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Fluidized Bed Scrubber – Perspectives for the Development of Gas Purification Methods

Skruber ze złożem fluidalnym – perspektywy rozwoju metod oczyszczania gazów

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Keywords: *fluidized bed scrubber, emission reduction, deodorization, air pollutants*

Abstract
Air pollution caused by odorous compounds, including hydrogen sulphide and ammonia, presents a serious challenge due to their toxicity and odour nuisance. This paper discusses methods for reducing air pollutant emissions, focusing on the fluidization process as an effective solution. The use of fluidized bed scrubbers for the removal of these contaminants is highly effective, due to the intensive mixing of gases with the reaction medium, which increases the contact surface area and enhances cleaning efficiency. Industrial applications of these technologies, which significantly reduce odour emissions and improve air quality, are also presented.

Słowa kluczowe: *płuczka fluidalna, ograniczanie emisji, dezodoryzacja, zanieczyszczenia powietrza*

Streszczenie
Zanieczyszczenie powietrza przez odory, w tym siarkowodór i amoniak, stanowi poważne wyzwanie ze względu na ich toksyczność i uciążliwość zapachową. W pracy omówiono metody ograniczania emisji zanieczyszczeń do powietrza, koncentrując się na procesie fluidyzacji jako efektywnym rozwiązaniu. Zastosowanie skruberów ze złożem fluidalnym w usuwaniu tych zanieczyszczeń wykazuje wysoką skuteczność dzięki intensywnemu mieszaniu gazów z medium reakcyjnym, co zwiększa powierzchnię kontaktu i efektywność oczyszczania. Przedstawiono także przemysłowe zastosowania tych technologii, które znacząco redukują emisje odorów i poprawiają jakość powietrza.

Introduction

Air pollution is one of the most serious ecological and health challenges of the modern world. Emissions of industrial gases, including nitrogen oxides (NOx), sulphur oxides (SOx), and volatile organic compounds (VOCs), contribute to the formation of smog and acid rain, and have detrimental effects on human health and ecosystems [7,27]. In response to growing environmental awareness and stricter regulatory requirements, industries are compelled to adopt advanced emission reduction technologies aimed at minimizing the environmental impact of their activities. Air pollutants such as hydrogen sulphide (H_2S) and ammonia (NH_3), though comprising a relatively small percentage of total emissions, play a crucial role in shaping air quality due to their toxicity, potential to transform into other harmful substances, and strong odour impact. Hydrogen sulphide, known for its characteristic rotten egg smell, is not only a nuisance for residents of industrial areas but is also toxic at high concentrations, causing respiratory irritation, headaches, and, in extreme cases, loss of consciousness [8]. Ammonia, widely used in agriculture and industrial processes, also poses significant health risks, causing eye, skin, and respiratory tract irritations [23].

Reducing emissions of waste gases, including odorous compounds, is therefore a crucial aspect of air quality management in industrial facilities and municipal operations, aimed at minimizing the release of harmful substances into the atmosphere. In practice, a variety of technologies are employed, which can be classified into primary and secondary methods, each with its specific applications, advantages, and limitations.

Primary methods for reducing pollutant emissions focus on prevention and minimization at the production stage. These include technological changes and the implementation of cleaner production technologies. Optimizing combustion processes is one of the main strategies, involving the control of parameters such as temperature, fuel-to-air ratio, and residence time in the reaction zone, which allows for the reduction of nitrogen oxides (NOx) and other pollutants. An example of this is the staged combustion method, where fuel is burned in multiple stages under varying oxygen conditions [10]. Another approach is fuel modification. Using fuels with lower contaminant content, such as natural gas, biofuels, or hydrogen, can significantly reduce emissions. Compared to coal, natural gas emits less CO_2 and contains virtually no sulphur, eliminating SOx emissions [21]. Another effective method is flue gas recirculation, which involves reintroducing a portion of the exhaust gases into the combustion chamber to lower the flame temperature, thereby reducing NOx formation. This technique is widely used in industrial boilers and gas turbines [9]. Additionally, the use of sorbents in the combustion process, such as limestone, enables the binding of pollutants (e.g., SOx) during combustion,

