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Review paper

TREATMENT OF FLUE GAS AND COAL TO REDUCE AIR POLLUTION-OVERVIEW

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Abstract: This paper presents the procedures that can be used to reduce air pollution that originates from the burning of fossil fuels. Research has shown that burning coal is the largest source of emissions of greenhouse gases such as carbon dioxide, sulfur oxides, nitrogen oxides and suspended particles. In order to reduce the emission of harmful agents from thermal power plants, several procedures based on various technologies are applied. It is possible to treat the already created flue gases created by burning coal in the classic way, treatment of the coal itself before the start of combustion in the thermal power plant and special procedures for coal treatment. Very effective procedures applied to protect air from pollution in the energy sector are: flue gas desulphurization (FGD), coal purification before the combustion process (coal washing), coal gasification and coal combustion in a fluidized bed. The paper also provides a detailed account of the advantages and disadvantages of the procedures described with an analysis of the contribution of scientific research in defining the technology itself.

Keywords: air protection, flue gas desulfurization, coal washing, coal gasification, coal combustion in a fluidized bed

1 INTRODUCTION

Environmental degradation implies pollution of air, soil and watercourses as three inseparable components. These problems became particularly pronounced in the era of urbanization, industrial and technological development. Air pollution is a type of pollution that is transferred to both land and water. Air is polluted when an excess of aerosols and chemicals are present in the atmosphere compared to air from a pristine environment. Air pollutants are any physical, chemical or biological agents that have the

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ability to adversely affect air quality. Sources of air pollution can be classified into two groups according to the way of their origin:

1. Natural (volcanic eruptions, forest fires, wind-blown dust) and 2. Anthropogenic (industrial processes, fossil fuel combustion, waste treatment, construction and agricultural activities) (Lee, Hadibarata and Yuniarto, 2020; Borm, 2002).

Recently, the increase in the concentration of air pollutants has reached alarming proportions. The dominant pollutants are nitrogen dioxide NO_2, sulfur dioxide SO_2, carbon monoxide CO and suspended particles whose diameter is 10 µm and smaller, known as PM10 µm and PM2.5 µm. Sources of gaseous pollutants are the emission of gases from industrial plants, thermal power plants, car exhaust gases, burning of agricultural waste, individual fireplaces in households, etc. (Singh et al., 2022).

High levels of air pollution adversely affect human health by causing various respiratory diseases. Also, they negatively affect natural processes in ecosystems, which is reflected in the flora and fauna. In the immediate vicinity of the source of pollution, pollutant deposition and the formation of barren soil occur. Weakly developed vegetative cover threatens the habitat of a large number of animal species (Zvereva, Toivonen and Kozlov, 2008).

Therefore, it is important to implement protective measures and prevent the direct discharge of polluting substances into the surrounding area. Purification of contaminated flue gases and removal of all substances that may have a harmful effect on the environment is necessary. Research has shown that thermal power plants that have a traditional way of burning coal are by far the biggest source of greenhouse gas emissions such as: carbon dioxide, sulfur oxides, nitrogen oxides and suspended particles. Coal is responsible for 90% of SO_2 emissions, 70% of dust emissions, 67% of nitrous oxide emissions and 70% of CO_2 emissions (Melikoglu, 2018; EIA, 2018).

In order to reduce the emission of harmful agents from thermal power plants, several procedures are applied in various stages of the process. It is possible to treat the already created flue gases created by burning coal in the classic way, treatment of the coal itself before the start of combustion in the thermal power plant and special procedures by which coal is converted into gas or combustion is carried out in a fluidized state.

Experts dealing with this issue have also introduced the term "clean coal technology" to highlight the importance of this topic. The basis of the concept of this technology is the procedures that improve the quality and efficiency of coal, as well as its environmental acceptability in all stages of its life cycle. This solution includes three main categories (Chen and Xu, 2010): 1. Coal enrichment, 2. Coal transformation - supercritical combustion and combustion in an oxygen atmosphere, and 3. Flue gas treatment.

The application of "clean coal technology" is increasingly important given the greater need for energy sources. The application of this technology prevents the emission of harmful combustion products from thermal power plants: spent particles, oxides of sulfur, nitrogen, mercury. In this way, not only air pollution is prevented, but also contamination of the surrounding soil and the occurrence of acid rain. It also has an effect on the reduction of global warming and climate change (Rybak et al., 2024; Blaschke, 2008).

2 FLUE GAS AND COAL TREATMENTS

In order to prevent air pollution by burning coal, several procedures are applied: flue gas desulfurization (FGD), coal purification before the burning process (coal washing), coal gasification and coal burning in a fluidized bed (Jafarinejad, 2017).

