermal nature of heterogeneous processes is manifested in the difference between the gas temperatures and the solid phase, where the gas (blast) temperature is much lower than the temperature of the coal seam walls.

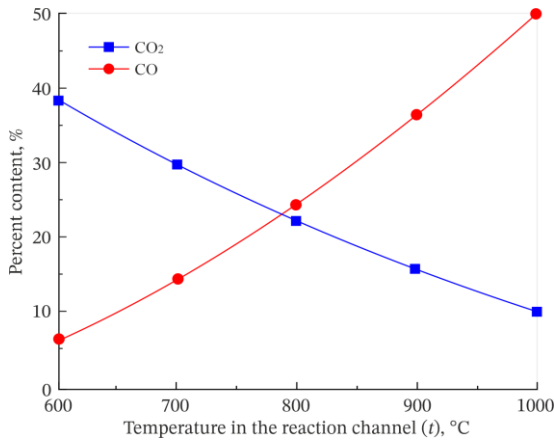


Figure 3. Temperature dependence of CO and CO₂ content in gasification products

This is a major disadvantage of traditional underground coal gasification methods, as this difference of temperatures makes it difficult to produce high-calorific synthetic gas.

With an increase in the gasification temperature, the reduction reaction (3) rate accelerates in the following ratios:

- at 850°C, if the rate is taken as a unit, then at 1000°C the reduction intensity increases by 20-22 times;
- at 1200°C, the reduction intensity increases by 150-170 times compared to 850°C;
- at 1500°C, the reduction intensity increases by 1600 times compared to 850°C.

Graphic dependence of the reaction rate (ω) on temperature (t) is presented in Figure 4.

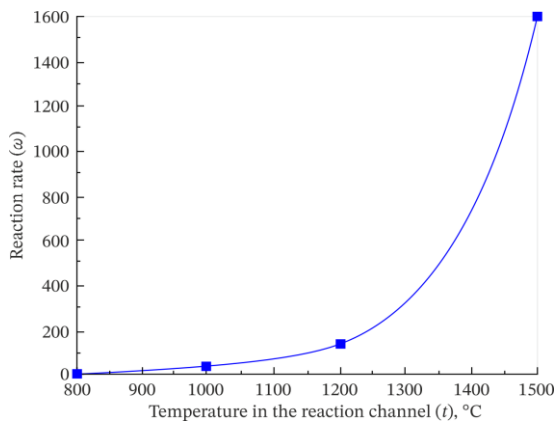


Figure 4. Dependence of CO₂ reduction reaction rate on the coal surface on temperature

The carbon dioxide reduction process depends not only on temperature, but also on the time of CO₂ contact with the coal surface. The temperature range from 850°C to 900°C requires 35-65 minutes of CO₂ contact with hot coal to set reaction equilibrium (3). At a temperature of 1000°C it takes 2-3 minutes, and at a temperature above 1000°C it takes only a few seconds.

At a temperature of 1100°C, the CO content in the gas mixture can reach 90-95% after a few seconds of carbon dioxide contact with the hot coal surface. The theoretical gas composition in air blast at a temperature of 1000-1100°C is 35-65% of CO and 0.1% of CO₂.

It is important to note that thicker coal seams can provide advantages in terms of gas production and efficiency, as thicker coal seams can distribute heat more efficiently due to their larger volume.

This can lead to more uniform temperature distribution within the seam, promoting efficient gasification reactions. Figure 5 shows how the coal seam thickness affects the producer gas calorific value.

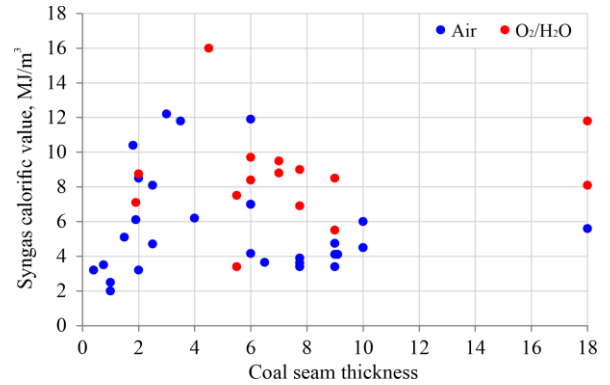


Figure 5. Influence of the coal seams thickness on the average calorific value of producer gas (data from Table 1)

From the above, it can be concluded that in order to increase the efficiency of the underground coal gasification (UCG) process, it is necessary to maintain a high temperature in the reaction channel, in particular, in the reduction zone. It is important to note that this is the temperature at the contact surface and at a certain depth inside the coal seam, since the oxidizing agent (oxygen) has the ability to penetrate into the pore space of the coal.

There are several effective ways to ensure the temperature increase in the reaction channel of the gasifier, in particular, by heating of the blast supplied to the reaction channel.

3.2. Variation of injecting gasification agents

One of the factors that increases the underground coal gasification process intensity is the combination of different types of blast supplied to the gasifier. At the same time, the presence of water vapor has a significant influence on the mechanism and rate of the carbon monoxide oxidation reaction, which limits the UCG process [92]-[95]. Therefore, the choice of the blast type (with or without the use of steam) will be determined by the ultimate goal of underground gasification, while the steam content and blast volume are selected both using analytical methods and experimentally.

Conventional UCG technology involves injecting an air blast into an underground gasifier and ensures stable production of low-calorific gas with a calorific value of up to 4.5 MJ/m³ [96]-[100]. This gas is used to generate electricity, steam and hot water for consumer needs. However, for economic reasons, low-calorific gas can only be transported over a distance of up to 30 km [20]. These limitations significantly reduce the possibilities of use of UCG technology.

Modern trends in the development of underground coal gasification technology are based on the use of various blast mixtures. These flows can be a combination of air with oxygen, steam or carbon dioxide, as well as steam-carbon or oxygen-carbon mixtures [101]-[104]. Such a variety of blast mixtures makes it possible to obtain productive producer gas with a calorific value of up to 13-15 MJ/m³, which is 3-4 times higher than the figures achieved at industrial underground gasification stations.

