www.czasopisma.pan.pl www.journals.pan.pl

Archives of Environmental Protection
Vol. 51 no. 4 pp. 27–37

PL ISSN 2083-4772
DOI: 10.24425/aep.2025.157226

Dust emission reduction using wastewater from a wet flue gas desulfurization (WFGD) absorber: a case of zero liquid discharge (ZLD) implementation

Arkadiusz Świerczok[1]*, Dariusz Łuszkiewicz[1], Krzysztof Mościcki[1], Maria Jędrusik[1], Artur Sobczak[2]

[1]Politechnika Wrocławska, Poland
[2]Zespół Elektrociepłowni Wrocławskich KOGENERACJA S.A., Poland

* Corresponding author's e-mail: arkadiusz.swierczok@pwr.edu.pl

Keywords: fly ash, wastewater discharge, electrostatic precipitator, flue gas conditioning, wet flue gas desulphurization

Abstract. Actions aimed at reducing the harmful impact of industry on the environment are currently of great importance. The article presents a solution for the simultaneous reduction of dust emission and removal of sewage from a municipal combined heat and power plant. The research focused on injecting treated wastewater (or its mixture) originating from the wet flue gas desulfurization (WFGD) system into a flue gas stream upstream of an electrostatic precipitator (ESP) to clean emissions from a pulverized coal boiler. The installation utilized the waste heat of the flue gases to completely vaporize the injected liquid, while simultaneously improving ESP efficiency by conditioning the flue gases.

Tests were conducted on a system capable of injecting up to 6 m³/h of liquid into a flue gas flow with an average volume of approximately 125,000 Nm³/h. Throughout the testing phase, the conditioning liquid was confirmed to evaporate completely. No increases in pollutant concentrations - such as SO_2, HCl, HF, or NH_3 – were observed in exhaust gases at injection temperatures of around 200°C. Additionally, a decrease in particulate matter downstream of the ESP was recorded following the liquid injection.

The findings indicate that this installation allows for effective disposal of wastewater streams. Moreover, liquid injection into flue gases can improve ESP performance without extensive or costly upgrades, which is especially beneficial for existing industrial plants.

Introduction

The development of industry initially led to an increase in pollutant emissions. Only with the emergence of the concept of sustainable development did greater attention begin to be paid to the environmental costs incurred by humanity as a result of growing industrial production. This gave the governments of developed countries the impetus to take action to protect the environment, including the protection of atmospheric air. As a result, a number of legal regulations were introduced in this area. For example, in Europe, the overarching legal act concerning the prevention and control of air, water and soil pollution, as well as the reduction of waste generation from large industrial installations, is Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions (IED - integrated pollution prevention and control) (EU Directive 2010). The actions resulting from these regulations have contributed, and continue to contribute, to a significant reduction in air pollution (Amman et al. 2020).

Another global trend nowadays is the implementation of industrial processes in accordance with the principles of the circular economy (CE), including the reduction of waste and sewage generation, which are often unavoidable. A particular approach to wastewater management is known as zero liquid discharge (ZLD), a strategy aimed at completely preventing any liquid waste from leaving the boundaries of a plant or facility (Tong and Elimelech 2016). One common source of industrial wastewater is the wet flue gas desulfurization system used in power plants. Raw wastewater from this source typically contains high levels of heavy metals, sulfates, chlorides, suspended solids (primarily gypsum), nitrogen compounds, and organic substances. This complexity necessitates either the expansion of existing sewage treatment facilities or the installation of evaporators to ensure compliance with national standards and BAT (Best Available Techniques) conclusions (MME&IN Regulation 2010, EU Decision 2017).

Issues related to limiting the harmful impact of the growing human population on the environment are also of great importance. Research is being conducted in this area, and various actions are being taken to mitigate this impact, including the protection of atmosphere (Starzomska 2024, Klyta 2023) and water resources (Wolska 2024, Pilco-Nunez 2024), as well as increased attention to waste-related issues (Ciesielczuk 2023, Primus 2024). Nevertheless, the need to reduce emissions from various industries, including fossil-fuel-based energy production, which remain dominant in Poland, continues to play an important role.