2.1 Flue gas desulphurization (FGD)

FGD is a purification technique that uses alkaline reagents, usually calcium-based, to remove SO_2. The procedures can be dry, semi-dry and wet, depending on the aggregate state of the used reagent. Lime-wet flue gas purification processes using wet limestone technology, the so-called gypsum process, are most widely used. More than 90% of flue gas desulphurization plants in the world operate according to this principle. The reason for this is the high efficiency, 90-95%, the relatively low consumption of sorbent, as well as the possibility of using the resulting waste product, i.e. gypsum (Ghosh, Biswas and Datta, 2024; Mchabe et al., 2021; Zhao and Zou, 2021).

The procedure is based on washing flue gases with an aqueous suspension of limestone or lime in an adsorption reactor, which produces lime sulfite $CaSO_3$. Limestone or slaked lime powder, after preparation in the form of a water suspension, is introduced into the adsorber using pumps. Additional oxygen saturation enables the conversion of $CaSO_3$ into $CaSO_4$, which, after being separated from the solution, goes on to further processing (washing and drying), which finally produces gypsum ($CaSO_4 \bullet 2H_2O$). A special system of circulation pumps, pipelines and nozzle systems guarantees intensive flue gas washing in the adsorption tower. The effectiveness of the process depends to a large extent on the intensity of the flue gas washing.

The FGD lime-wet process additionally removes HCl and HF compounds, as well as ash from the flue gases. This waste is then subjected to chemical treatment to remove heavy metals. As a result of washing, flue gases are cooled down to a temperature of around 50^{o}C, which is why it is necessary to reheat them before they are taken to the chimney. Heating is carried out in special heaters. However, it is possible to introduce the cooled flue gases into the chimney without heating, which reduces investment costs. Furthermore, due to the reduction of the resistance to the flow of flue gases, the operating costs are also reduced due to the reduction of the energy consumption for the fan drive. There is also a flue gas removal system using a "wet chimney" installed on the adsorber. Due to the possibility of introducing all the mentioned variables, it is necessary, when analyzing the operation of the flue gas processing plant, to always take into account the local operating conditions for the given object, that is, the plant (Sekulic, Jovanovic and Kasic, 2012; Stojiljkovic et al., 2009).

2.2 Coal purification before the combustion process (coal washing)

Coal cleaning is an effective procedure that reduces the concentration of harmful elements present in coal. In the washing plants, using appropriate mining equipment, the coal is first crushed and sifted, whereby fractions of a certain size are obtained. The cleaning process itself is based on mixing coal of a certain fraction with heavy liquids of a certain density. Zinc chloride $ZnCl_2$ solution is used as a heavy liquid and the density with which the procedure starts is 1100-1300 kg/m^3 and ends with a density of 1800-1900 kg/m^3. During immersion, impurities settle (sink), and clean coal remains on the surface (floats), so this analysis is called float-sink analysis or FS-analysis. The resulting coal fractions are measured and their ash content is determined. Ash represents the non-burnable residue, i.e. the inorganic part of coal. It can be considered that the higher the quality of the coal and the higher the heat capacity, the lower the ash content. Coal also contains large amounts of combustible sulfur. By cleaning coal, it is possible to remove this harmful element. Therefore, the sulfur content is determined on each separated coal fraction, except for ash (Knezevic, 2012).

Graphical presentation of coal FS analysis is done according to the method conceived by Henry and Reinhardt. This method of graphical representation provides for the construction of 4 curves: the curve of the boundary layers, the curve of the average ash content in the fractions that float, the curve of the average ash content in the fractions that sink, and the curve of the stratification density. By applying Henry-Reinhardt curves, it is possible to make a balance with two products (clean coal and tailings) and with three (clean coal, intermediate product and tailings), (Cebeci and Ulusoy, 2013). The effectiveness of the procedure depends on the degree of liberation of the mineral containing the element to be removed. With this procedure, in addition to ash and pyrite sulfur, mercury associated with pyrite is also removed (Miller, 2011).

In the preparation of coal, the main goal is to separate the coal, as a useful component, from impurities. This can also be achieved by processes that include coarse and medium purification, as well as fine and ultrafine (in spirals, separators, conventional and column flotation cells). The treatment of coal before its combustion in the thermal power plant affects the reduction of the percentage of ash formation, fly ash, and the concentration of sulfur dioxide in the flue gases. All of this contributes to better air quality in the thermal power plant area. Also, by cleaning, coal becomes of better quality, because it has a higher calorific value (Kostovic et al., 2022).

