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Use of magnetic fields for intensification of coal gasification process

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Abstract

Underground coal gasification is an alternative method for mining coal from thin and ultra-thin seams, which enables conversion of solid fossil fuels into combustible gases at the site of coal occurrence. At the same time, in the case when the coal seam thickness is critically small for the effective course of thermochemical reactions, it is necessary to intensify the gasification process. This paper studies one of the possible methods to intensify the process of underground coal gasification due to the influence of magnetic fields on the injected blast supplied into the gas generator gasification channel. Research tests conducted on a bench setup confirm the effectiveness of injected blast activation in a magnetic field by creating magnetic field inhomogeneity by placing permanent magnets and a discrete solid magnetized phase in a special device. For the first time, the dependence of changing growth of carbon participation during the solid fuel gasification process on changing magnetic field strength in the range of 0-600 E has been determined. It has been proven that the injected blast magnetization can significantly intensify the underground gasification process by increasing the carbon participation share in the fuel, which may be of practical importance for increasing the yield of combustible components.

Keywords:
underground coal gasification; intensification; coal; magnetic fields; carbon

1. Introduction

The shortage and rising cost of fossil fuels, the environmental problems of traditional mining practice and use of coal, the historical perspective of depletion of readily available fuel resources mark the signs of a global energy crisis, the negative consequences of which accumulate over time (**Armaroli and Balzani, 2007; Puchkov, 2015; Bekbassarov et al., 2015; Koval et al., 2021**). Production technologies and opportunities for the development of unconventional hydrocarbon resources became more actual from year to year (**Zhaslan et al., 2022; Dairbekova et al., 2021**). This is conditioned by the constantly growing needs of mankind for energy resources with a forced transition to mining of increasingly poor and hard-to-reach deposits (**Ranjith et al., 2017; Zhang et al., 2021**). The current situation requires extraordinary efforts of science and technology in the search for fundamentally new technologies for the mining of fossil fuels, which make it possible to include them in the industrial use of deposits, the mining of which by conventional methods is currently unprofitable.

In the absence of sufficient oil and natural gas reserves in Ukraine (**Mikhlin, 1997**) and Europe (**Halstead et al., 2019; Gençşü et al., 2020**), solid fossil fuels are the main source of energy and chemical raw materials. Reserves of bituminous and brown coal, which are sufficient to meet the energy needs in the current century, are the most important natural resource for most countries (**Heinberg 2010; Bondarenko 2010; Bondarenko 2015**). However, the deterioration of the mining-geological conditions of underground coal mining (low-thickness seams, great depths, increased rock pressure,

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dangerous gas-dynamic phenomena) limits production volumes, increases the cost of coal and affects the growth of miners' injuries (**Nosal et al., 2021; Rylnikova and Mitishova, 2021**). The high cost of transporting natural minerals also has a significant impact on pricing and logistical difficulties (**Abdullayev et al., 2016; Zhussupov et al., 2018; Bakyt et al., 2020; Abdullayev et al., 2021**).

The bulk of coal mined today has an increased ash content and contains a number of harmful impurities. Harmful impurities create unfavorable conditions for the use of minerals or have a harmful effect on the environment, including living organisms (**Pavlychenko and Kovalenko, 2013; Lewińska and Dyczko, 2016 Buzylo et al., 2018; Bexeitova et al., 2018**). A significant part of the coal reserves belongs to the off-balance category, which excludes their economically feasible mining using traditional technologies (**Bondarenko et al., 2007**). Under these conditions, the optimization of mining coal deposits using various technologies, including by underground thermochemical processing of coal seams, in particular, underground coal gasification (UCG), acquires significant prospects.

It should be noted that the world's first experimental research on the underground gasification of coal seams was carried out in Ukraine at the Lysychansk station "PidzemHaz" (1933). For several decades, there have been three underground coal gasification (UCG) stations in Ukraine – Lysychansk, Horlivka and Synelnykove. This made it possible to accumulate significant technological experience of performing work and prove not only the reliability of the underground coal gasification technology, but also the need to move from the stage of experimental work to the creation of industrial underground gasification stations. In 1963, extensive development of gas fields in Western Siberia began, and the cheap gas coming to the European part of the former USSR has led to the loss of industrial interest in UCG (some underground gasification stations were maintained for some time as research-and-development units) (**Bhutto et al., 2013; Derbin et al., 2015; Green, 2018**).

The current level of scientific-technical progress has provided a new stage in the UCG technology development. This became possible due to the solution of a number of technical problems: directional drilling of boreholes in rocks and coal seams (**Dreus et al., 2016; Panova et al., 2021; Ihnatov, 2021**); combinations of oxidizer feeding (**Lozynskyi et al., 2016**); controlled retraction and injection point along the working zone of the borehole (**Kasani and Chalaturnyk, 2017**); reverse technologies (**Falshtyns'kyy et al., 2013**); backfilling of goaf (**Petlovanyi et al., 2021**); new types of underground gas generators (**Svetkina et al., 2010**); reducing the risk of environmental problems both on the surface (**Gorova et al., 2013; Popovych and Voloshchyshyn, 2019; Bosak et al., 2020**) and underground (**Karabyn et al., 2019; Baimukhanbetova et al., 2020; Kobylkin et al., 2020**). An important achievement in the technologies of recent years is the increase in the calorific value of the resulting producer gas up to 11-12 MJ/m^3, which has significantly increased the UCG technology competitiveness (at stations of the 60s of the XX century, this indicator was in the range of 2.8–4 MJ/m^3) (**Wiatowski et al., 2015; Laciak et al., 2016**).