Figure 6 illustrates the variations in syngas composition and calorific values observed during the field test relative to the oxygen content in the injected air.

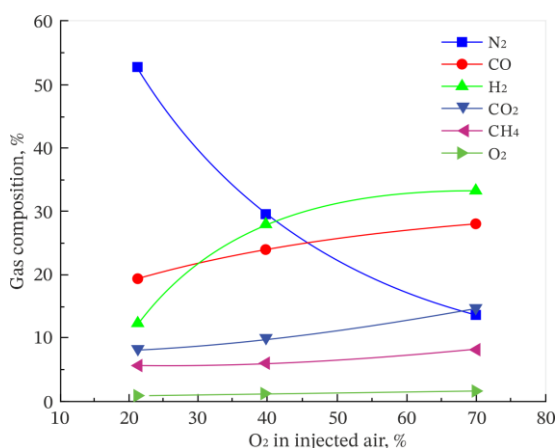


Figure 6. Influence of O₂ in injected air on produced syngas properties

The results demonstrate a substantial enhancement in gas quality that can be achieved through O₂-enriched operation during Semi-industrial tests on enhanced underground coal gasification at Zhong-Liang-Shan coal mine (China) [105].

The implementation of O₂-enriched operation in the UCG process leads to improved coal combustion. Consequently, the increased heat release enhances gasification reactions, resulting in accelerated release of volatile substances and decomposition of higher hydrocarbons into H₂ and CH₄. In the perspective UCG technology development, it will be possible to obtain producer gas from coal, the calorific value of which will be close to the calorific value of natural gas (20-30 MJ/m³). This opens up new opportunities and prospects for using gas obtained from underground coal gasification as a substitute for natural gas and its use in various industries, including electricity generation and other energy needs.

3.3. Variation of pressure in UCG reactor

Conventional underground coal gasification technology is based on thermochemical reactions occurring in a reaction channel under a pressure of 0.2-0.3 MPa [84]. However, the intensity of heterogeneous processes increases when a higher pressure is used in the underground gasifier [106]-[110]. Thus, by increasing the pressure in the gas gasifier, more efficient and productive gasification processes can be achieved.

Excessive pressure in a pressurized underground gasifier, together with the presence of reservoir water in the coal from which hydrogen is formed, creates favorable conditions for obtaining a natural gas substitute, namely methane, by reactions (5) and (6). This leads to an increase in methane yield, which has a positive effect on the consumer properties of gas produced as a result of underground coal gasification. In this process, the pressure in the underground gasifier can be maintained at a sufficiently high level, but it is important not to exceed the hydrostatic pressure in order to avoid hydropneumatic rock explosion and gas emission to the surface. Compliance with safety measures makes it possible to ensure efficient and safe operation of an underground gasifier for producing methane from coal.

An increase in pressure creates a higher gas density, which, in turn, improves the conditions for effective gas-solid contact with coal particles. This enhanced contact leads to a notable increase in the gasification reaction rate [111].

Figure 7 displays the outcomes of the field tests conducted to examine the impact of operational pressure on the enhanced UCG process, with a primary focus on assessing the producer gas quality [105].

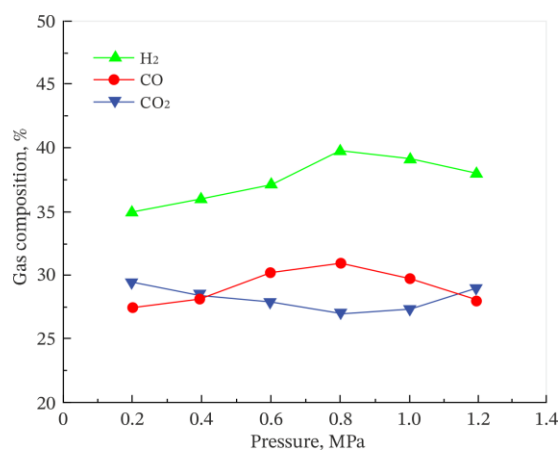


Figure 7. Influence of pressure on produced syngas composition

The field test reveals that when cyclically changing the pressure, there is a significant reduction in heat loss. Moreover, the heat rate and gasification rate are approximately 1.2 and 1.6 times higher, respectively, compared to operating under fixed pressure conditions.

Consequently, the calorific value of the syngas experiences a remarkable increase of more than 25% compared to the fixed pressure operation. An increase in pressure in an underground gasifier contributes to an increase in methane formation (direct carbon hydrogenation and carbon monoxide reduction), and both of these reactions occur with the release of heat. This results in an increase in CH₄ and H₂O content, and at the same time to a decrease in CO and H₂ concentration in accordance with the reactions (5) and (6).

At medium depths, coal seams can be gasified at a pressure of 2-3 MPa without the risk of hydraulic fracturing of the rock stratum and underground gasifier depressurization. Using steam-oxygen blast at this pressure, it is possible to obtain raw gas with a calorific value in the range of 9.0-10.0 MJ/m³. After purification from CO₂, the producer gas can have a calorific value in the range of 12.5-15.0 MJ/m³. Using such pressure during gasification, it is possible to obtain an effective result and ensure a high quality of the resulting gas, which can be used for various energy purposes.

An increase in pressure by 10 times (from 0.3 to 3.0 MPa) makes it possible to reduce the well diameter by half while saving injection blast costs. This optimization makes it possible to achieve efficient system operation and reduce the costs for constructing and maintaining wells. In addition, maintaining a pressure exceeding the pressure of underground water allows for the underground coal gasification process in the formed cavity and almost completely prevents the leakage of gases from the gasifier. This provides a high level of safety and control over the process, which is very important in the aspect of dealing with gas resources and preventing unwanted gas emissions into the environment. Such engineering solutions facilitate the efficient and safe use of underground coal gasification technology.