2.3 Coal gasification

Coal gasification is the conversion of coal into gaseous fuels, i.e. synthetic gas or syngas. The conversion is done by interacting with agents that act as oxidants such as water vapor, air or oxygen. Complete gasification involves the conversion of all the carbonaceous material contained in the coal into gaseous products. After the procedure is completed, ash remains as the only solid material (Ward, 2013). Gasification is by nature a thermal process of gas production from the natural reaction of coal with oxygen, air or steam. Coal gasification has an advantage over other energy production technologies because it belongs to clean technologies. With this method, the classic process of burning coal is eliminated. The performance of the procedure depends on the type of coal and the construction of the gasifier itself (Muhammed et al., 2023; Midilli et al., 2021).

By applying an integrated system of a combined gasification cycle, steam and hot air under pressure or oxygen are mixed with coal and during the reaction a gaseous product, syngas, is formed. The resulting mixture of carbon monoxide, hydrogen, carbon dioxide and water vapor is then cleaned, burned in a gas turbine to produce electricity. Cleaning the gas mixture involves removing mercury, sulphur, particulate matter and other trace contaminants so that only CO, CO_2 and hydrogen remain. The method allows reaching a fuel efficiency of 50%. With this relatively new technology, poorer quality coals can be treated, which otherwise could not be used for direct combustion in thermal power plants (Visionias Inspiring Innovation, 2025). The process of coal gasification to obtain pure hydrogen takes place as follows (MWCOG, 2025):

Step 1: Mixing coal powder with oxidants at a high temperature (up to 1800 °C), during which gasification and gas formation occur, which are a source of energy. The resulting gas consists of H_2, CO and traces of CO_2, CH_4 and water vapor.

Step 2: The resulting gas is cooled and purified to remove mercury, sulfur, trace contaminants and particles. CO, CO_2 and hydrogen remain in the purified gas. The purification of the gasification product is much easier and simpler than the purification of flue gases from thermal power plants that work in the traditional way of burning coal.

Step 3: Transport of the gas to the reactor where the CO conversion is carried out. At the end of the process, the gas consists mainly of hydrogen and CO_2.

Step 4: Further purification of the gas and separation into separate hydrogen and CO_2 streams. After this stage, the hydrogen is ready for use, and the CO_2 is sent for sequestration. Sequestration is the process of extracting carbon from CO_2 and depositing it in a previously prepared place. In this way, the emission of CO_2 into the atmosphere is reduced (Mondal et al., 2024).

Step 5: The resulting hydrogen is ready for further use such as: combustion in a gas turbine to produce electricity, conversion to electricity in a fuel cell, use as a fuel in an internal combustion engine and use as a chemical.

2.4 Combustion of coal in a fluidized bed

Coal combustion in a fluidized bed is a process that takes place in a special combustion reactor. The coal powder is suspended in the air stream which is injected into the reactor in pressurized jets. The fuel retention time in these specialized boilers is long enough to ensure complete combustion. Also, fuel, i.e. coal, can be mixed with limestone, which contributes to a more efficient removal of sulfur (Visionias Inspiring Innovation, 2025).

The conditions in the reactors are such that the material is constantly in a fluidized state and behaves like a boiling liquid. This state is maintained by means of an emulsion of gas bubbles that continuously mix the solid phase, whereby good heat transfer between the gas and solid phases is enabled. In the upper part of the reactor there is a gas phase, and in the lower part there is a material with a thickness of 0.2-0.5 mm. The main stages of thermochemical conversion take place within or above the fluidized bed (Liu et al., 2014; Iannello, Morrin and Materazzi, 2020; Nunes, 2020).

Combustion of coal particles in a fluidized bed is a complex procedure and takes place in three phases: drying, loss of volatile substances and combustion. The entry of coal particles into the combustion reactor due to the high temperature leads to rapid loss of moisture (drying) and volatile substances. It can be said that the heat in the reactor is spent on heating and drying the coal particles and the endothermic reaction of evaporation. The reaction of burning carbon is exothermic, so they contribute to the increase of temperature in the reactor. The difference in the temperature of a burning coal particle and the surrounding medium depends on the characteristics of the coal and carbon and on the oxygen concentration in the surrounding gas. According to the literature data, the temperature of the air is up to 400°C, and the combustion products up to 900°C (Komatina, Manovic and Dakic, 2006; Oka, 1994).

The process of burning coal in a fluidized bed represents a great advance in solving the pollution problems that arise from burning coal in the classic way in thermal power plants. The application of this technology and the construction of modern reactors have made a great contribution in the field of energy and coal combustion.

3 ANALYSIS OF ADVANTAGES AND DISADVANTAGES OF FGD AND COAL TREATMENT TECHNOLOGY

3.1 FGD technologies

Experts who research coal as an energy source believe that progress in this area is evident. This was contributed by the application of coal cleaning and gasification procedures, as well as combustion in a fluidized bed. Progress was contributed by defining the mechanism of desulfurization and mass transfer, defining the kinetics of oxidation, finding the possibility of reusing desulfurization products, as well as the possibility of optimization and simulation of procedures. Scientific research, setting the foundation and defining the mechanism of dry, semi-dry and wet desulfurization processes have made a great contribution to the understanding of this field. A critical review of the concept of these technologies is a prerequisite for new knowledge and improvements in this area, which eliminates their shortcomings (Pandey et al., 2005).