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reducing their emissions into the atmosphere [1]. In the context of odour reduction, primary methods focus on minimizing the sources of unpleasant smells. One approach is the optimization of fermentation and composting processes in agriculture and waste management by controlling parameters such as temperature, humidity, and oxygen availability, which reduces the emission of volatile organic compounds (VOCs) responsible for odours [19]. The use of covers on fermentation tanks and enclosed systems in wastewater treatment plants helps to contain odours and limit their release into the atmosphere [16].

Secondary methods focus on removing pollutants from waste gases after they have been generated. One of the fundamental techniques is absorption. Wet absorption involves passing gases through an absorbing liquid (e.g., solutions of hydroxides, acids, or organic compounds), which chemically or physically binds the pollutants. An example is the absorption of SO_2 in a sodium hydroxide solution, forming sodium sulphate [14]. Commonly used devices in this context are scrubbers, which operate by passing gases through an absorbing liquid (water or chemical solutions) that physically or chemically removes the pollutants. An example is wet scrubbers used to remove SOx using calcium solutions, which produce gypsum ($CaSO_4$) as a by-product. Semi-dry scrubbers involve spraying the gas with fine droplets of the absorbing liquid, which then quickly evaporate, leaving dry reaction products for separation. Alternatively, dry and semi-dry absorption methods use dry sorbents (e.g., lime, soda) in powder form that react with pollutant gases, forming solid products that are subsequently removed from the gas [22].

Another sorption method is adsorption, where gaseous pollutants are attracted to the surface of a solid adsorbent. Activated carbon, with its large specific surface area, is effective in removing organic pollutants and some inorganic compounds (e.g., Hg) from waste gases through physical adsorption [26]. Zeolites and other porous materials are also used in adsorption processes due to their structural selectivity and efficiency in adsorbing pollutants such as VOCs and NOx.

Catalytic and non-catalytic reductions are advanced secondary techniques. Selective Catalytic Reduction (SCR) uses catalysts (e.g., V_2O_5/TiO_2) to reduce NOx with ammonia (NH3) or urea ($CO(NH_2)_2$) at temperatures of 300-400°C, achieving NOx reductions of up to 90%. Selective Non-Catalytic Reduction (SNCR) involves injecting ammonia or urea into the combustion zone at the appropriate temperature (850-1100°C) to reduce NOx without using a catalyst. This method is less expensive but also less effective than SCR [18].

Biological gas purification methods are an important and efficient alternative to traditional chemical and physical technologies. These methods rely on microorganisms to biodegrade pollutants present in waste gases, transforming them into less harmful or completely harmless products. One of the most commonly used technologies in this context is biofilters. Biofilters consist of a layer of porous material, such as compost, peat, vermiculite, or synthetic materials, on which a biofilm of microorganisms develops. Waste gases pass through the biofilm layer, where pollutants are adsorbed onto the surface and biodegraded by the microorganisms. Biofilters are particularly effective in removing organic compounds and certain inorganic compounds, such as hydrogen sulphide (H_2S) and ammonia (NH_3) [17].

Each of these methods has its specific applications, advantages, and limitations. The choice of the appropriate technology depends on the type of pollutants, the specifics of the industrial process, operational costs, and regulatory requirements. Combining different techniques often allows for achieving the highest gas purification efficiency while minimizing the negative environmental impact.

2. The application of fluidization processes in reducing gaseous pollutant emissions

The fluidization process involves introducing a solid into a dynamic state using a flow of gas or liquid, causing the bed to become mobile and behave like a fluid [15]. Fluidized beds have found wide applications in various industries, including chemical, metallurgical, and energy processes, due to their exceptional properties such as intensive mixing, high heat and mass transfer efficiency, and the ability to operate over a wide range of parameters. Examples of applications include energy production, fuel processing, petrochemical refining, mineral processing, polymerization, food and pharmaceutical engineering, as well as air and water purification [6]. Modern research on fluidization focuses on improving the efficiency and control of various industrial processes. In recent years, new technologies such as vibrating beds and circulating fluidized beds have been introduced, which enhance particle distribution and process efficiency [3].