Simultaneously, technologies for the integrated use of gasification products have been developed: cogeneration energy generation systems, including the inclusion of producer gas into the combined cycle of power plants; conversion of producer gas into liquid hydrocarbons using "gas to liquid" (GTL) technology – into synthetic oil and, based on it, into synthetic motor fuel, oils and other chemical raw materials (**Brand et al., 2019; Kurbaniyazov, 2021**). The most successful pilot projects have proven the possibility of high capital investment efficiency (the experience of Australia (**Perkins et al., 2016**), China (**Xie et al., 2020**), Republic of South Africa (**Pershad et al., 2018**)) and have led to the development of numerous projects for new UCG stations. Special conditions of the occurrence of coal seams require new methods for mining the reserves. Underground gasification is one of the effective methods. Due to the difficulties in providing Ukraine with natural gas, this problem is of particular relevance (**Bazaluk et al., 2022**).

To date, a large number of technological solutions related to the intensification of the UCG process have been scientifically proven, tested and patented (**Bazaluk et al., 2021**). Most technological solutions are based on the study of the gasification process chemical mechanism and, based on it, the identification of gaps that can be compensated by physical, chemical or technological action (**Wang et al., 2009; Shafirovich and Varna, 2009**). Based on the principles of chemical mechanisms of the underground gasification process, the UCG process intensification is possible in the following ways: temperature increase in the gasification channel (**Hu et al., 2021**); reversal of the injected blast current (**Cui et al., 2014**); combining of the injected blast (**Huang et al., 2021**); increasing the pressure in the underground gas generator (**Zagorščak et al., 2020; Kapusta et al., 2020**); application of pulsating injected blast (**Debelle et al., 1992; Baskanbayeva et al., 2021**); control of water inflow into the underground gas generator (**Rudakov et al., 2012; De and Prabu, 2017**); injection backfilling of the goaf (**Bondarenko et al., 2009**); improvement of resource recovery rate for UCG through the gasifier size management (**Li et al., 2020**) and the use of magnetic fields (**Kolokolov et al., 2000**). The use of magnetic fields is possible mainly in two fundamentally different directions, namely: electromagnetic heating of solid fuel and the impact on the injected blast by electromagnetic fields (**Kolokolov et al., 2000**).

In view of the fact that different methods have different effects on the gasification process efficiency and on the actual production costs of the resulting producer gas, it is proposed to study the intensification method, which is the most expedient in terms of cost. Thus, as a priority method of intensifying the underground coal gasification process, it is proposed to focus on the use of magnetic fields, namely, the impact on the injected blast by electromagnetic fields.

In addition to the above methods of intensifying the gasification process of low-thickness seams, the manufacturability of the process can also be improved by simultaneously putting into operation multilevel gas generators. The essence of this technology is that the developed technological schemes for mining coal seams, in which disjunctive and plicative geological disturbances are concentrated, make it possible to gasify coal using vertically inclined-horizontal boreholes due to the transition of the geological disturbance outside the zone of increased rock pressure influence (**Petlovanyi et al., 2019**). This method of borehole tracing makes it possible to maintain injection and gas production boreholes in the rocks with minimal deformations (**Małkowski et al., 2013; Falshtynskyi et al., 2016**). The coal gasification stability during the transition of low-amplitude geological disturbance is ensured by sufficient sealing of the underground gas generator and preliminary backfilling of the mined-out space in the zone of increased rock fracturing (**Falshtynskyi et al., 2014**).

To substantiate the method of intensifying the impact on the injected blast by electromagnetic fields, it is necessary to conduct research tests to study the activation process of the molecules in the injected blast steam-air mixture by creating an inhomogeneous magnetic field. At the same time, it is first necessary to analyze how the steam-air mixture molecules are excited, as well as how the water and oxygen molecules are activated.

2. Theoretical Background

2.1. *The mechanism of excitation of the molecules in an injected blast steam-air mixture*

In the process of underground and/or surface coal gasification, the most promising in terms of calorific value and the possibility of producing synthetic products is the gas obtained by using steam-air injected blast. When hot coal interacts with water vapor, the following **Reactions 1** and **2** take place:

$$C + H_2O = CO + H_2 - 132650 \text{ kJ/kmol} \quad (1)$$

$$C + 2H_2O = CO_2 + 2H_2 - 89664 \text{ kJ/kmol} \quad (2)$$

They are accompanied by heat absorption, that is, coal cooling. To maintain the seam burning, the injected blast must contain oxygen, usually oxygen from the air. In this case, the following **Reactions 3** and **4** occur:

$$C + O_2 = CO_2 + 395660 \text{ kJ/kmol} \quad (3)$$

$$2C + O_2 = 2CO + 218860 \text{ kJ/kmol} \quad (4)$$

When comparing **Reactions 1** and **2**, it is seen that an increase in the water vapor amount in the injected blast can lead to an increased yield of a non-combustible component of the producer gas CO_2. To avoid this with the same amount of steam-air injected blast, it is necessary to pre-activate water molecules. To intensify the heat transfer process according to **Reactions 3** and **4**, it is necessary to activate air oxygen molecules.

The traditional method of such activation is heating the injected blast which is supplied into the gasification zone. However, to obtain a noticeable effect, as practice shows, the injected blast must be heated up to 800-1000°C and higher, which creates additional technological difficulties and is accompanied by energy costs (**Saik and Berdnyk, 2022**).

In addition to the traditional method, from the gas chemistry practice, the method of activation of gases by a glow discharge is known (**Guang-Liang et al., 2005; Chen et al., 2006**). The glow discharge itself is one of the types of stationary independent electric discharge in gases, which is formed, as a rule, at low gas pressure and low current. Due to the hydrogen activation in a glow discharge, the complete dissociation of hydrogen molecules into atoms already occurs at a temperature of 800°C. Whereas with traditional methods of heating hydrogen to this temperature, only 10-8% of gas molecules dissociate, and at 2600°C, only 50% of hydrogen molecules dissociate.