3.1.1 Wet procedure

The wet FGD process is very effective in removing SO_2 from flue gases, but the expert public points out that it also has its disadvantages. The main disadvantage is the high initial investment costs for the equipment and the high operating costs. The wastewater from the desalination plant is highly corrosive and contains pollutants derived from coal and limestone. They contain high concentrations of total dissolved solids, suspended solids, chloride, fluoride, nitrate and nitrite. Also, the wet FGD system is expensive due to the large amount of energy required to operate the pumps. This is especially evident when sea water is used in the plant. Power plants near the sea and the ocean, with a capacity of up to 1000MW, use pumps to supply the necessary amounts of water, which significantly increases the cost of the desulfurization process itself. Regardless of its drawbacks related to large investments, wet desulphurization technology is the most widespread, because it has the highest efficiency. In recent years, the reactors used in this procedure have been significantly improved and optimized, so the costs are also lower. This is also supported by the possibility of using a by-product of this procedure - plaster, which contributes to reducing waste and disposal costs (Li et al., 2022).

3.1.2 Dry procedure

The dry process is an alternative to the wet process for FGD and is based on injecting powdered reagents directly into the furnace. The procedure requires much less space and does not require the disposal of by-products, but it is less efficient than the wet procedure and can be used in power plants with a capacity of up to 1000 MW, unlike the wet procedure, which is used in power plants with a much larger capacity. In the dry SO2 adsorption process, besides powdered limestone, metal oxides and solid compounds such as copper oxide, activated carbon, activated manganese oxide, alumina, red mud etc. are used. However, it was found that they are not efficient adsorbents, because SO2 is only adsorbed on the surface. Great progress in the field of dry adsorption was achieved by modifying adsorbents and defining the mass transfer model of two-phase flow between gas and solid in reactors. The dry desulfurization process can be divided into three different technologies: 1. Desulfurization by injecting calcium; 2. Circulating Fluidized Bed Desulfurization and 3. Activated Coke Desulfurization Technology (Li et al., 2022).

Desulphurization technology by injecting calcium into the furnace is characterized by low investment, low operating costs and the absence of waste water. However, the disadvantage is low efficiency, 20-50%, while limestone utilization is only 10% (He, 1989). In order to increase the use of limestone, and thus the efficiency of the process, a limestone injection procedure with additional activation of unreacted calcium was developed in Finland. Namely, a device with nozzles for wetting limestone is installed in the activation reactor, and in this way the speed of desulphurization increases (Anthony, et al., 2005).

Circulating fluidized bed desulfurization technology was first installed in Munich in 1984. and proved to be very effective (Graf, 1986). It is based on the injection of slaked lime powder into the fluidized bed where it reacts with SO2 from the flue gas that is fed to the bottom of the bed. After desulfurization, the compressed flue gas is discharged from the top of the fluidized bed.

Activated coke desulphurization technology appeared in 1960. It is based on the adsorption of SO2 from flue gases with the help of activated coke particles produced from coal, whereby after adsorbing SO2, the activated coke can desorb it at high temperatures, thus creating the conditions for a repeated desulphurization process (Zhang, Su and Zhou, 2000; Skopec, Hrdlička and Vodička, 2021).

The subject of study by researchers in this field was the way to activate carbon from coal to form a pore structure to obtain activated carbon. Some have used steam for activation (Rubio et al., 1998) and have concluded that the resulting activated carbon has the same desulfurization capacity as commercial activated carbon, thereby reducing its economic cost. The combination of treatment in furnace atmosphere and multi-stage hydrothermal autoclaves gave such a structure of activated semi-coke that it could be used for sulfur and nitrate removal together which was a very significant data (Zhang et al., 2017).

3.1.3 Semi-dry process

Semi-dry desulfurization technologies are also advancing, which is reflected in the constant optimization of process conditions and the increase of desulfurization efficiency. The development of cheap and highly active adsorbers that can be recycled (e.g. semi-dry ash) reduces the costs of performing the procedure itself. Semi-dry desulfurization technology does not require energy for reheating or wastewater treatment, so operating costs are lower compared to the wet process. Also, it does not require a large space for the installation of the necessary equipment as with the wet process. However, the efficiency of the procedure is at a lower level compared to the wet procedure (Wang, 2018). Within this technology, the following most important methods are used: spray drying, pouring of powder particles and circulating fluidized bed.