In the context of gas purification, fluidized beds are used in both primary and secondary methods. In primary methods, such as fluidized bed combustion (FBC), the fluidization process enables efficient fuel combustion, significantly reducing NOx emissions through optimized combustion conditions and the application of reburning technology. The fluidization process ensures intensive mixing and uniform heat distribution, which promotes the complete combustion of lower quality fuels with high moisture content, such as biomass and waste, thereby reducing the formation of pollutants [20].

In secondary methods, the fluidization process is used to remove pollutants from exhaust gases by bringing the gas into contact with an active medium that adsorbs or reacts with the pollutants. Fluidized bed scrubbers represent one of the most advanced technologies for cleaning exhaust gases due to their high efficiency, versatility, and ability to operate under a wide range of conditions. Fluidized bed scrubbers utilize a dynamic bed of fine particles that are fluidized by the gas flow. The fluidization process ensures intensive mixing of the gas with the reactive medium, increasing the contact surface area and thereby enhancing the cleaning efficiency [20]. Fluidized scrubbers effectively handle hot gases by integrating cooling sections that cool the gases before they enter the fluidized bed. This feature makes them suitable for applications involving high-temperature gases, such as those from waste combustion processes. For example, fluidized bed systems are effective in removing ammonia through the use of appropriate sorbents, which can either physically adsorb or chemically react with NH3. In the case of adsorption, activated carbon is often used due to its large specific surface area and its ability to adsorb ammonia from gases. Alternatively, the chemical removal of ammonia can be achieved using acidic sorbents, such as sulfuric acid, which reacts with ammonia to form ammonium sulphate ($(NH_4)_2SO_4$), a compound that is easy to separate and remove from the process [14].

Experimental studies [11] have shown that the application of three-phase fluidization for carbon dioxide capture results in a three – to six-fold increase in the effective mass transfer surface area, leading to a proportional increase in CO_2 throughput. This enhances the absorber's capacity to process the gas and minimizes the amount of solvent required. Based on the experimental results, a detailed mathematical model for a pilot-scale CO_2 capture column was developed and verified, and later scaled up for industrial applications. This model describes the process of turbulent contact absorption, taking into account the hydrodynamics and mass transfer between the liquid and gas phases. Another study on flue gas desulfurization using circulating fluidized beds (CFB) demonstrated a sulphur dioxide (SO_2) removal efficiency exceeding 94%. This was achieved through a heterogeneous reaction model that accounts for both the external and internal diffusion of SO_2 and its reaction with reagent particles [5].

Kim et al. (2003) conducted studies on the removal of H_2S, NH_3, and benzene using a fluidized bed bioreactor and a biofilter. Their results showed that the fluidized bed bioreactor achieved critical removal rates of 12 g/m³/h for H_2S, 11 g/m³/h for NH_3, and 28 g/m³/h for benzene, which were higher than those achieved by the biofilter [23]. The average removal efficiencies of H_2S, NH_3, and benzene by the fluidized bed bioreactor were 95±3%, 99±1%, and 98±5%, respectively, compared to 96±4%, 95±4%, and 97±3% for the biofilter. In another study, Chung et al. (2001) investigated the removal of H_2S and NH_3 using a fluidized bed bioreactor with immobilized cells of *Pseudomonas putida* (for H_2S) and *Arthrobacter oxydans* (for NH_3). The study showed that the removal efficiency of H_2S remained above 95% at an inlet concentration below 30 ppm, while the removal efficiency of NH_3 exceeded 90% at an inlet concentration below 100 ppm [4].