Taking the above premises into account, this article presents the results of research on the use of a mixture of sewage from a WFGD installation for conditioning flue gases upstream of an electrostatic precipitator. The main goals of the study were to ensure dust concentration downstream of the ESP remained at the level of 25 mg/Nm^3 and to eliminate the sewage stream by evaporating it in the hot flue gas flow.

Exhaust gas conditioning upstream of electrostatic precipitators is generally carried out to beneficially modify the physicochemical properties of the gas and, consequently, improve the effectiveness of the dust collector (Parker et al. 1997). Several methods of exhaust gas conditioning are described in the literature and used in industrial practice. For example, adding a small amount of gaseous SO_3 to exhaust gases leads to a reaction with water vapor and the formation of a sulfuric acid H_2SO_4 mist, which acts as an electrolyte. This compound is adsorbed on the surface of solid particles, wetting them and simultaneously reducing dust resistivity. Exhaust gas conditioning with SO_3 produced by catalytic oxidation of SO_2 present in the gas stream (Battles et al. 1998), or by injecting liquid sulfur dioxide or solid sulfur (Porle et al. 1996).

Another method involves conditioning exhaust gases with ammonia, however, this approach is primarily intended to increase particle cohesion or to raise dust resistivity to the desired level (Katz 1981). The simultaneous injection of SO_3 and ammonia is considered significantly more effective than using either SO_3 or ammonia alone (Hilborn 1993, Lund et al. 1998, Shanthakumar et al. 2009). One application of this method is the conditioning of exhaust gases containing large amounts of combustible particles and highly mineralized dusts (Lund et al. 1998).

Conditioning exhaust gases with water is commonly used to cool and humidify gases produced in dry technological processes, such as those in the cement industry (Parker et al. 1997). Another solution is the ADA-ES system, introduced in the mid-1990s in the United States, which conditions exhaust gases with water and chemical additives (Durham et al. 1998, Schwab and Hawks 2000). Injection of an aqueous solution of phosphate salts (known as ADA-23) into exhaust gases upstream of an electrostatic precipitator reduces dust resistivity and improves electrical performance of the ESP (Durham et al. 1998, Baldrey et al. 1997).

For the purposes of the described research, it was assumed that humidifying exhaust gases before they enter the ESP would positively influence its performance and enhance collection efficiency, consistent with findings reported in numerous studies (Parker et al. 1997, Navarrete et al. 2015, Chenghang 2017, Shuangchen 2016). The expected benefits included:

- lowering the volumetric flow rate of cleaned exhaust gases by reducing their temperature, which in turn decreases gas velocity within the ESP chamber,
- increasing the moisture content of the flue gases, which helps reduce the resistivity of high-resistivity ashes – an important factor for ESP operation, as it lowers the risk of back corona,
- improving dust properties at the ESP inlet, since mechanical agglomeration reduces the proportion of submicron particles, leading to lower overall dust emissions.

The issue of reducing the amount of sewage discharged from power plants can be addressed using several approaches:

- Methods using evaporators and crystallizers – the sewage stream from the treatment plant is evaporated in specialized devices powered by technological steam. As a result, a solid waste stream is produced, which must be landfilled or blended with fly ash (Tong and Elimelech 2016).
- Methods using spray dryers – these systems divert a portion of exhaust gases upstream of an air heater, where the sprayed wastewater is evaporated. The evaporation products are then transported back into the exhaust gas channel upstream of the dust collector (Shuangchen 2016).
- Stabilizing methods – mixtures consisting of gypsum, ash, sewage, and lime are prepared.
- Use of flue-gas heat to evaporate wastewater directly in front of the dust collector (Brown 1998).