3.4. The use of pulsating blast

One of the methods for intensifying an underground gasifier operation can be the use of pulsating blast with alternating cycles. Pulsating blast can be organized by setting special pulsators on the air supply and gas outlet pipelines, which provide a discontinuous structure of gas-dynamic pulses. The main peculiarity of such a pulse is significant amplitude of pressure and flow rate. The influence of each

subsequent pulse on the gas-generating system should occur before the end of the transient process in the gas-generating system caused by the previous pulse [63], [112]-[115].

Carbon in the seam interacts with CO₂, H₂O, O₂ and H₂ both on the outer contour surface and on the inner surface of macro- and micropores. The depth to which gaseous substances penetrate into the coal seam pores depends on the ratio of the rates of chemical reaction and gas transfer to the reacting surface. That is, in addition to the chemical reaction rate, another important factor is the rate of movement of gaseous substances in the seam pores.

Numerous experimental studies have observed that ash in coal has a negative effect on gasification process. The resulting melted ash crust on the combustible coal outer surface prevents the contact of gaseous reagents with solid coal, complicating the gasification process [116]-[119]. In order to eliminate the negative ash crust impact and regulate the resulting gas quality, pulsating blast with elements for turbulating gas-blast flows is used. This method makes the gasification process more efficient, ensuring the production of high-calorific gas with less influence of the ash crust on the process. After all, the use of pulsating turbulent blast leads to the emergence of a pulsating shock-like rate, which contributes to effective transportation of gases to the coal mass surface [120], [121]. This helps to remove unwanted crust from the coal layer surface, reduce the hydraulic resistance coefficient and equalize the gas flow rate over the entire channel cross-section.

Hydrodynamic processes occurring in an underground gasifier during pulsating blast can be described using a system of quasilinear hyperbolic Equations (7)-(9) [122]:

$$\frac{\partial}{\partial t}(\rho w) + \frac{\partial}{\partial x}(p + \rho w^2) + \frac{\lambda}{2D} \rho w / w' = 0; \tag{7}$$

$$p = \rho c^2; \tag{8}$$

$$0 < x < 1; t > 0, \tag{9}$$

where:

x – coordinate along the reaction channel axis;

t – time;

p, w, ρ – average cross-sectional pressure, velocity, and gas density;

D – channel diameter;

λ – friction coefficient;

c – sound velocity.

Figure 8 shows a graph of the pulsating mode of coal seam gasification.

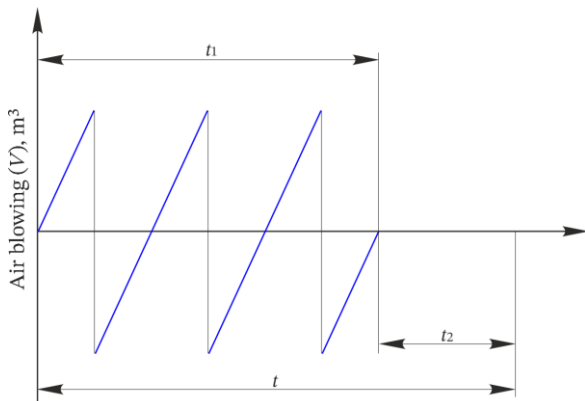


Figure 8. Graph of the pulsating mode of coal seam gasification

An underground gasifier is first supplied with a small amount of blast (V), such as air, steam or carbon dioxide, to heat the coal seam. The pulsation curve over time (t) consists of several harmonic sinusoidal components. The blast process is paused for a period of time (t_2), and then the cycle ($t = t_1 + t_2$) is repeated again, etc. Obviously, in this case, the gas quality will depend on the ratio of phases in time, that is, the greater the rarefaction phase (t_2), the more calorific the producer gas will be, so it is necessary to apply changes in gas-blast flow rates.

The pulsating turbulent flow causes a shock-like change in the rate of gaseous reagents, which will blow ash away from the reduction reaction surface. This will increase the gas release intensity, since the coal mass reaction surface will become accessible to blast reagents (oxygen, steam, carbon dioxide). In addition, pulsating blast loosens the coal mass surface and leads to a significant increase in gas release. At the same time, the reactions of the seam carbon interaction with gases (CO₂, H₂O, O₂) occur not only on the outer contour surface, but also on the inner surface of macro- and microfractures. As a result of the coal mass thermal destruction (pyrolysis) and under the influence of hydrostatic pressure, as well as the release of volatile substances, the fracturing and porosity of coal increases over time. After that, after a certain period of time, a pulsating blast can be supplied and the gasification process can be carried out on a fundamentally new basis – by gasification not only on the combustion face surface, but also in newly formed microfractures.

In this way, the use of pulsating blast facilitates the opening of the reaction surface for access of gaseous substances, resulting in an increase in the gasification process intensity. In addition, pulsating turbulent blast ensures coal mass surface loosening, resulting in even greater gas release intensification. In such a case, a continuous turbulent method of supplying blast, for example, using blowers or exhaust smoke exhausters may be useful. This will ensure stable gasification process intensity and maximize the potential of the pulsating blast efficiency.

3.5. Reversing of the blast flows

Results of bench studies on the mechanism, kinetics and thermodynamics of reactions (1)-(6) show that the organization of the coal gasification process with high intensity and high energy efficiency is possible by increasing the coal mass temperature in the reduction zone through the use of reversing blast flows.

Reversing the direction of gas flows reflects a periodic change in the supply and withdrawal directions. This interaction of flows makes it possible to transform the oxidation zone into a reduction zone and vice versa [123]-[127]. When, due to the thermal effects of endothermic reactions (2)-(4), the temperature in the reduction zone is reduced to 600-800°C, the gas-blast flow is reversed. As a result, the cooled reduction zone becomes oxidation one (it is again heated), and the heated oxidation zone again becomes a reduction one.