The spray drying method was developed in Denmark in the "Niro" company in the seventies of the last century. The concept is based on spraying the lime suspension into the absorption tower in the form of fine droplets with the help of a rapidly rotating sprayer. Droplets of $Ca(OH)_2$ quickly adsorb SO_2, dry and a solid desulphurization product remains. The efficiency of the procedure depends on the superposition of the absorption process with the drying process, while the SO_2 content in the flue gas has no effect on the desulphurization rate, which is a major advantage of the method (Hill and Zank, 2000; Karlsson and Klingspor, 1987). In order to improve the adsorbent utilization rate and the desulphurization rate, adsorbers have been developed as mixtures of two components such as fly ash/quicklime and fly ash/slaked lime mixtures (Sanders, Keener and Wang, 1995).

The method with poured powder particles contributed to the achievement of desulphurization efficiency close to that achieved by the wet method, which is considered a major advance in the field of semi-dry technologies. Also, it has brought significant economic benefits. As the main place (reactor) in this method, where the SO_2 extraction reactions take place, is actually a cast bed of powder particles. A suspension of slaked lime or some other alkaline powder is continuously sprayed into a bed of coarse particles (usually several hundreds of microns), most often quartz sand, to absorb SO_2. The reactions of desulfurization and suspension drying are carried out simultaneously in the bed of powder particles (Guo, Noriaki and Kato, 1996).

The method of desulphurization with a circulating fluidized bed was created at the suggestion of the University of Cincinnati. With this technology, the vertical fluidized bed is the main body of the reactor, where high-temperature flue gas is drawn into the fluidized bed at high speed, after which the absorption reaction takes place. Circulating fluidized bed can be used both for dry and semi-dry desulphurization. The absorbent used in this method (limestone, fly ash) is recyclable (Jiang, Keener and Khang, 1995).

3.2 Treatment of coal

3.2.1 Coal gasification

Coal gasification is recognized as the basis of clean coal utilization technology. The significant advantage of this technology is reflected in the way of electricity production, production of hydrogen-rich synthetic gas and reduced SO_2 emissions. The obtained synthetic gas is used in combined cycle technology for the production of electricity with a theoretical efficiency of energy production exceeding 45%, which contributes to the comprehensive efficiency of coal use. Also, the concentrations of SO_2 and H_2 can be increased in the produced gas through synthesis gas steam reactions, which reduces the consumption of electricity for SO_2 removal and the production of high-quality hydrogen (Kim et al., 2013).

A major advance in this area has been the introduction of new gasification technologies including supercritical water gasification, plasma gasification, chemical loop gasification, separation gasification, and subsurface gasification. Conventional gasification procedures have been replaced in recent years by new technologies such as fixed bed technology, fluidized bed technology and flow technology, which eliminated all the disadvantages of old technologies (Matamba, Iglauer and Keshavarz, 2022; Fan and Jin, 2022). However, it should be emphasized that the expert public agrees that even today there is room for progress in conventional gasification in the direction of designing large-sized reactors, better control of gaseous pollutants, use of solid residues, etc. On the other hand, with the help of sophisticated techniques and knowledge, there are conditions for the development of catalytic and microwave gasification, as a process of the future, but currently there are no conditions for their commercial application due to technical shortcomings (Dai et al., 2023).

3.2.2 Combustion of coal in a fluidized bed

The fluidized bed technology has its advantages, as it is very flexible in terms of the properties of the materials being processed, such as the heat value of the raw material, moisture content, particle size and density, sulfur content, etc. Also, it has superior performance in terms of heat and mass transfer. Namely, the advantages compared to other technologies are homogeneity of temperature, increased speed of heat transfer, good mixing of solid particles and the possibility of carrying out further processes such as drying of particles. Also, this technology gives two options in terms of configuration, namely bubbles and circulating fluidized beds (Miccio et al., 2021).

One of the main disadvantages of this technology is the occurrence of agglomeration phenomena due to the sintering of the bed caused by the alkali present in the fuel, especially waste and residues, which leads to a breakdown in the plant and urgent emergency interventions (Hupa, 2012). In order to alleviate the agglomeration phenomenon, cheap alternative materials, such as SiO_2, are used in practice to inhibit this phenomenon. The problem with processes in a fluidized bed is the occurrence of the fragmentation phenomenon, which leads to a decrease in the efficiency of the process. This is especially pronounced in the case of less reactive fuels (Chirone, Massimilla and Salatino, 1991).