Compared to the expensive glow discharge method, there is a cheaper and technically simpler method for activating the molecules of the injected blast steam-air mixture, which involves the imposition of a magnetic field on the injected blast mixture. Its essence is that the molecules of the steam-air mixture become unstable due to the reorientation of the spins binding electrons in inhomogeneous magnetic fields. Since the precession frequency of electrons (protons) is different, the imposition of an external inhomogeneous magnetic field, the gradient of which can be traced at distances equal to the molecular size, leads to a reorientation of the spins of some electrons (protons) without others. In this case, the whole molecule passes from a stable (singlet) state into a triplet state with a higher internal energy. Such transitions in quantum physics are called intercombination transitions.

2.2. *Activation of water and oxygen molecules in an external magnetic field*

It is known that any electron in a molecule has an orbital magnetic moment (due to movement around the atom) and a spin moment (due to rotation around its own axis). According to the *Pauli exclusion principle*, no more than two electrons with oppositely directed spins can be in one orbital (**Meetham, 1988; Psarras, 2014**). The presence of such electrons (which are called paired) determines the stability of the bond (see **Figure 1, I**).

When superimposing an external magnetic field, the spin of one of the electrons is reoriented (see **Figure 1, II**). In this case, there is a splitting of the initial energy level into 3,5,7… states, differing in the energy of states (see **Figure 2**). According to the Pauli exclusion principle, when the spin of one of the paired electrons is reoriented, it must move to another orbital, that is, a state with a higher energy must be realized (see **Figure 1, III, IV**) and the bond stability will be violated.

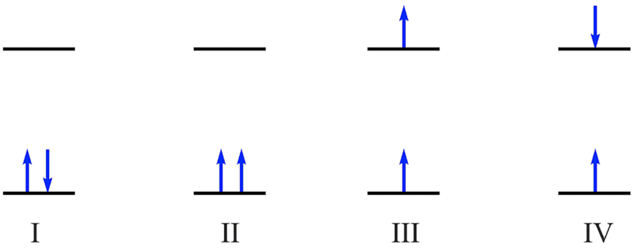

Figure 1: Singlet and triplet state of electrons: I – singlet ground state; II – triplet ground state; III – excited triplet state; IV – excited singlet state.

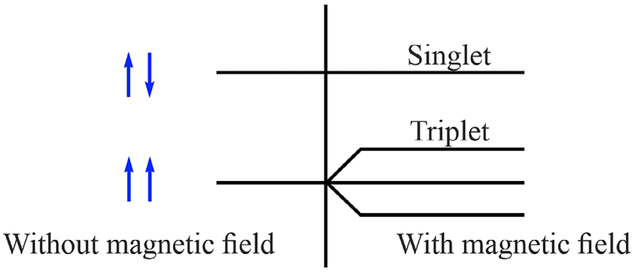

Figure 2: Effect of a magnetic field on a spin

In the H_2O molecule, the interaction of H^+ ions with an oxygen ion is performed through *p*-electrons, which bind the indicated ions to each other. In this case, the spins of each of the *p*-electrons are opposite to the spins of the H^+ ion with which the *p*-electron interacts. One bound pair *p*-electro-ion H^+ has antiparallel magnetic moments with the second similar pair (see **Figure 3, I**). This position characterizes the stable singlet state of the water molecule, which is generally diamagnetic.

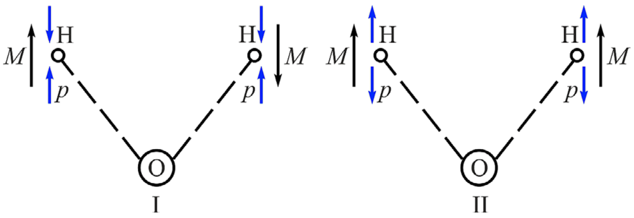

Figure 3: Water molecule state: I – singlet state; II – triplet state

When the spin of one of the *p*-electrons is reoriented (due to the intercombination transition in an external inhomogeneous magnetic field), the spin of the H^+ ion (proton) associated with it is reoriented. The water molecule transforms into a triplet state (see **Figure 3, II**) and from diamagnetic becomes paramagnetic, since the magnetic moment of one H^+ -*p*-electron pair becomes parallel to the magnetic moment of the second similar pair.

For a water molecule in the singlet state, any proton can bind two molecules in a chain, that is, it forms a hydrogen bond, the energy of which is less than the valence one, but greater than Van der Waals forces and is about 4 kcal/mol. In the triplet state (see **Figure 2**), the probability of hydrogen bond formation is reduced by half, as it can be formed only by the proton whose spin is antiparallel to the H^+ spin of the triplet-excited H_2O molecule.

The rupture of hydrogen bonds (in our case, a decrease in their concentration) is accompanied by an increase in the internal water energy, which leads to an additional increase in its chemical activity. When water evaporates, the hydrogen bonds between its molecules are completely ruptured, but as the water vapor cools (fog formation), the hydrogen bonds in the water droplets are restored. There will be half as many such bonds for water that has been treated in a magnetic field. Accordingly, the coal gasification process using a steam-air injected blast activated in a magnetic field will be more efficient.

Thus, the mechanism of water activation in magnetic fields is based on two processes:

- the transition of H_2O molecules from the singlet to the triplet state, and
- reducing the probability of the formation of hydrogen bonds between water molecules.