The temperature T of the considered reduction zone section can be calculated using the Formula:

$$T = \frac{\gamma \lambda_0 t - kWq}{\gamma \lambda}, \tag{10}$$

where:

γ – coal density;

λ_0 – heat capacity of coal;

T_0 – the reacting gas initial temperature;
 k – gasification rate constant in the kinetic domain;
 C – the concentration of the gaseous reagent in the calculated volume of the gasified coal layer;
 q – the reaction thermal effect;
 λ – specific heat capacity of coal.

By reversing the direction of gas flows, it is possible to increase the gas flow rate in the gasification channel, which in turn contributes to the efficient removal of carbon monoxide (CO) from the reaction surface [128]-[131]. This leads to an increase in the rate of reactions (2)-(4), since more favorable conditions are created. In the case when the gas flow moves at a high speed and is characterized by significant non-thermal properties, that is, with a low supply temperature, the underground gasification productivity may decrease due to the rapid cooling of the reaction surface. However, this disadvantage is easily compensated for by preheating the supply at the surface by using the physical heat of the source gases from the underground gasifier. It is likely that at a high total flow rate, CO concentration on the reaction channel wall will be so low that the inhibitory effect of CO can be neglected under this process conditions.

An analysis of the thermodynamic properties of the reactions occurring in the reduction zone shows that at elevated temperatures (1000-1300°C) that occur in the reduction zone when the direction of gas-dynamic flows changes, carbon dioxide (CO₂) and water vapor (H₂O) are almost completely converted into carbon monoxide (CO) and hydrogen (H₂). However, in underground gasifiers, the degree of conversion of gaseous reagents (CO₂ and H₂O) is generally limited to 30%. The volumetric content of carbon dioxide converted can be calculated by the Formula (11):

$$\mu = \left(PW - P_{CO_2} (1 + \psi \rho) \right) \frac{1}{\rho}, \tag{11}$$

where:

P – gas mixture pressure;
 W – initial CO₂ concentration in the gas flow;
 P_{CO_2} – the partial CO₂ pressure in the gas phase volume;
 ψ – the concentration of the equilibrium gas mixture components given the change in the gas phase volume in partial pressure units;
 ρ – the volume fraction of CO₂ conversion in equilibrium condition per combustion face unit area.

The CO₂ dissociation degree (4) is calculated by the pressure change in the system:

$$d = \frac{2(P_2 - P_1)}{P_1}, \tag{12}$$

where:

P_1 and P_2 – initial and final pressure in the system.

Figure 9 presents graphs of changes in the temperature distribution parameters of the combustion face before and after the mode of reversing [132]. As research results show, gasification process destabilization occurs when the oxidation zone is more than 50% ahead of the reduction zone. This results in the transfer of thermal energy from thermochemical reactions to the gasifier reduction zone [133]. The implementation of reversing levels the combustion face and activates gasification processes, creating conditions for balancing the gasification process.

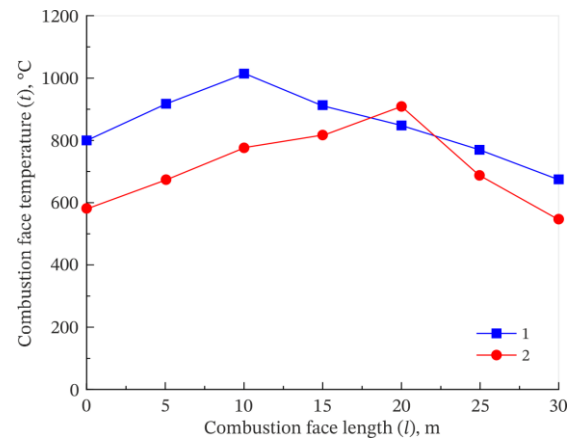


Figure 9. *Combustion face temperature distribution parameters: 1 – before reversing; 2 – after reversing*

The implementation of CO₂ and H₂O reduction reactions under conditions close to thermodynamic equilibrium has the potential to significantly enhance the gasification process, which in turn will lead to a 4-fold increase in the gasifier productivity. In addition, this will increase the thermal yield of gas up to 8 times compared to standard conditions. Intensification of reactions (2)-(4) with a high conversion degree is possible through additional heat supply to the reduction zone in the underground gasifier, achieved by combining different gasification zones. The use of this approach is relevant when, as a result of depletion of natural gas and oil reserves, the need arises to use solid fuel for all branches of inorganic and organic synthesis.

In view of the above, it can be argued that underground coal gasification process under natural conditions can be organized at a completely new technological level. To achieve this, it is necessary to change periodically (at intervals of up to several days) the direction of the blast and gas supply movement. This achieves two important results: firstly, a high temperature is maintained in the reduction zone and this creates favorable physical-chemical conditions for the underground gasification process, and secondly, the uniformity of the combustion front and homogeneity of the seam outgassing are ensured.

3.6. Injection backfilling of mined-out space

Ecological disposal of hazardous types of waste is an upcoming task of the future. For the coal industry, the issue of environmental protection is of particular importance because mining increases negative changes in the environment. They are largely manifested through: land alienation; waste rock dumping; slurry pond construction; the negative impact of mining operations on the earth's surface [134]-[138].

Underground coal gasification usually involves caving of the roof rock upper layers into the mined-out space. The size of the caving zone of the upper roof part depends on the characteristics of the coal seam and the rocks above it. In addition to the rock mass pressure, the caving intensity is affected by the high temperature accompanying the underground gasification process [139]. As a result of the penetration of heated gases into fissures, the roof rocks are heated, expanded and destroyed [140]-[143]. Collapsed rocks change the gasification channel geometry along the combustion face, and also have a negative impact on heterogeneous processes in the reaction channel. As a result of the chaotic caving of the upper rocks, additional pathways

are formed for gases that evade contact with the coal seam surface. Expansion of gasification channels due to these flows results in reduced efficiency of the underground gasification process [144]-[147].