Based on many years of experience, the authors proposed a solution that uses hot flue gas as a source of waste heat for eliminating the industrial wastewater stream. This approach avoids the need to construct additional technological lines equipped with devices such as evaporators, dryers, and systems for handling the individual products separated in these units. When wastewater is introduced into the flue gas channel upstream of the dust collector, the water evaporates and the compounds contained in the injected liquid are captured in the electrostatic precipitator and removed together with the fly ash.

Therefore, it has been suggested to inject a liquid – consisting of wastewater or a mixture of wastewater and water - into the flue gas duct upstream of the ESP. This method allows for the simultaneous conditioning of flue gases and removal of the wastewater stream. It is especially advantageous for existing plants, as it supports compliance with increasingly strict emission standards without requiring costly upgrades to the dust collection system, while also reducing at least a portion of the wastewater generated by the WFGD system.

Materials and Methods

Overview of the facility and injection system

A system designed for injecting conditioning liquid into the flue gases upstream of the electrostatic precipitator was installed on a water boiler (model WP-120) fired with hard coal (see Fig. 1). Dust collection was carried out using a horizontal electrostatic precipitator with two passes and three fields. The ESP was equipped with Sigma VI and IV type collecting electrodes with a 385 mm pitch, as well as rigid discharge electrodes consisting of pipe-and-blade assembles. The height of the electric field was 9.6 m, the length of each field was 3 x 3.8 m, and the specific collection area (SCA) was 63.8 m^2/m^3/s. After dust removal, the flue gases were directed straight to the chimney.