2.3. Activation of air oxygen molecules in an inhomogeneous magnetic field

The mechanism of oxygen activation is conditioned by the intercombination transitions of electron ions that bind two atoms into an O_2 molecule. Moreover, these transitions lead to the transition of binding electrons to antibonding orbitals. It is known that the O_2 molecule is stable when the number of binding electrons in it is greater than the number of antibonding ones. Binding electrons (paired) electrons have differently directed spins. When imposing an external magnetic field and, as a result of this reorientation of the spin of one of the paired electrons, the latter moves to an antibonding orbital, and the O_2 molecule becomes unstable.

According to modern concepts, the oxygen molecule has not one bond formed by two pairs of electrons, but one simple bond surrounded by two three-electron bonds. Typically, the strength of a three-electron bond is no more than half the strength of a single bond. If the bonds in the O_2 molecule were simply formed, then the total bond strength of the atoms in the molecule would be higher than a simple double bond. However, the imposition of an external magnetic field leads to a reorientation of the spins not only of the binding (paired) electrons, but also of the electrons forming a three-electron bond, that is, unpaired electrons. Due to this, the energy of binding the atoms in a molecule becomes less than the total binding energy.

Thus, the mechanism of oxygen molecule excitation in an external magnetic field includes two processes: the transition of one of the binding electrons to an antibonding orbital and the violation of the three-electron bond strength caused by the spin reorientation of at least one of the unbound electrons. By reducing the stability of oxygen molecules and their more rapid decomposition into atoms, the chemical activity of such an important injected blast component as oxygen, the presence of which is necessary for coal gasification, increases.

2.4. Activation of oxygen and water molecules by contacting with the dye surfaces excited by light to fluorescence

It should be noted that in the practice of chemical technologies, there is a known method of activating oxygen molecules by exposing the dye surfaces excited by light to fluorescence. After such an interaction, oxygen is transformed into such a state that it enters into chemical reactions that occur with ordinary (unactivated) oxygen. The fact that the oxygen molecule in the ground state has paramagnetic properties (at T=20°, æ= $104.4\cdot10^{-6}$) stimulates research in the direction of injected blast activation using magnetic fields. The activity provided in this way to O_2 and H_2O molecules in inhomogeneous magnetic fields is maintained, as experience shows, for 1-3 hours. Let us study the mechanism of such an aftereffect.

It is known that the phosphorescence and fluorescence phenomena of some substances are caused by the transition of part of their molecules to the triplet state. This has been directly confirmed by determining the magnetic susceptibility of an illuminated and unilluminated phosphorescent sample: the illuminated sample acquires paramagnetic properties due to the fact that the orientation of the spins of paired electrons becomes identical. The most sensitive method for detecting the triplet state of molecules of phosphorescent substances is the method of electronic paramagnetic resonance. The glow of liquids or solid bodies during fluorescence or phosphorescence phenomena continues for a long time after the source of excitation has ceased its operation. The mechanism of the consequences in the case of excitation of the injected blast steam-air mixture molecules using magnetic fields is similar to the mechanism of the fluorescence and phosphorescence phenomena. Its essence is in the following.

When exposed to an inhomogeneous magnetic field, the H_2O and O_2 molecules pass into the triplet state. At the same time, they find themselves, as it were, in an energy trap: on the one hand, they cannot release (emit) the excitation energy and pass into the ground – singlet state, since such a transition is prohibited by the selection rules. They can change their energy state, passing into a singlet state of the highest energy level, and then, radiating energy, return to the ground state, since the energy of collisions between molecules is insufficient for such transitions. Also, the molecules cannot transfer the electronic excitation energy to other surrounding molecules quickly enough by means of a non-radiative transition. This is due to the fact that each molecule, regardless of whether it is in a singlet or triplet state, is an isolated system with certain bonds, conditioned by the spin-spin relationship between nuclei, electron-nuclear interactions and spin-orbital electron interactions. When one of these bonds is destroyed (as a result of external interaction), a corresponding "adjustment" of other bonds occurs in the molecule. The process of vibrational damping of excitation occurs with the loss of small portions of energy, which is not enough to rearrange all the bonds in the excited molecule. The experience of studying the fluorescence and phosphorescence phenomena shows that damping of excitation due to vibrational motions of molecules and their collisions is not effective enough. When the energy level is split into sublevels, the process of transition to the initial energy level is long.

When exposed to an inhomogeneous magnetic field, the H_2O and O_2 molecules are "frozen" in the triplet state. However, since transitions between the triplet and singlet states are not strictly forbidden (weakly allowed), the excited state slowly transforms into the initial state. For gases, such transitions are a longer process than for liquids and solids, as with the fluorescence and phosphorescence phenomena (the absence of crystal lattices and, as a consequence, large distances between molecules affect). This will make it possible to conduct the underground coal gasification process with the injected blast activation in the magnetic fields on the surface and its further supply to the required depth of the gasification zone.

3. Materials and Methods

For the practical implementation of the excitation of molecules to activate the injected blast, it is necessary to determine what characteristics of the external magnetic field should be provided for the activation of water and oxygen molecules by the method of intercombination transitions.

It is known from literary sources that in the case of a hydrogen atom having one electron, its *s*-, *p*-, *d*- and *f*- states differ in the orbital magnetic moment value of any one energy level (for example, at $n=4$) and have the same value of energy or, as they say, do not split. However, in a magnetic field with strength of ~8000 oersted, splitting of the *s*-, *p*-, *d*- and *f*- states occurs, which is displayed in the spectrum of atomic hydrogen in the form of additional spectral lines. In addition, each *p*-, *d*- or *f*- energy sublevel splits into 3, 5, or 7 states differing in energy, respectively. As can be seen, in the case of a