When organizing the technological process of coal seam gasification with the backfilling of the mined-out space, constant contact of the gas-blast flows with the coal mass reaction surface is ensured and the necessary thermal conditions are provided for the gas-formation reactions to occur. This, in turn, increases the release of combustible gases, which contributes to the UCG process intensification [148]. Thus, the operating efficiency of underground gasifiers mainly depends on the intensification of the processes occurring in the reaction channel of the oxidation and reduction zone, as well as on the presence or absence of equally important mining-geological, hydrogeological and technical factors. Thermal energy released during the gas generation process is partially transported with it and can be utilized in gas outlet wells or on the surface using special heat exchangers [149], [150]. At the same time, a significant part of the heat remains in the mined-out space of the underground gasifier (accumulated in the caved roof rocks) and extends to the surrounding mass. Thus, the use of backfilling the mined-out space with clay, ash and slag waste or coal beneficiation tailings can change such a situation for the better.

As noted in [148], when the pressure on the combustion face increases from 1.0 to 3.0 MPa, the losses of the air mixture and gas increase and amount to 7.3-24.6% with a combustion channel length of 30 m. These parameters are sharply reduced when fractured roof rocks are pressurized with an injection backfill mixture. Thus, when the pressure in the gasifier changes by 1.0-3.0 MPa, the losses reach 2.5-11.6% (Fig. 10).

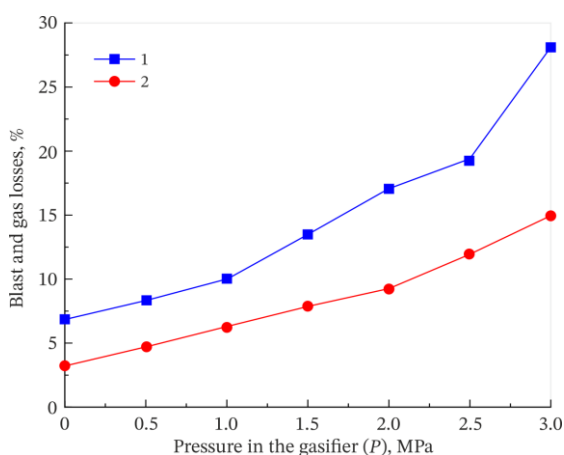


Figure 10. Dependence of air mixture and gas losses at different pressure values: 1 – without injection backfilling of the coal-overlying formation; 2 – with injection backfilling of the coal-overlying formation

It is impossible to completely avoid blast and gas losses in the underground gasifier due to rock heterogeneity and the change in its continuity in time and space during the coal seam outgassing [151]. Thus, reducing the fracturing of the stratified rock stratum by injecting clay solutions into the shear zone will reduce the migration of high-temperature UCG products into the rocks hosting the underground gasifier.

The use of an injection backfilling in the underground gasifier structure will reduce the loss of blast, gases and condensate in the underground part from 4 to 8%, as well as reduce the earth's surface subsidence above the underground

gasifier outgassed space by 70-76% of the coal seam thickness [152], [153]. The conduct of the gasification process at high pressure from 1 to 6 MPa, without rock stratum ruptures, at small and medium depths of gasified coal seam occurrence (70-350 m) ensure the process controllability [154]. In turn, pressurization of the gasifier underground part will allow concentrating the leakage of UCG products, thereby ensuring the effectiveness of “washing out” when post-cleaning the gasifier after the cessation of coal gasification work.

3.7. Use of catalysts

The use of catalysts to intensify the gasification process is one of the methods for increasing the efficiency and control over this process [155]-[157]. Catalysts are substances that accelerate chemical reactions without entering the reaction product and without changing their chemical structure. In the context of coal gasification, catalysts can influence the reaction process by increasing the reaction rate of converting coal fuel into gases. This can lead to an increase in gas fuel yield [158]. Accordingly, during gasification they can serve to accelerate chemical reactions, reduce the active energy of reaction activation, and improve the selectivity of desired product formation. A central objectives is to increase the yield of gases (in particular, methane) while minimizing solid waste formation [159], [160].

There are various types of catalysts, including heterogeneous (where the catalyst and reagents are in different phases, such as a metal catalyst in a solid state and gaseous reagents) and homogeneous (where the catalyst is dissolved in the reaction medium) [161]. Catalysts can change the reaction mechanism by accelerating certain steps or reducing activation energy. They can activate the surfaces of reagents, facilitating their reaction and the formation of desired products. Catalysts can be specialized for specific reactions, such as gas conversion to syngas (H_2 and CO) or to methane (CH_4) [162]. They can also affect reactions of removing sulphur and other pollutants. The author in [163] aimed to determine the manufacturability of this process when using iron (Fe) as a catalyst (Fig. 11).

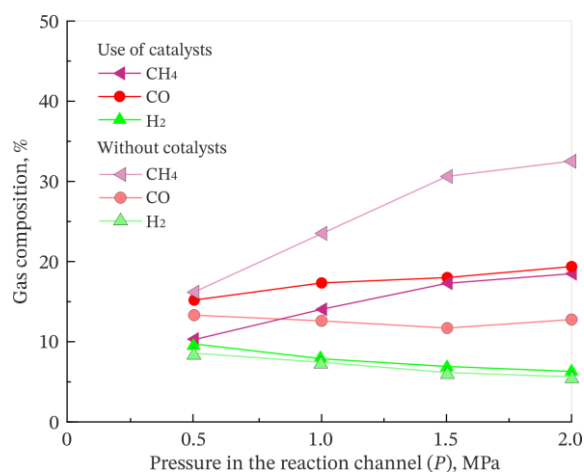


Figure 11. Graph of changes in the composition of combustible gases when the pressure changes in the gasifier

The use of catalysts requires studying their influence on various process parameters, such as temperature, pressure, coal fuel composition, etc. They can help improve the gasification process efficiency, reduce pollutant emissions and reduce the amount of waste generated. The use of cata-

lysts for coal gasification is an active research area, since the efficiency of catalytic processes can significantly improve the stability and productivity of gasifiers.