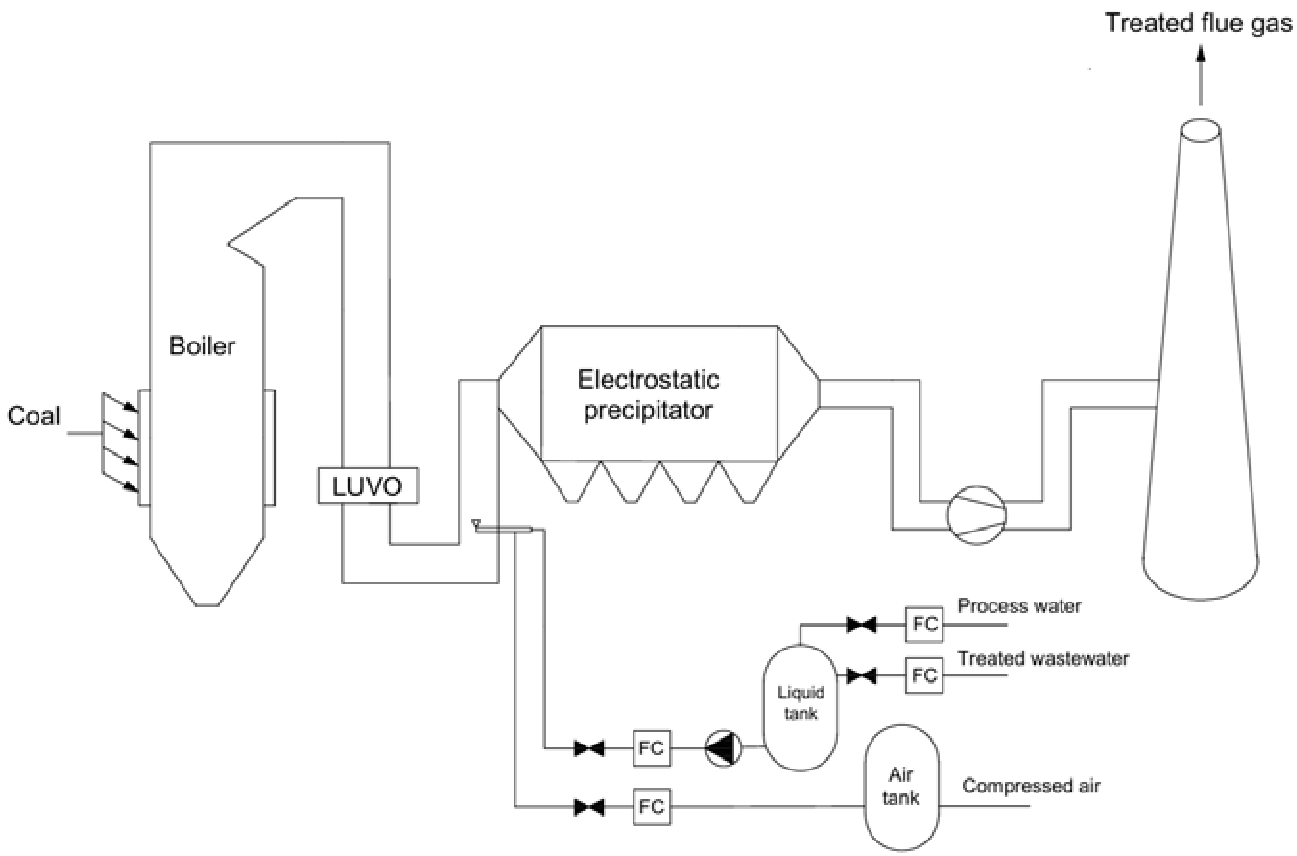


Fig. 1. Schematic diagram of the installation for injection of conditioning liquid into the flue gas duct in front of the ESP

A flue gas conditioning system was installed upstream of the electrostatic precipitator, consisting of the following key components:

- a compressed-air supply system,
- a system for delivering process water and treated wastewater,
- a conditioning liquid injection system with 10 injection lances equipped with appropriate fittings and Laval-type pneumatic nozzles,
- an automatic control system for regulating the operation of the conditioning installation.

The injection system was supplied with compressed air from existing compressors at a flow rate of 347 m^3/h and a pressure of 7 bar, with an additional 10 m^3 buffer tank equipped with the necessary fittings. The conditioning liquid fed into the system consisted of a mixture of pre-treated wastewater from the wet flue gas desulphurization process and process water. The system had a maximum capacity of 6 m^3/h, and the maximum working pressure of the conditioning liquid at the injection lances was 6 bar. A 10 m^3 liquid storage tank with the required fittings, along with control and measurement equipment, was also installed. The main operating parameters of the flue gas conditioning system are shown in Table 1.

Research description

The study examined the effect of the composition of the injected conditioning liquid on dust concentrations and levels of selected gaseous components downstream of the ESP, as well as on the properties of the dust collected in the ESP.

Experimental apparatus

The following equipment was used to perform the planned measurements:

- dust concentration downstream of the electrostatic precipitator: measured continuously using the automatic dust meter *Durag D-R 290*,
- chemical composition of exhaust gases: measured continuously using the *FTIR Gasmet DX 4000* analyzer,
- properties of dust collected in the ESP: analyzed under laboratory conditions, including particle size distribution

Table 1. Basic operating parameters of the exhaust gas conditioning installation

No.	Parameter	Unit	Value	
			min	max
1.	Stream of conditioning liquid	m^3/h	2	6
2.	Pressure of the conditioning liquid	bar	2.6	6
3.	Spraying air stream	Nm^3/h	1,750	2,400
4.	Spraying air pressure	bar	3.5	6

using the *Malvern* optical analyzer and chemical composition analysis of collected samples:

a) Mercury (Hg): atomic absorption spectrometry with amalgamation technique, Nippon Instruments Corporation (NIC) MA-2 Mercury Analyzer.
b) Sulfates: ion chromatography according to PN-EN ISO10304:2009, using a Dionex ICS-1100 ion chromatograph.
c) Chlorides: ion chromatography according to PN-EN ISO 10304-1:2009.

- structure and chemical composition of dust samples: analyzed using scanning electron microscopy with energy-dispersive spectroscopy (SEM/EDS) on a Prisma E instrument.