4 CONCLUSION

Solving the problem of air pollution in the energy sector has become imperative in countries that use fossil fuels. Emphasis is on clean coal processing technologies (coal gasification and coal combustion in a fluidized bed), which generate significantly less pollutants than conventional coal combustion in thermal power plants. In order to develop new technologies, a connection between science and practice is necessary. Results obtained in scientific research are very often difficult to apply in practice due to large economic investments and technical shortcomings. The development of catalytic and microwave gasification, as examples of this, as processes of the future, have not yet found their full application. Research in this field must progress, despite all the difficulties of practical application. Development of flue gas treatment technologies was contributed by the results of scientific research that defined adsorption mechanisms during desulfurization and mass transfer, defined oxidation kinetics, characteristics of the adsorbents themselves, found the possibility of reusing desulphurization products, as well as the possibility of optimization and simulation of procedures. Critical analysis of the concepts of these technologies is a prerequisite for new knowledge and improvements in this field, which also eliminates their shortcomings. The structure and chemical forms of coal itself are the subject of further scientific research. The researchers found that there are mechanisms of element binding that deserve attention such as the question under which conditions toxic elements (As, Hg) replace the major sulfide ions in coal. Also, certain rare mineral phases that are not common have been identified in the coal including native forms of W, Au and Ag, various Au and Pt phases. All of the above can affect the efficiency of the procedures presented in this paper. And finally, the following facts that are generally important for both science and practice should be highlighted: 1. Due to the increasing global pressure on the environment and the need for energy, constant research is necessary in the future with the aim of developing innovative technologies for the clean conversion of coal into energy and the reduction of greenhouse gas emissions and 2. Focusing on solving practical engineering problems in terms of designing economically viable plants is essential.

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REFERENCES

ANTHONY, E.J. et al. (2005) LIFAC ash-strategies for management. *Waste Management*, 25 (3), pp. 265-279. https://doi.org/10.1016/j.wasman.2004.11.005

BLASCHKE, W. (2008) Clean Coal Technologies-The first step is coal preparation. *Polityka Energetyczna-Energy Policy Journal*, 11 (2), pp.7-13. https://epj.min-pan.krakow.pl/Issue-2-2008,6353

BORM, P.J.A. (2002) Particle toxicology: from coal mining to nanotechnology. *Inhalation Toxicology*, 14 (3), pp. 311–324. DOI: 10.1080/08958370252809086

CEBECI, Y. and ULUSOY, U. (2013) An optimization study of yield for a coal washing plant from Zonguldak region. *Fuel Processing Technology*, 115, pp. 110-114. https://doi.org/10.1016/j.fuproc.2013.04.014

CHEN, W. and XU, R. (2010) Clean coal technology development in China. *Energy Policy*, 38 (5), pp. 2123–2130. DOI: 10.1016/j.enpol.2009.06.003

CHIRONE, R. MASSIMILLA, L. and SALATINO, P. (1991) Comminution of carbons in fluidized bed combustion. *Progress in Energy and Combustion Science*, 17 (4), pp. 297-326. https://doi.org/10.1016/0360-1285(91)90006-9

DAI, F. et al. (2023) Recent Progress on Hydrogen-Rich Syngas Production from Coal Gasification. *Processes*, 11 (6), 1765. https://doi.org/10.3390/pr11061765

EIA (2018) *Changes in Coal Sector Led to Less SO_2 and NOx Emissions from Electric Power Industry.* [Online] EIA. Available from: https://www.eia.gov/todayinenergy/detail.php?id=37752 [Accessed 20/03/25].

FAN, C. and JIN, H. (2022) Numerical simulation of gasification of a shrinking char particle in supercritical water. *Fuel*, 318, 123692. https://doi.org/10.1016/j.fuel.2022.123692

GHOSH, D., BISWAS, D. and DATTA, A. (2024) Absorption height in spray tower for wet-limestone process in flue gas desulphurization. *Materials today: Proceedings*, In press. https://doi.org/10.1016/j.matpr.2024.02.001

GRAF, R. (1986) First operating experience with a dry flue gas desulfurization (FGD) process using a circulating fluid bed (FGD-CFB). *Circulating Fluidized Bed Technology*, Proceedings of the First International Conference on Circulating Fluidized Beds, Halifax, Nova Scotia, Canada, November 18–20, 1985. pp. 317-327. https://doi.org/10.1016/B978-0-08-031869-1.50038-7

GUO, Q.M., NORIAKI, I. and KATO, K. (1996) Process Development of Effective Semi-Dry Flue Gas Desulfurization by Powder-Particle Spouted Bed. *Kagaku Kogaku Ronbunshu,* 22 (6), pp. 1400-1407. https://doi.org/10.1252/kakoronbunshu.22.1400

HE, H.G. (1989) In-furnace Sorbent Injection-based Desulfurization Technolog. *Therm Power Generat 5,* 7-9+6. CNKI:SUN:RLFD.0.1989-05-001.