In general, the use of catalysts in coal gasification identifies the potential for process improvement, but requires detailed research, adaptation of catalysts to specific conditions, and implementation in practice to achieve significant positive results.

3.8. Use of magnetic fields

The use of magnetic fields for intensifying the coal gasification process is one of the specific technologies that can influence various gasification aspects, such as reaction rate, reducing the temperature threshold of reactions, reducing the amount of raw materials required to obtain a certain amount of gas, etc. It is worth noting, however, that this technology requires more detailed research and validation [164]-[166].

It is known that magnetic fields can contribute to the increase of mass transfer in the reaction medium, which can lead to an increase in the rate of chemical reactions. In addition, the reaction temperature threshold is reduced, allowing less energy to be used for gasification. Moreover, magnetic fields can affect molecular bonds in hydrocarbon compounds, increasing their splitting during gasification [167]-[169]. It should be noted that this intensification method helps to reduce the formation of solid residue (tar) as a result of gasification reactions, which in turn can lead to an increase in the yield of syngas from coal gasification.

The paper [170] studies one of the possible methods to intensify the process of underground coal gasification due to the influence of magnetic fields on the blast supplied into the gasifier gasification channel. Research test conducted on a bench setup confirms the effectiveness of blast activation in a magnetic field by creating a magnetic field inhomogeneity by placing permanent magnets and a discrete solid magnetized phase in a special device. Based on the conducted research, it has been revealed that the carbon participation share in the gasification process varies depending not only on the magnetic field strength, but also on the gasification temperature. The obtained results of the change in the carbon participation share depending on the temperature variation in the gasification zone with the blast magnetization of 500 E are shown in Figure 12.

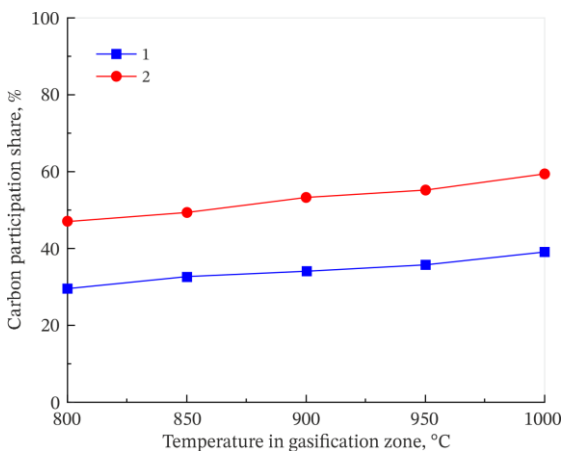


Figure 12. Carbon participation share in solid fuel gasification at a temperature change in the gasification zone and magnetic treatment of the blast mixtures (at magnetic field strength of 500 E): 1 – the blast mixtures not treated with a magnetic field; 2 – the blast mixtures treated with a magnetic field

It should be emphasized that research in this direction is still ongoing, and to date the practical implementation of this technology may be limited. Achieving positive results requires a deep understanding of the physical-chemical aspects of the interaction between magnetic fields and coal gasification process. Furthermore, continuous collaboration among interdisciplinary teams of scientists and engineers is essential to overcome the current limitations and advance the practical implementation of this technology.

3.9. Gasifier design optimization

By optimizing the design and structure of the gasifier, it is possible to provide better heat and mass exchange, which will improve gasification results. A series of experimental studies involving the gasification process modeling presented in research [171]-[175] has helped substantiate the effect of technological and technical innovations in gasifier designs on the parameters of the coal seam gasification process.

The developed and tested bench setup for modeling underground coal gasification process has design and technical solutions aimed at supplying blast immediately to the combustion face to ensure intensification of the gasification process of thin coal seams, taking into account specific mining-geological conditions. Consequently, three possible gasifier designs are analyzed as for the gasification process efficiency [176]:

- without a flexible pipelines for directing blast to the reaction channel face (design I);
- with flexible pipeline for directing blast through perforated nozzles to the reaction channel face (design II);
- with flexible pipelines and activator in the reaction channel, with blast direction towards the reaction channel face (design III).

Figure 13 represents the results of research series.

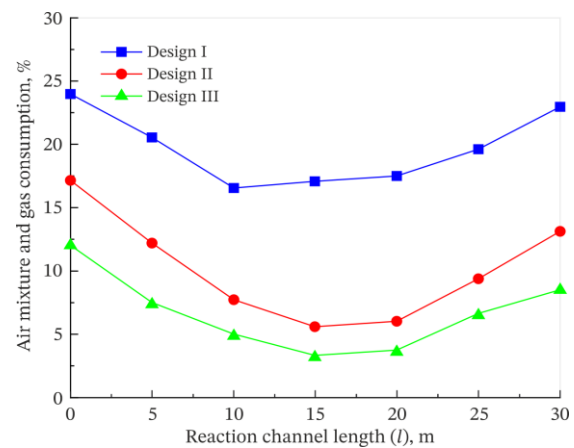


Figure 13. Dependences of the losses of blast, producer gas and coal on the gasifier design

If a blast flows from the side of the mass, then the release of gas into the gasified space is stimulated somehow by the large volumes of this space, deformation, and rock caving into the gasification zone, as well as the available excessive pressure in it. Coal is better gasified through the blast injection well than through the gas-outlet well. Thus, this is a point with a higher concentration of coal losses over the area and thickness of the seam. Moreover, this is conditioned not only by the unilateral direction of the blast flow, but also by the fact that the advance of reaction zones of gasification along the channel length is accompanied by the deteriorating aerodynamic conditions. Finally, there will be a moment when there is no sufficient length for the reaction zones [177].