Pollutant concentration measurements were performed at an industrial facility. Before the measurements, the *Durag* analyzer was calibrated according to the QAL2 procedure, and the *Gasmet* analyzer was calibrated using reference gases before each measurement series (series I-III). The properties of dust samples and conditioning liquids were analyzed in laboratory conditions. Samples from the first ESP zone were used to determine grain composition, as only in this zone enough dust accumulated. Averaged samples were used to determine chemical composition, in the proportion of 80% from zone 1, 15% from zone 2 and 5% from zone 3 of the dust collector.

During the tests, samples of hard coal were collected and prepared in accordance with ISO standards EN ISO 17025:2005 in a certified laboratory. Fuel analyses included measurements of calorific value, carbon, hydrogen, sulfur, ash, and moisture content. All results were based on analyses of the fuel in the operational state, i.e., it is directly fed into the boiler.

Conditioning liquid injection upstream of ESP

Conditioning liquid injections were also investigated. Three measurement series were conducted under the established boiler operating parameters (125 MWt), each starting with "zero" state in which no liquid was injected:

- series I: injection of process water into the flue gas (without wastewater addition). During this process, concentrations of H_2O, HF, NH_3, and HCl were measured, and the facility's monitoring equipment was observed. Samples of fuel, process water from the storage tank, and ash from three ESP zones were collected.
- series II: injection of a blend consisting of 20% (by weight) treated wastewater and 80% process water. The concentrations of H_2O, HF, NH_3, and HCl were measured, facility monitoring data were recorded, and samples of process liquid and ESP ash (three zones) were collected.
- series III: injection of 100% treated wastewater into the flue gas, with measurements of H_2O, HF, NH_3, and HCl concentrations, monitoring of the facility's measuring equipment, and collection of media samples.

For all three series, the liquid injection parameters were kept constant: a liquid flow rate of 3.2 m³/h and an airflow rate of 2,400 Nm³/h. Throughout the study, dust concentration in the cross-section downstream of the ESP was continuously monitored.

The parameters of coal burned during the tests are presented in Table 2.

Results and discussion

The outcomes of the three series of injection system tests are outlined in the following subsections.

Pollutants in exhaust gas

The measurement results obtained from the boiler monitoring system and the flue gas parameter measurements conducted using the FTIR analyzer are presented in Fig. 2.

The analysis of the pollutant measurement results in the exhaust gas showed that injecting process water (see Fig. 2a) did not affect the levels of SO_2, HF, HCl, and NH_3 in the exhaust. When process water was injected into the flue gas, the water vapor content increased from 5.3% to 6.2%. Additionally, a decrease in dust concentration in the flue gas (as shown in Table 3) and a drop in flue gas temperature in the measurement area from 166°C to 148°C was observed.

Injecting 20% treated sewage into the channel also did not affect the concentrations of SO_2, HF, HCl, and NH_3 in the exhaust gas (see Fig. 2b). However, it did lead to an increase in water vapor content in the exhaust, along with a decrease in dust concentration (as shown in Table 3) and a reduction in exhaust gas temperature downstream of the ESP.

Similarly, in the previous measurement series, injecting 100% treated sewage into the duct did not influence the levels of SO_2, HF, and NH_3 in the exhaust gas (see Fig. 2c). For HCl,

Table 2. Results of elemental analysis of fuel

No.	Parameter	Unit	Value
1.	Calorific value	kJ/kg	23,800
2.	Heat of combustion	kJ/kg	27,055
3.	Total moisture	%	10.4
4.	Ash, in working condition	%	15.8
5.	Sulfur, in working condition	%	0.44
6.	Carbon, in working condition	%	61.6
7.	Hydrogen, in working condition	%	3.5