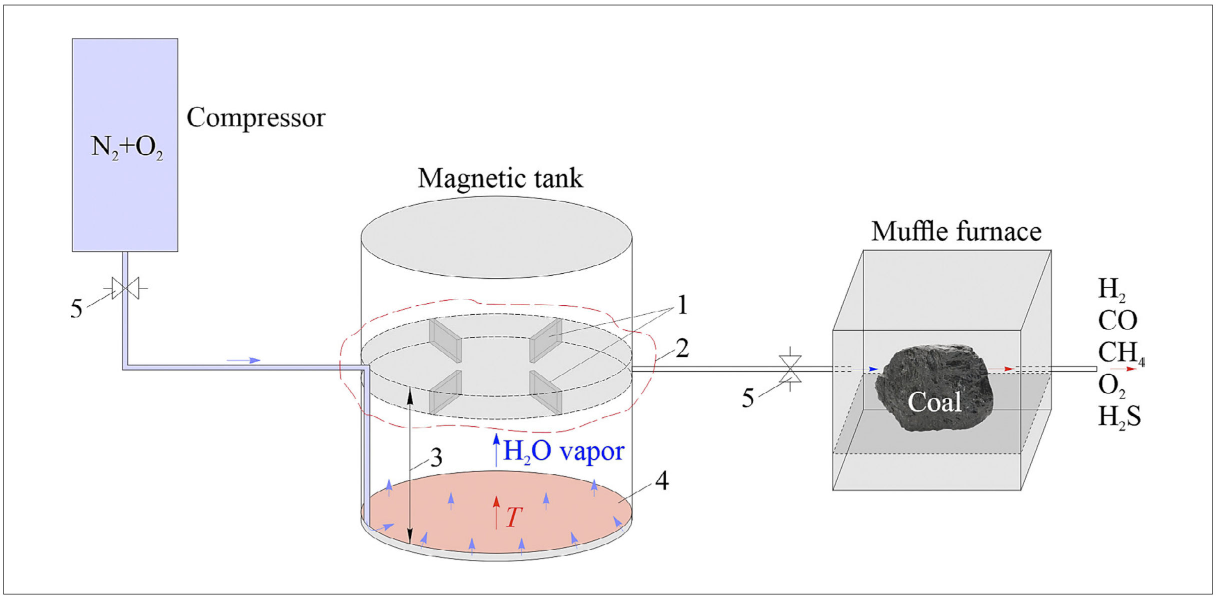

Figure 4: General view of a "magnetic tank" type device with a magnetic system inserted in it: 1 – removable magnetic system; 2 – ferrite-barium tiles of permanent magnets; 3 – the tank section filled with a 10-15 mm magnetite iron ore and filled with water; 4 – electric furnace; 5 – adjusting valve.

Table 1: Proximate and ultimate analysis of coal

Proximate analysis					**Ultimate analysis**				**Combustion heat (Q^r), MJ/kg**	**Coal density (γ), g/cm^3**
W^r, %	**W^a, %**	**A^c, %**	**S^d, %**	**V^{daf}, %**	**C^{daf}, %**	**H^{daf}, %**	**O^{daf}, %**	**Nr, %**		
1.7	2.2	38.2	1.3	37.0	80.7	6.3	6.8	4.9	24.6	1.45

hydrogen atom, sufficiently powerful magnetic fields are required to ensure such changes. There are two options for solving the problem of transferring molecules to an active state using magnetic fields.

1) The first option is in the use of alternating magnetic fields, the frequency of which provides resonance phenomena in the molecule. For example, the spin-spin interaction (J, Hz) between nuclei, which in the nuclear magnetic resonance method leads to splitting known as "fine structure", and in most cases has a value from 20 to 40 Hz. At the same time, relatively small energies correspond to the magnetic field acting on one nucleus as a result of the presence and certain orientation of another nucleus.

2) The second approach to solving the problem of the activation of molecules in magnetic fields is to use inhomogeneous magnetic fields such that their inhomogeneity should be traced at the level of molecular sizes. Such an inhomogeneity of the magnetic field (at the level of the molecular size) should provide, in particular, a displacement in the electron density zone towards a lower magnetic field strength in the zone of their interaction.

Let us study the possibility of practical realization of the method for activating the injected blast steam-air mixture molecules by creating an inhomogeneous magnetic field.

The development of various designs of devices for activating the injected blast steam-air mixture using inhomogeneous magnetic fields is based on two important provisions, which are as follows:

1) For the magnetic fields created with the help of permanent magnets, the maximum strength gradient is observed at the phase interface "ferromagnet – external environment". Therefore, with periodic contact of water and oxygen molecules with the phase interface, the corresponding inhomogeneity of the external magnetic field will be provided.

2) A significant magnetic field inhomogeneity can be created by mutually perpendicular orientation of the similar magnetic poles of permanent magnets.

It is possible to assess the influence of magnetic fields directly on the injected blast by methods of spectroscopy, electron and nuclear paramagnetic resonance, electrochemical potentials, etc. Our task is to activate the injected blast to increase the efficiency of the coal gasification process, which is conditioned by the use of indirect methods, where the research subject is a change in the technological characteristics of the gasification process as a result of the impact of magnetic fields on the injected blast. In order to assess the injected blast activation impact on the coal gasification process, a device has been created in this study, in which the necessary parameters of the magnetic field are implemented.

In order to implement the injected blast preparation technology using inhomogeneous magnetic fields, a "magnetic tank" type device is used to intensify the coal gasification process. The device is a metal tank suitable for working under pressure. The general schematic view of a "magnetic tank" type device is shown in **Figure 4**.

The inner tank capacity is divided into sections using plates with ferrite-barium tiles of permanent magnets of 250 E strength. The gaps between the sections are filled with particles of magnetite iron ore with a size of 10-15 mm. This arrangement makes it possible to maintain the ore particles in a magnetized state. At the tank bottom, there is a spiral tube with holes through which the air is injected from the compressor. The container is filled with water at the level of the upper edge of the plates with magnetic tiles. Thus, the injected blast air is blown through water, and in this case it contacts with the surfaces of magnetic tiles, as well as the surfaces of magnetized particles of magnetite iron ore, which are in the gaps between the tiles. The container is placed on an electric furnace to create conditions for boiling the water.