Involvement in gasification of off-balance and abandoned reserves of thin and very thin coal seams using designs and technological schemes of gasifiers with controlled flexible pipelines, perforated nozzles and activators provides adaptive activation of oxidation and reduction processes with a controlled transition zone between them in the gasifier reaction channel [178]. Control and controllability of the gasifier along the reaction channel length is provided by a dosed separate supply of the blast flow to the combustion face in each active zone of the reaction channel. This results in the reduced losses of blast, producer gas and solid fuel; this also ensures uniform advance of the active zones of the reaction channel combustion face during coal seam gasification.

Implementation of the above mentioned technological solutions in the gasifier design and technological solutions for coal seam gasification will significantly reduce the time spent on forming the reaction channel and beginning of the mine gasifier operation in active mode of coal gasification.

3.10. Control of water-inrush into underground gasifier

Effective implementation of underground coal gasification process is ensured if the coal seam is surrounded by impermeable side rocks, which prevent gas leakage, reduce pressure and thermal energy losses [179], [180]. Therefore, to ensure the underground gasifier pressurization, it is important to have plastic clays or dense water-saturated rocks in the geological section of the coal seam bottom and roof [181]. Water-inrush has a significant impact on the underground gasification process. Excess moisture has a negative effect by slowing down chemical reactions, especially those that absorb heat (2)-(4), which can even stop gasification. Lack of moisture can cause undesirable temperature conditions, melting of the ash part of the coal seam, formation of slag and gas flow disruption. On the other hand, a moderate amount of moisture absorbs heat during gasification, improving the energy efficiency of the process by enriching the gas with hydrogen and carbon monoxide. To reduce the negative moisture impact on the underground gasification process, a temporary decrease in the water level can be used [182]-[184].

One of the key factors in determining the suitability of coal seams for gasification is the permeability ratio between the coal mass and the adjacent rocks, rather than simply the permeability of the coal seam itself [185]-[188].

The paper [189] discusses the concept of water-inrush rate in coal gasification. This rate indicates how quickly ground water enters the gasification area around coal seams. The rate is influenced by rock permeability and water pressure. The paper describes experiments conducted in China to understand the impact of water-inrush on gasification. When water-inrush decreases, gas quality improves. If water-inrush is too high, gas quality decreases due to cooling effects. The relationship between the calorific value of gas and water-inrush rate is shown in Figure 14.

Strategies for controlling water-inrush are to increase pressure and maintain high temperatures in the gasification channel. Experimental results show that appropriate water-inrush rate enhances gas quality, but excessive inflow can reduce gas quality at the initial stage of gas production. Figure 15 illustrates how the water-inrush rate affects the gas composition. As water-inrush decreases, the quality of the resulting gas improves markedly. Conversely, excessive water-inrush poses a risk of lowering gas quality due to associated cooling effects.

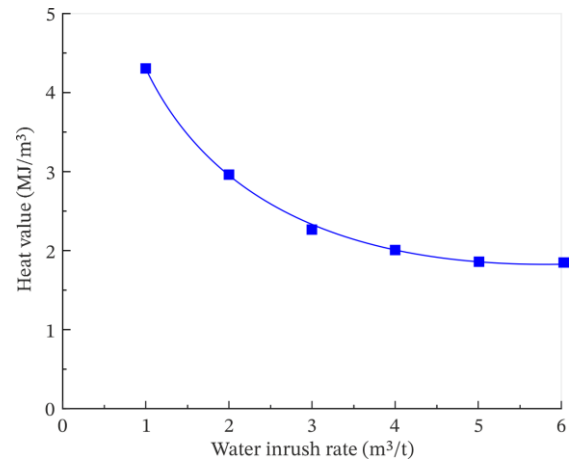


Figure 14. The relationship between the calorific value of gas and water-inrush rate

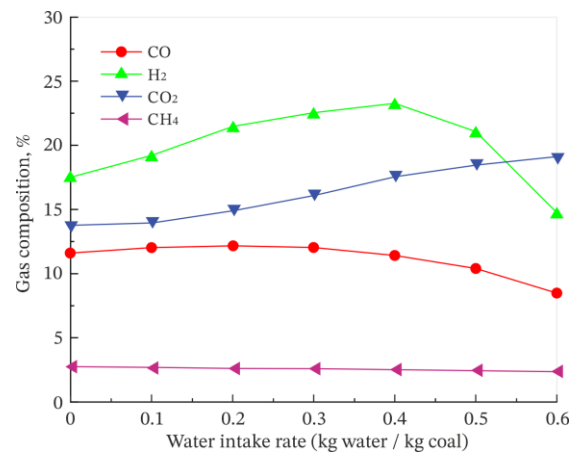


Figure 15. The influence of water-inrush rate on the gas composition

To address this challenge, two strategies are proposed: elevating air pressure and maintaining elevated temperatures inside the gasification channel. The experimental findings emphasize that a suitable water-inrush rate improves gas quality. However, water-inrush overabundance can lead to a decrease in gas quality during the initial gas generation stage.

4. Discussion and future perspectives

In the age of constant search for more efficient and sustainable energy sources, underground coal gasification is coming to the fore as one of the alternative technologies for producing gaseous fuel. The process of underground coal gasification involves a complex system of chemical reactions and physical processes that ensure the conversion of coal raw materials into producer gas.

When analyzing the current state of underground coal gasification technology, it is clear that this industry is beyond laboratory research. However, the current state of the technology reflects a certain pause in development due to high technical complexity and environmental aspects.

The presented chemical mechanism of the underground gasification process identifies key reactions and dependences that play a role in the production of producer gas. However, an important factor is to increase the quantity and quality of gas generation. To achieve this purpose, several directions for process intensification have been analyzed. In particular, the influence of increasing temperature in the reaction channel has been studied. Higher temperatures increase the reaction rate, thereby increasing gas release. But this approach

requires careful control, since during underground gasification it is important to maintain a balance between physical rates and kinetics of chemical reactions.