HILL, F.F. and ZANK, J. (2000) Flue gas desulphurization by spray dry absorption. *Chemical Engineering and Processing: Process Intensification*, 39 (1), pp. 45-52. https://doi.org/10.1016/S0255-2701(99)00077-X

HUPA, M. (2012) Ash-Related Issues in Fluidized-Bed Combustion of Biomasses: Recent Research Highlights. *Energy & Fuels*, 26 (1), pp. 4-14. https://doi.org/10.1021/ef201169k

IANNELLO, S., MORRIN, S. and MATERAZZI, M. (2020) Fluidised Bed Reactors for the Thermochemical Conversion of Biomass and Waste. KONA Powder and Particle Journal, 37, pp. 114–131. https://doi.org/10.14356/kona.2020016

JAFARINEJAD, S.H. (2017) *Control and Treatment of Air Emissions*. Chapter 5, Petroleum Waste Treatment and Pollution Control, pp. 149-183. https://doi.org/10.1016/B978-0-12-809243-9.00005-5

JIANG, M.X., KEENER, T.C. and KHANG, S.J. (1995) The use of a circulating fluidized bed absorber for the control of sulfur dioxide emissions by calcium oxide sorbent via in situ hydration. *Powder Technology*, 85 (2), pp. 115-126. https://doi.org/10.1016/S0301-9322(97)88546-1

KARLSSON, H.T. and KLINGSPOR, J. (1987) Tentative modelling of spray-dry scrubbing of SO_2. *Chemical Engineering Technology*, 10 (1), pp. 104-112. https://doi.org/10.1002/ceat.270100114

KIM, J. et al. (2013) Hydrogen production via steam gasification of ash free coals. *International Journal of Hydrogen Energy*, 38 (14), pp. 6014–6020. https://doi.org/10.1016/j.ijhydene.2012.12.058

KNEŽEVIĆ, D. (2012) *Priprema mineralnih sirovina*. Beograd: Rudarsko-geološki fakultet Beograd, Univerzitet u Beogradu.

KOMATINA, M., MANOVIC, V. and DAKIC, D. (2006) An Experimental Study of Temperature of Burning Coal Particle in Fluidized Bed. *Energy & Fuels*, 20 (1), pp. 114-119. https://doi.org/10.1021/ef050222o

KOSTOVIĆ, M. et al. (2022) Coal cleaning before combustion-practice and experience in Serbia. *Underground mining engineering*, 41, pp. 23-30. DOI: 10.5937/podrad2241023K

LEE, B.X.Y., HADIBARATA, T. and YUNIARTO, A. (2020) Phytoremediation Mechanisms in Air Pollution Control: a Review. *Water, Air, & Soil Pollution*, 231, 437. https://doi.org/10.1007/s11270-020-04813-6

LIU, Y. et al. (2014) Novel fluidized bed dryer for biomass drying. *Fuel Processing Technology*, 122, pp. 170–175. DOI:10.1016/j.fuproc.2014.01.036

LI, X. et al. (2022) Summary of research progress on industrial flue gas desulfurization technology. *Separation and Purification Technology*, 281, 119849. https://doi.org/10.1016/j.seppur.2021.119849

MATAMBA, T., IGLAUER, S. and KESHAVARZ, A. (2022) A progress insight of the formation of hydrogen rich syngas from coal gasification. *Journal of the Energy Institute*, 105, pp. 81-102. https://doi.org/10.1016/j.joei.2022.08.001

MCHABE, D. et al. (2021) Development of an integrated model for absorption of sulphur dioxide in limestone slurry. *Chemical Engineering Science*, 229, 116050. https://doi.org/10.1016/j.ces.2020.116050

MELIKOGLU, M. (2018) Clean coal technologies: A global to local review for Turkey. *Energy Strategy Reviews*, 22, pp. 313–319. https://doi.org/10.1016/j.esr.2018.10.011

MICCIO, F. et al. (2021) Fluidized Bed Combustion and Gasification of Fossil and Renewable Slurry Fuels. *Energies*, 14 (22), 7766. https://doi.org/10.3390/en14227766

MIDILLI, A. et al. (2021) A comprehensive review on hydrogen production from coal gasification: challenges and opportunities. *International Journal of Hydrogen Energy*, 46 (50), pp. 25385-25412. https://doi.org/10.1016/j.ijhydene.2021.05.088

MILLER, B.G. (2011) *Clean Coal Engineering Technology*. Butterworth: Heinemann. https://doi.org/10.1016/C2009-0-20236-4

MONDAL, A. et al. (2024) Impact and potential of carbon sequestration and utilization: fundamentals and recent developments. *International Journal of Coal Preparation and Utilization*, 44, 12, pp. 2018-2043. https://doi.org/10.1080/19392699.2024.2305940