The "magnetic tank" type device has been tested during the process of coal burning. The proximate and ultimate analysis of coal is given in **Table 1**.

All Ukrainian coal of a gas rank, even within the same coal seam layer, have specific proximate and ultimate analysis (**Koveria et al., 2019; Fedorov, et al., 2020; Antoshchenko et al., 2021**). In this case, an experimental study must be conducted for every possible condition.

The gasification process is modeled as follows. From the mobile compressor, the air is injected into a magnetic tank located on the electric furnace. The magnetic system for the tank is removable. This makes it possible to create a steam-air mixture both without the use of magnetic fields and with their use, receiving an activated injected blast.

The magnetic tank through the inlet tube is connected to the compressor and tightly closed with a lid. Through the outlet tube from the magnetic tank, a steam-air mixture is supplied into the muffle furnace, which contains a coal sample for burning. From the side of the injected blast supply, the muffle furnace is tightly closed. To regulate the pressure of the steam-air mixture, on the fitting of the injected blast supply into the furnace, an adjusting valve is set. The coal sample is in a metal substrate and heated in the furnace to the temperature of coal burning. From the opposite side of the injected blast supply into the furnace, a hole is made to remove gaseous coal combustion products. The hole has an outlet tube with the ability to measure the temperature of the gases emerging from it and the analysis of their composition.

Using the constant values obtained as a result of the experiments, the following process characteristics have been determined:

- pressure of the air injected into the tank from the compressor (according to the compressor pressure gauge readings);
- pressure in the "magnetic tank" when the valve of the injected blast supply into the furnace is turned off (according to the readings of the pressure gauge on the tank);
- the amount of water in the "magnetic tank" – 1.2 l;
- the temperature of the water poured into the "magnetic tank" is 90°.

After setting the fixed values, a pre-weighed coal sample with dimensions of 15×15×15 cm on a metal substrate is placed into a heated muffle furnace. The dimensions of the muffle furnace were 50×50×50 cm. The sample is introduced into the furnace from the side of the outlet of combustion products (see **Figure 4**) through a door in the furnace wall, which is then hermetically closed. After that, the valve for supplying steam-air injected blast to the furnace is turned on and at the same time a stopwatch is turned on. During the experiment, the pressure gauge readings on the tank and the time of supplying the injected blast onto the sample are recorded. Then the coal sample is taken out of the furnace and weighed. By analogy with the experimental determination of coal ash content, the value of the ratio of the sample residue weight to its initial weight is determined. Such experiments have been conducted with and without a magnetic system inserted into the tank, with the same time interval for the sample to stay in the furnace and under the conditions of injected blast equal intensity. Separate samples of coal are used for experimental studies at a variable temperature regime from 800 to 1000°C (800, 850, 900, 950 and 1000°C) and magnetic field strength from 0 to 500 E (0, 50, 100, 200, 300, 400, 500 and 600 E). In total, 40 experimental procedures have been performed for coal with the similar proximate and ultimate composition.

4. Results and Discussion

The first experiments conducted on the above-described device model provided encouraging results and, at the same time, revealed the need for further improvement of the device design. When water is heated and water vapor is formed, the hydrogen bonds between water molecules are broken. According to the calculations, a significant amount of energy, about 4-6 kcal/mol, is spent on this. When boiling water comes into contact with the surfaces of magnets and ore (at the "solid-liquid" phase interface), they are in the zone of an inhomogeneous magnetic field, the gradient of which is traced at the level of molecular sizes. The polarity with the same name of the magnetic poles in the opposite currents of the fields creates the same field inhomogeneity in the volume. The magnetic field inhomogeneity provides intercombination transitions of the spins of H^+ ions and unseparated electron pairs of H_2O molecules. This sharply reduces the concentration of hydrogen bonds in water and, accordingly, reduces the energy costs for water evaporation. Due to intercombination transitions, water molecules pass into the triplet (excited) state. Through evaporation and when air is blown through the water, such activated molecules are removed into water vapor. The resulting steam-air mixture is used as an injected blast component in the coal gasification process.

The results of comparing the experiments on the relative value of the unburned coal residue have revealed that the preparation of the injected blast using a magnetic system makes it possible to increase the coal gasification rate. When activating the injected blast using magnetic fields, the relative value of the unburned coal mass decreases by 12-17% compared to the unburned mass in the absence of a magnetic system in the tank for preparing of air for blasting.

Experimental studies have confirmed the possibility of activating the injected blast in a magnetic field by creating a magnetic field inhomogeneity by placing permanent magnets and a solid discrete magnetized phase in the "magnetic tank" device. It has been determined that for the optimal creation of this heterogeneity, the following magnetic field parameters should be implemented in the design of the "magnetic tank" device:

- strength 10-40 kA/m;
- induction in a magnetized material (permanent magnet plates) 0.18-0.4 T;
- magnetic flux 80-100 A/m;
- strength gradient 30-100 a/cm.

Experimental studies have shown that the magnetic treatment of the injected blast significantly increases the carbon participation share in coal during gasification (see **Figure 5**). In this case, with a temperature change in the gasification channel, the carbon share increases.

In the absence of injected blast magnetization at a temperature in the muffle furnace of 900ºC, the carbon participation share is 34%, and when using a magnetic device with a magnetic field strength of 50 E, the carbon participation shares increase by 5%. It should be noted that the maximum carbon share value, namely 53%, is observed at a magnetic field strength of 600 E, while the difference between the magnetic field strength of 500 E is only 1%. Thus, it can be assumed that a further increase in the magnetic field strength will not lead to a more intense carbon participation share in the process of solid fuel gasification.