The efficiency of fluidized bed scrubbers in removing ammonia and hydrogen sulphide depends on several key factors, including the type and properties of the filling material, operating conditions (temperature, pressure, gas flow rate), and reactor configuration [25]. There are known examples of industrial applications of fluidized bed scrubbers [26]. For instance, the INSTAL AIRECO® technology developed by INSTAL WARSZAWA was awarded in the GreenEvo – Green Technology Accelerator competition organized by the Ministry of Environment (Poland). This patented solution consists of devices that effectively neutralize odorous, toxic, and hazardous substances across various industries. The main component of the system is a scrubber, where the cleaning bed, tailored to specific needs, operates in a fluidized manner. The system is fully automated. The result of the device's operation is the reduction of compounds that negatively impact the environment, including in pumping stations, wastewater treatment plants, waste management, and agriculture, as well as in industries such as food, chemical, and paper production.

3. Examples of industrial use of fluidized bed scrubbers

An interesting example of the industrial application of fluidized bed scrubbers is the implementation of INSTAL AIRECO for a sewage sludge drying facility at a plant producing lightweight aggregates from waste materials. The installation was designed for the two-stage neutralization of air pollutants, with its primary goal being the deodorization of emitted gases. The system consists of two identical counterflow conical scrubbers with a three-phase fluidized bed. These devices provide high mass transfer coefficients, allowing the system to operate correctly under varying gas and liquid flow rates, handling airflows of up to 10,000 m³/h. Air from the drying facility, containing high-molecular-weight sulphur compounds and amine groups responsible for unpleasant odours, is directed through a cyclone and pipelines to an exhaust fan. The air then enters the first acid scrubber, where it is exposed to strong oxidizing agents in an acidic environment. This process involves passing the air through a fluidized bed, to which a working solution—a mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) with a phase transfer catalyst—is supplied from above. The process is controlled based on pH measurements of the working solution. After passing through the acid scrubber, the air is directed to the alkaline scrubber, where the purification process continues using sodium hydroxide (NaOH). The operation and flow of liquid and gas in the alkaline scrubber are identical to those in the acid scrubber. By utilizing this two-stage gas cleaning installation, a high efficiency of deodorization and minimization of the odour impact of the facility has been achieved.

Another area where fluidized bed scrubbers are used for gas purification in wastewater management is sewage pumping stations. Due to the specific operational requirements of retention systems and the need for deodorization installations with high flexibility and the ability to operate intermittently, a system based on a single-stage chemical scrubber was chosen for a sewage pumping station in Lower Silesia. The installation was designed to manage odours and air pollutants from four sewage retention tanks, each with an active capacity of 15,376 m³. To achieve effective deodorization, two parallel lines were implemented, each with a maximum capacity of 12,000 m³/h. Air is delivered to the deodorization system through a duct network, and all air from the tanks is directed for purification, preventing unorganized emissions of pollutants into the environment. The air is purified using a working solution based on sulfuric acid and a phase transfer catalyst or hydrogen peroxide. The automation system of the deodorization installation ensures precise dosing of chemicals and the monitoring and control of the entire installation's operation.

During the modernization of another sewage pumping station, the air extraction and purification system was upgraded to reduce the emission of pollutants such as ammonia, hydrogen sulphide, mercaptans, and triethylamine. The gases are extracted from the screening evacuation rooms, the screen hall, and the intake chambers. The project implemented a two-stage deodorization system, ensuring a 95% reduction in pollutant emissions. The system consists of two main lines: standard ventilation, which directs gases to a two-stage gas purification system consisting of a UV reactor and an activated carbon filter, and emergency ventilation. Air extracted by the emergency ventilation system is directed to a two-stage gas purification installation, which includes an acidic chemical scrubber with a fluidized bed (first stage) and a catalyst for oxidizing thiol and sulphide compounds (second stage). The deodorization system is equipped with a control and automation system, ensuring constant pH monitoring and chemical dosing according to the appropriate algorithm. The liquid that sprays the bed circulates in a closed loop, with water supplied as needed. The implemented deodorization system has significantly reduced the impact of the facility on the olfactory quality of the surrounding air.