MUHAMMED, N.S. et al. (2023) Hydrogen production, transportation, utilization, and storage: Recent advances towards sustainable energy. *Journal of Energy Storage*, 73, Part D, 109207. https://doi.org/10.1016/j.est.2023.109207

MWCOG (2025) *Hydrogen production from coal*. [Online] MWCOG. Available from: https://www.mwcog.org/file.aspx?&A=6lJMMDOHmOUL2TT9fb7pcrAAeY5PdpMxMeZbS9eJzyo%3D [Accessed 18/03/25]

NUNES, L.J.R. (2020) Potential of Coal-Water Slurries as an Alternative Fuel Source during the Transition Period for the Decarbonization of Energy Production: A Review. *Applied Sciences*, 10 (7), 2470. https://doi.org/10.3390/app10072470

OKA, S.N. (1994) *Sagorevanje u fluidizovanom sloju-procesi i priprema*. Beograd: Jugoslovensko društvo termičara.

PANDEY, R.A. et al. (2005) Flue gas desulfurization: physicochemical and biotechnological approaches. *Critical Reviews in Environmental Science and Technology*, 356 (6), pp. 571-622. https://doi.org/10.1080/10643380500326374

RUBIO,B. et al (1998) Influence of low-rank coal char properties on their SO2 removal capacity from flue gases. 2. Activated chars, *Carbon*, 36 (3), pp. 263-268. https://doi.org/10.1016/S0008-6223(97)00190-5

RYBAK, A. et al. (2024) Analysis of the Impact of Clean Coal Technologies on the Share of Coal in Poland's Energy Mix. *Energies*, 17 (6), 1394. https://doi.org/10.3390/en17061394

SANDERS, J.F., KEENER, T.C. and WANG, J. (1995) Heated Fly Ash/Hydrated Lime Slurries for SO2 Removal in Spray Dryer Absorbers. *Indistrial and Engineering Chemistry Research*, 34 (1), pp. 302-307. https://doi.org/10.1021/ie00040a032

SEKULIĆ, Ž., JOVANOVIĆ, V. and KAŠIĆ, V. (2012) Litotamnijski krečnjak ležišta “Dobrilovići” u odsumporavanju dimnih gasova. *Rudarski radovi*, 3, str. 41-44. doi: 10.5937/rudrad1203041S

SINGH, A.A. et al. (2022) Air Pollution: Sources and its Effects on Humans and Plants. *International Journal of Plant and Environment*, 8 (1), pp. 10-24. https://doi.org/10.18811/ijpen.v8i01.02

SKOPEC, P., HRDLIČKA, J. and VODIČKA, M. (2021) Dry additive desulfurization in oxyfuel bubbling fluidized bed combustor. *Fuel*, 283, 118945. https://doi.org/10.1016/j.fuel.2020.118945

STOJILJKOVIĆ, D. et al. (2009) Izbor optimalnog tehničkog rešenja postrojenja za odsumporavanje dimnih gasova na TE „Kostolac B". *Termotehnika*, 35 (3-4), str. 231-249. https://scindeks.ceon.rs/issue.aspx?issue=8651

ZHANG, K. et al (2017) Multi-stage semi-coke activation for the removal of SO_2 and NO, *Fuel*, 210, pp. 738-747. https://doi.org/10.1016/j.fuel.2017.08.107

ZHANG, X.J., SU, Y.B. and ZHOU, P. (2000) Studies on Sulfur Dioxide Adsorption on the Improved Active Coke. *Environmental Protection Science*, 05, pp. 4-6. 10.16803/j.cnki.issn.1004-6216.2000.05.002

ZHAO, M. and ZOU CH. (2021) An investigation into the influence of dissolution rate on flue gas desulfurization by limestone slurry. *Separation and Purification Technology*, 276, 119356. https://doi.org/10.1016/j.seppur.2021.119356

ZVEREVA, E.L., TOIVONEN, E. and KOZLOV, M.V. (2008) Changes in species richness of vascular plants under the impact of air pollution: a global perspective. *Global Ecology and Biogeography*, 17 (3), 305-319. DOI: 10.1111/j.1466-8238.2007.00366.x

VISIONIAS INSPIRING INNOVATION (2025) *Clean coal technologies*. [Online] VISIONIAS. Available from: https://d19k0hz679a7ts.cloudfront.net/value_added_material/Clean-Coal-Technologies.pdf [Accessed 18/03/25].

WANG, X.M. (2018) Technology about dry desulfurization and semi-dry desulfurization. *Electric Power Environ Protect*, 34(01), pp. 45-48. CNKI:SUN:DLHB.0.2018-01-010.

WARD, C.R. (2013) *Coal Gasification*, Chapter Coal Gelogy, Reference Module in Earth Systems and Environmental Sciences. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.05437-3