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 injected blast magnetization of 500 E are shown in **Figure 6**.

Analyzing the data shown in **Figure 5** and **Figure 6**, it follows that the injected blast magnetization makes it possible to significantly intensify the underground gasification process due to an increase in the carbon share in the fuel, which can be of practical importance for increasing the yield of combustible components. Thus, this research in practical terms confirms the hypothesis expressed by prof. Kolokolov O.V. at the end of the XIX century about the possibility of using magnetic fields to intensify the gasification process. Moreover, it appears that the impact on the injected blast by electromagnetic fields will have more significant effects than the direct impact on solid fuel by electromagnetic heating, given the cost of electricity (**Kolokolov et al., 2000**). In the experimental studies conducted under the supervision of prof. Kolokolov O.V., to study the impact of injected blast magnetization, coal with a particle size of 0.1-6.0 mm and a total weight of 100 g was placed in an electrically heated quartz tube and heated to 800°C. At the same time, a magnetized air blast was fed into special holes. The injected blast rate was 2 m/s, and the magnetic field strength reached a maximum of 300 E. Laboratory studies conducted with the participation of V.S. Falshtynskyi, have confirmed that the reaction of burning carbon itself proceeds faster and affects the process of injected blast magnetization. The obtained results of this study confirm the results of previous studies,

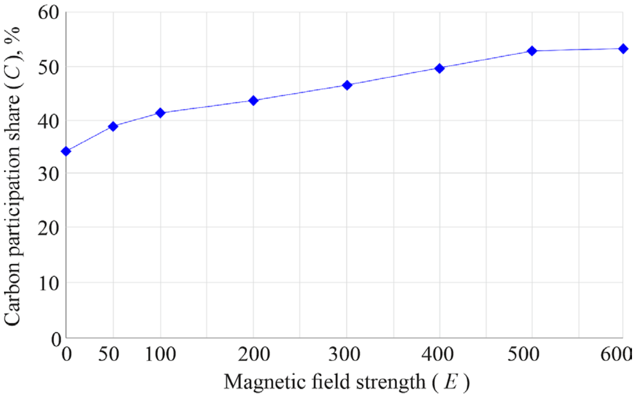

Figure 5: Graph of the change in the carbon participation growth during solid fuel gasification process, depending on the change in the magnetic field strength parameters during magnetization of the injected blast (at T = 900ºC).

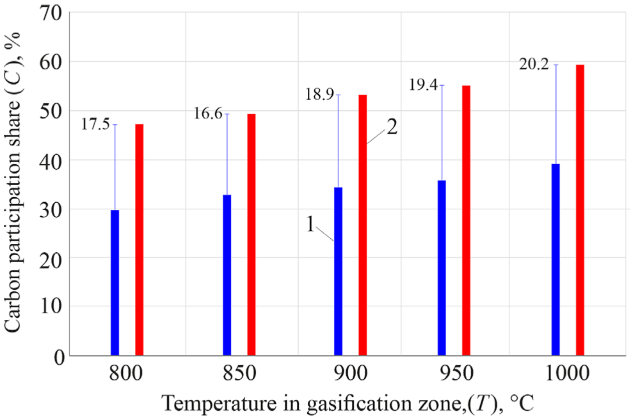

Figure 6: Carbon participation share in solid fuel gasification at a temperature change in the gasification zone and magnetic treatment of the injected blast mixtures (at magnetic field strength of 500 E): 1 – the injected blast mixtures not treated with a magnetic field; 2 – the injected blast mixtures treated with a magnetic field.

taking into account a significantly expanded temperature range from 800 to 1000°C and magnetic field strength from 0 to 600 E.

The maximum value of the carbon participation share at a magnetic field strength of 500 E is observed at a temperature in the gasification zone of 1000ºC with a gradual decrease with decreasing temperature in the muffle furnace. In percentage units, the carbon participation intensity during the treatment of the injected blast mixture with a magnetic field varies from 16.6 to 20.2%, depending on the temperature in the gasification zone under a constant action of a 500 E magnetic field. Since maintaining a high temperature in the gasification channel is a rather complex technological task, thus, in subsequent research we will focus on the temperature value in the gasification zone of 900ºC at a magnetic field of 500 E. That is, the process intensity is 18.9%.

As is known, one of the ways to intensify the underground gasification process of solid fuels is the use of oxygen. Oxygen is obtained from the air by the method of low-temperature rectification or water electrolysis, while the costs of its obtaining are quite high. Therefore, the process of underground coal gasification will be energy-intensive and become low-profit. In our opinion, it is possible to use not expensive oxygen to intensify the UCG process, but physical fields that provide electromagnetic heating of the coal seam with a great effect, as well as the influence of magnetic fields on the injected blast composition. The use of electrophysical influences on the coal mass and the injected blast composition will allow for the creation of a new combined UCG technological process. It is possible to maintain the syngas calorific value during industrial in-situ gasification by applying operational measures such as varying the gasification agent flows and supplying it using a controlled retracting injection point. At the same time, the conditions for a balanced flow of physical rates and thermochemical balance of the gasification process should be observed. Compliance with such a balance is possible when using the developed MTBalance software product, which has been tested industrially at the Barbara experimental mine in Poland (**Falshtyns'kyy et al., 2010**).