An interesting example highlighting the challenges associated with the use of fluidized bed scrubbers in air purification is another installation at a sewage pumping station. The INSTAL AIRECO installation was designed to improve air quality by reducing odour nuisances resulting from the operation of the pumping station. The installation consists of a single conical scrubber with a three-phase fluidized bed. The device ensures proper operation for a wide range of gas and liquid flow rates, from 1000 to 5000 m³/h. Air from the sewage pumping station is directed through pipelines to an exhaust fan that works with the station's air circulation system and is then fed into the scrubber. The purified gas is treated with oxidizing agents in an acidic environment. Air is introduced from the bottom into the lower tank (above the surface of the working solution) and passed counter-currently through the fluidized bed, onto which the working solution (a mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) with a phase transfer catalyst) is supplied from above. The dosing of reagents is automated and dependent on the measured pH value of the working solution. An analysis of the installation's efficiency was conducted during the winter and during periods of full load of the sewage pumping station. It was found that the deodorization installation operated stably and effectively at low ambient temperatures, i.e., below – 5°C. No odour nuisance was detected during periods of full load of the sewage pumping station. The odour intensity was measured according to the German standard VDI 3940, using an intensity scale of 0–6, where 0 indicates no odour, 1 – very weak, 2 – weak, 3 – distinct, 4 – strong, 5 – very strong , and 6 – extremely strong odour [2]. The average odour intensity at full load indicated very limited odour occurrence. Odour classified as very faint was present within the pumping station; no odours were identified at other measurement points. Additionally, studies on the efficiency of the installation were conducted at various pH values of the working solution. It was found that the absorption of odorous compounds present in the air extracted from the pumping station chamber was most effective in an acidic environment. The next stage of optimization involved determining the pH value that would minimize acid consumption while maintaining odour emission levels that prevent impact on the surrounding area. The optimal pH value of the working solution was determined experimentally. Laboratory tests indicated that ammonia derivatives were the primary source of odour nuisance at the facility. The efficiency of ammonia removal was found to be 74.3%. Based on the analyses, it was demonstrated that the installed gas-phase pollution removal system effectively solves the problem of odorous emissions throughout the entire range of sewage flows during the hydrological year, for both operational and maintenance modes of the pumping station. A necessary condition for the absence of odorous compound emissions into the environment is maintaining the air intake flow rate at a level that ensures a vacuum in the pumping station chamber greater than the vast majority of vacuum fluctuations occurring within it.

An example of an industrial implementation outside of the water and wastewater management sector is the air deodorization system at a mushroom farm. The INSTAL AIRECO installation was designed to effectively neutralize ammonia (85%) and hydrogen sulphide (95%) from the air exhausted from the bunkers where mushroom substrate production takes place. The system consists of two scrubbers operating in parallel, each servicing five bunkers, with a total capacity of 50,000 m³/h. The composting process of materials (manure, straw) in the bunkers, lasting from 12 to 18 days, generates significant amounts of odorous pollutants such as ammonia, organic amines, and hydrogen sulphide, which were previously emitted into the atmosphere, causing odour nuisances. Studies confirmed the high efficiency of the installation. Measurements taken before and after the scrubbers showed a significant reduction in ammonia and hydrogen sulphide concentrations, demonstrating the system's effectiveness under real operating conditions. The installation is highly flexible, capable of removing ammonia from concentrations ranging from ppm to several hundred mg, with an efficiency of ≥85%. This is particularly important as studies have shown that the emission of ammonia during the production of mushroom substrate depends on external temperature, the location of the measurement point, and the phase of the composting cycle, thus exhibiting high variability. Ammonia concentrations in the air flowing through the ventilation ducts ranged from 70 to 3000 mg/m³, while natural convection with open exhaust vents to the atmosphere resulted in concentrations from 20 to 50 mg/m³. Before the installation of the scrubbers, large amounts of ammonia were released into the environment, causing potential nuisances. Olfactometric analysis of the surroundings confirmed that odour risks were eliminated. To further purify the air, a biofilter was installed as a second stage of cleaning. The biofilter was designed as an unorganized emitter with a capacity of 70,000 m³/h and an area of 490 m². The biofilter fill consists of a support layer of conifer wood chips and an active layer of bark and conifer wood chips. The biofilter is irrigated through a system of watering pipes, with optimal operating parameters including a temperature not exceeding 65°C and humidity not less than 45%. The biofilter operates at low temperatures (25-35°C) and high moisture parameters (humidity 99%), ensuring aerobic degradation of pollutants by microorganisms.