The choice of blast reagents and the mechanism for their supply into the reaction channel are important. Variation in the composition of gasification reagents can affect reaction kinetics and gas release, but this approach also poses the difficulty of maintaining consistent injection quality. By using controlled moving injection points, O₂-enriched operation and varying operating pressure, advanced UCG operation techniques can demonstrate enhanced gas flow control, resulting in significantly improved UCG productivity, achieving higher heat efficiency, and producing higher-quality syngas.

Changing the pressure in the reactor can affect reaction equilibrium and coal consumption, but this also poses technical difficulties to safely controlling pressure.

The use of pulsating blast, reversing of blast flows, the use of catalysts, exposure to magnetic fields – each of these methods helps to intensify gas generation, but their effectiveness may depend on specific geological conditions and a specific technological scheme.

An important aspect is the gasifier design optimization, which can contribute to a more efficient course of reactions and intensified gas generation.

Water-inrush has a significant impact on the underground coal gasification process. The presence of water in the reaction channel influences chemical reactions and thermal effects. Maintaining a stable water-inrush level helps to improve the gas quality, increasing its energy efficiency. Otherwise, excessive water-inrush may result in deterioration of gas quality due to the cooling effect. It is recommended to maintain elevated air pressure and temperature in the reaction channel to control water-inrush and achieve optimal gas quality.

Variation and combination of different intensification methods can lead to improved efficiency and economic feasibility of underground coal gasification. The prospects for further research in the direction of intensifying gas generation in the reaction channel during underground coal gasification are quite extensive and important for the development of this technology.

The use of computer models and numerical methods will allow for a detailed study of the interaction of various factors in the underground coal gasification process. Optimization of parameters such as temperature, pressure, composition of blast reagents, etc., helps to increase the thermochemical process productivity. Additional laboratory and field experiments will confirm the modeling results and investigate the influence of various factors on the gasification process. This can help identify the most effective and economically feasible methods.

Further development of the technology should take environmental aspects into account. Research into the impact of underground coal gasification process on the environment, as well as the development of methods for reducing negative impacts will be important tasks.

An important aspect of further research is cooperation between different branches of science. By combining the efforts of chemists, engineers, geologists, ecologists and other specialists, it is possible to find the most optimal solutions and achieve scientific breakthroughs. The development of new intensification methods should be accompanied by their implementation in real practice. To achieve this, it is important to develop pilot projects and case studies to test the effectiveness and economic feasibility.

In general, further research in the direction of intensifying gas formation in the reaction channel during underground coal gasification is extremely important for improving and promoting this technology, thereby making a significant contribution to the development of a modern energy sector and reducing dependence on traditional energy sources.

5. Conclusions

The presented chemical mechanism of the underground gasification process identifies key reactions and dependences that play a role in the gas production. However, an important factor is to increase the quantity and quality of gas generation. To achieve this purpose, several directions for process intensification have been analyzed.

A critical analysis of research results related to chemical reactions, temperature dependence, and the influence of various factors on the content and composition of gases in gasification products is presented. The experimental research results indicate the influence of pressure, increasing oxygen concentration and magnetic field on the producer gas properties. The dependences of air mixture and gas losses on various pressure parameters and the use of an injection backfilling have also been revealed. The influence of temperature changes in the gasification zone and magnetic processing of the air supply mixture on the carbon content in the gas, as well as the participation of carbon in the gasification process, are emphasized. The influence of the gasifier design on the losses of air mixture, producer gas and coal has been determined. In addition, the influence of water-inrush in the gasifier on the producer gas composition has been analyzed.

The specified results indicate important aspects and relationships in the coal gasification process and can serve as a basis for further research and optimization of the intensification process. Systematized results contribute to a better understanding of coal gasification mechanisms and can be useful for the further development of underground coal gasification technology.

Acknowledgements

The presented results have been obtained within the framework of the research work GP-512 “Co-gasification of carbon-containing raw materials during ultrathin coal seams gasification with a focus on hydrogen production”, state registration No. 0123U100985 funded by the Ministry of Education and Science of Ukraine. The study was carried out as part of the project “Belt and Road Initiative Center for Chinese-European studies (BRICCES)” and funded by the Guangdong University of Petrochemical Technology. The author expresses gratitude to the heading editor, as well as anonymous reviewers for useful suggestions and recommendations taken into consideration during revision.

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Критичний огляд методів інтенсифікації процесу газоутворення в реакційному каналі при підземній газифікації вугілля (ПГВ)

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Мета. Критичний аналіз наявних методів інтенсифікації процесу газоутворення в реакційному каналі для покращення ефективності та економічної доцільності технології при газифікації вугільних пластів. В роботі детально розглянуті аспекти хімізму і технічних параметрів даного процесу з метою з'ясування можливостей підвищення ефективності та продуктивності.

Методика. Оглядове дослідження ґрунтується на підході, який включає аналіз розвитку підземної газифікації вугілля, дослідження хімічних реакцій у реакційному каналі, вивчення впливу факторів, таких як температура, тиск, склад дуття та генераторного газу тощо. Систематизація даних експериментальних досліджень проведена на основі глибокого аналізу наукових робіт опублікованих в рецензованих виданнях.

Результати. Представлені систематизовані результати досліджень дев'яти основних методів інтенсифікації процесу газоутворення в реакційному каналі при підземній газифікації вугілля. Виявлені фактори, які мають найбільший вплив на газоутворення в реакційному каналі.

Наукова новизна. Результати досліджень вказують на можливості покращення процесу підземної газифікації вугілля. Виявлені взаємозв'язки між різними факторами сприяють більш глибокому розумінню хімічних та фізичних процесів у реакційному каналі.

Практична значимість. Отримані результати можуть бути використані для оптимізації процесу підземної газифікації вугілля, підвищення продуктивності та якості газоутворення. Зазначені результати можуть слугувати основою для подальших наукових досліджень та інноваційних розробок отримання альтернативного виду палива.

Ключові слова: підземна газифікація вугілля, газоутворення, інтенсифікація, хімічні реакції, ефективність, оптимізація