In practical terms, "magnetic tank" capacity for industrial use is calculated based on the initial parameters of the magnetized injected blast required amount to ensure the constant exposure to a 500 E magnetic field. The magnetization device is set between the mouths of two boreholes, an injection borehole and gas production borehole. Such an arrangement will make it possible to quickly change the magnetized air flow when reversing the injected gas flows. As a rule, both permanent magnets and solenoid-type electromagnets are used in industrial magnetic devices of complex designs. The physical essence of the impact of magnetic fields is explained by the transfer of molecules into an excited state under the influence of Lorentz forces. Excited oxygen molecules enter into gasification chemical reactions at a faster rate. More precisely, it is not the reaction itself that changes, but the processes in a heterogeneous system occurring under the impact of a magnetic field. If the change in the structure of oxygen molecules is taken as primary, then the change in the chemical reaction rate should be considered secondary.

The conducted experiments have revealed significant defects in the design of the "magnetic tank" type device. For example, there is no possibility of determining and adjusting the water vapor amount in the injected blast. An excess of water vapor in the injected blast reduces the efficiency of the coal gasification process. In this regard, options for separate supply of water vapor (activated in a magnetic field) and air blast have been developed. In addition, a "magnetic filter" type device has been developed, in which the initial injected blast (air mixed with water vapor) is passed through the slotted gaps of unipolar magnetic systems. A combination of a "tank" and "filter" type device is also possible. For example, vapor can be prepared with a magnetic system submerged in water. The resulting vapor is then mixed with air and passed through a magnetic filter. The operating efficiency of these devices can be assessed by changing the technological characteristics of the coal gasification process. For example, by varying the injected blast rates for burning the same volume of coal or, with an equal consumption of injected blast activated and not activated by magnetic fields, or by changing the yield of gasification products. The implementation of these works is a task for further research.

In addition to the above noted, it is obvious that when using the injected blast magnetization, as an element of intensification, it is necessary to adjust the rate of the fire face advance. At the same time, it is necessary to understand that the injected blast magnetization affects the outgassing activity, but it is not the same as the outgassing rate. The carbon outgassing activity caused by the impact of magnetic fields will take place in the oxidizing zone of the gasification channel, while the effect on the reducing zone is leveled. Thus, the prospects for further research are to adjust the parameters of the fire face advance of an underground gas generator, taking into account the parameters of the gasification process intensification by magnetic fields, with obtaining a pattern of change in the fire face advance along the gasification channel length, when using injected blast with magnetization and without magnetization, based on the predicted fire face line development, confirmed experimentally.

Specific practical recommendations on the use of magnetic fields to intensify the gasification process can be provided after conducting in-situ research in real mining-geological conditions, which is also an integral part of further research.

5. Conclusions

The mechanism of steam-air injected blast activation using the magnetic fields consists in intercombination transitions of oxygen and water molecules from a singlet (stable) state to a triplet (excited) state due to the reorientation of the binding electron spins in an inhomogeneous magnetic field, the gradient of which is traced at the molecular size level.

To activate the injected blast during the coal gasification process, a significant inhomogeneity of the magnetic field can be created by using constant magnetic fields of low strength by contacting magnetized solid surfaces and gaseous products of injected blast.

It has been determined that the intensity of carbon participation during the injected blast mixture treatment with a magnetic field varies from 16.6 to 20.2% depending on the temperature (from 800 to 1000ºC) in the gasification zone under a constant magnetic field action of 500 E.

The conducted experimental studies have confirmed the possibility of increasing the rate of coal combustion when using magnetic fields in the process of underground coal gasification. The following research works should be continued in the direction of improving the design of devices for magnetic injected blast preparation, which can provide an optimal increase in the coal gasification process parameters.

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SAŽETAK

Primjena magnetskih polja za intenziviranje procesa uplinjavanja ugljena

Podzemno uplinjavanje ugljena alternativna je metoda eksploatacije ugljena iz tankih i vrlo tankih slojeva, koja omogućuje pretvaranje krutih fosilnih goriva u zapaljive plinove na mjestu nalazišta ugljena. Istodobno, u slučaju kada je debljina sloja ugljena kritično mala za učinkovit tijek termokemijskih reakcija, potrebno je intenzivirati proces uplinjavanja. U ovome radu proučava se jedna od mogućih metoda intenziviranja procesa podzemnoga uplinjavanja ugljena primjenom magnetskoga polja na injektirani mlaz koji se dovodi u kanal uplinjavanja generatora plina. Ispitivanje provedeno na stolnome uređaju potvrđuje učinkovitost aktivacije injektiranoga mlaza u magnetskome polju stvaranjem nehomogenosti magnetskoga polja, postavljanjem permanentnih magneta i diskretne čvrste magnetizirane faze u poseban uređaj. Prvi je put utvrđena ovisnost promjene rasta udjela ugljika tijekom procesa uplinjavanja krutoga goriva o promjeni jakosti magnetskoga polja u rasponu od 0 do 600 E. Dokazano je da se magnetiziranjem injektiranoga mlaza može znatno intenzivirati proces podzemnoga uplinjavanja povećanjem udjela ugljika u gorivu, što može imati praktičnu važnost za povećanje prinosa gorivih komponenti.

Ključne riječi:
podzemno uplinjavanje ugljena, intenziviranje, ugljen, magnetska polja, ugljik

Author’s contribution

Vasyl Lozynskyi (PhD., Associated Professor): participated in all work stages, paper submission and revision, and completed literature review. **Volodymyr Falshtynskyi** (PhD., Associated Professor): initialized the idea, managed the whole process and supervised it from the beginning to the end, including running experimental tests. **Pavlo Saik** (PhD., Associated Professor): performed verification of the results. **Roman Dychkovskyi** (Dr. Tech. Sci., Professor): developed a methodological approach, **Bakhyt Zhautikov** (Dr. Tech. Sci., Professor): provided the interpretations and presentation of the results. **Edgar Cabana** (Dr. Tech. Sci., Professor): data analysis and graphical support.