4. Research perspectives

To expand the application range and enhance the potential efficiency of pollutant removal in fluidized bed scrubbers, research is being conducted to optimize process parameters. As part of the planned analyses, studies will be carried out at the INSTAL AIRECO research installation (Figures 1 and 2) at the Faculty of Environmental Engineering of Wrocław University of Science and Technology. These studies aim to determine the required contact time for reagents, the optimal dose of hydrogen peroxide, and the concentration of the catalyst depending on the pollutant load in the odorous air and the air flow rate, as well as the maximum air flow rate for a given cross-section and bed height that ensures the desired reduction level of odorous compounds (pollutant concentration in the exhaust air at the threshold of olfactory detection). The research will focus not only on the efficiency of removing individual substances, such as hydrogen sulphide and ammonia, but also on the overall degree of deodorization.

Fig. 1. Research installation INSTAL AIRECO
Rys. 1. Instalacja badawcza INSTAL AIRECO

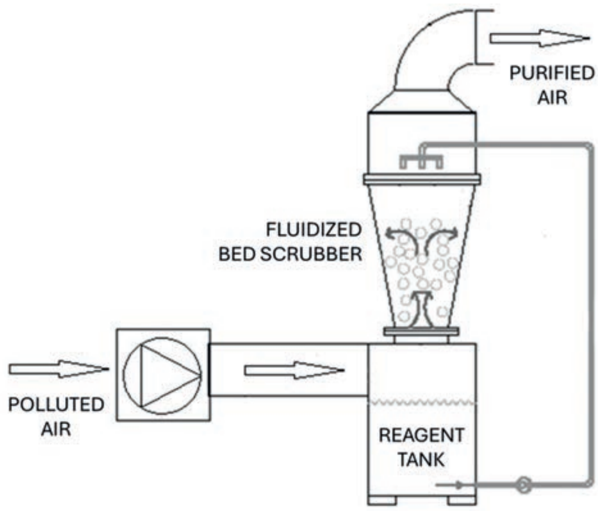

Fig.2. Technical schematic of the research installation
Rys. 2. Schemat instalacji badawczej

5. Summary

The circular economy relies, among other things, on the reuse of materials previously considered waste. At sites where these materials are processed, odorous air emissions are often encountered. Consequently, with the development of the circular economy, there will be an increasing demand for effective air purification methods. Another factor driving the need for such installations is the rising standards for air quality near existing facilities. Additionally, residential development is encroaching closer to areas burdened by emissions, further emphasizing the need for efficient air purification solutions.

Fluidization technology has demonstrated high efficiency in removing odours such as hydrogen sulphide and ammonia due to the intensive mixing of gases with the reactive medium. Examples of industrial applications of fluidized bed scrubbers confirm their effectiveness and operational flexibility. The future development prospects for this method include further optimization of process parameters and the development of new sorbents and catalysts that can enhance purification efficiency. Moreover, it is essential to conduct further research on the integration of fluidization technology with other air purification methods, as well as on scaling and adapting these technologies to various types of industrial installations. Continued research and innovation in this field are crucial for effective air quality management and minimizing the negative impact on the environment.

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