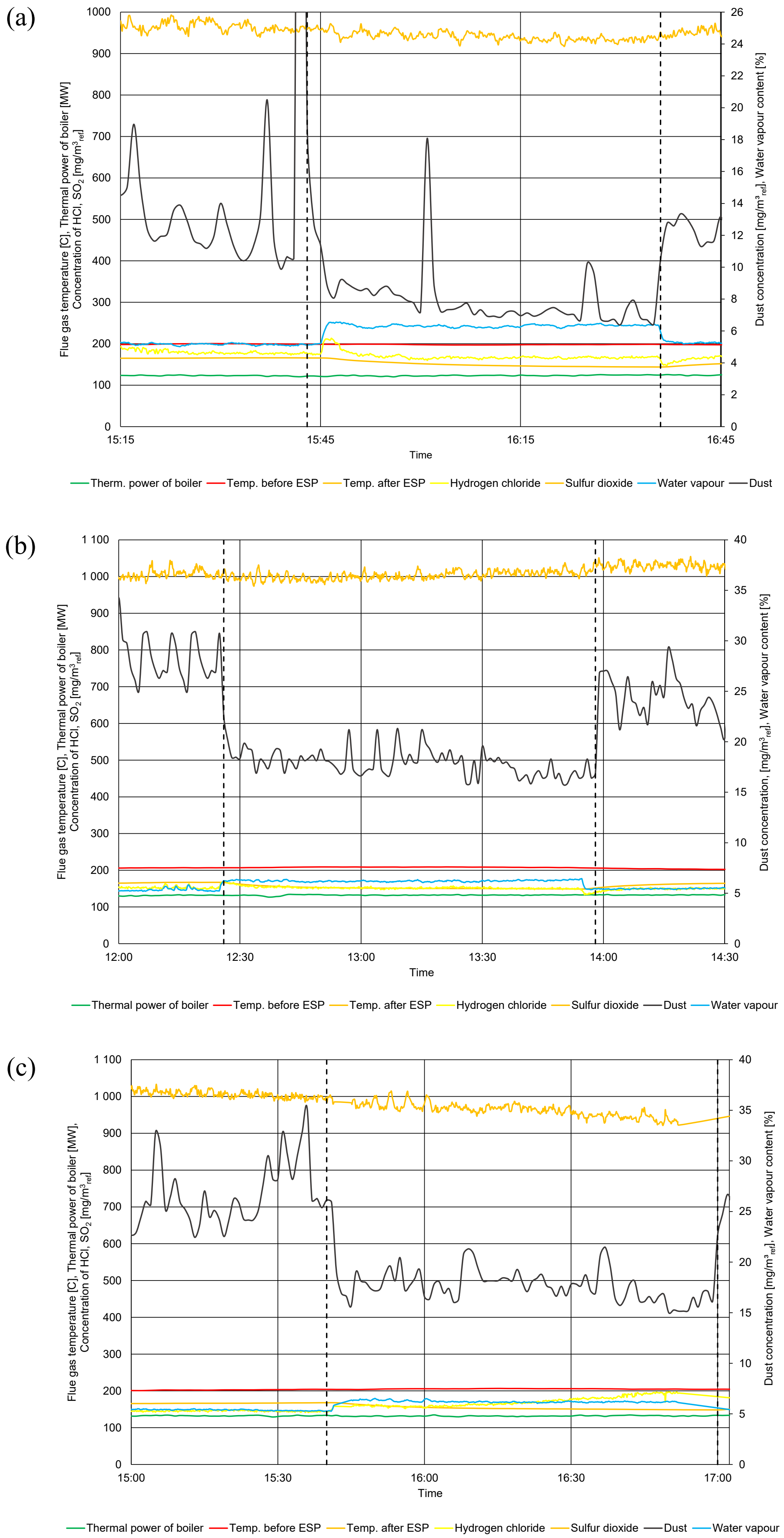


Fig. 2. Boiler operation parameters and concentration measurement results for: **a** series I, **b** series II, **c** series III

Table 3. Dust concentration in the flue gas under reference conditions*

Lot No.	Conditioning liquid	No injection, mg/m^3_{ref}	With injection, mg/m^3_{ref}	Reduction of emission, %
I	Process water	18	12	33
II	20% of sewage treated	22.5	13.8	38
III	100% treated sewage	17.8	13.7	24

* reference conditions: dry gas at a temperature of 273.15 K, and a pressure of 101,3 kPa, calculated for oxygen content in the flue gas O_2 = 6 vol %.

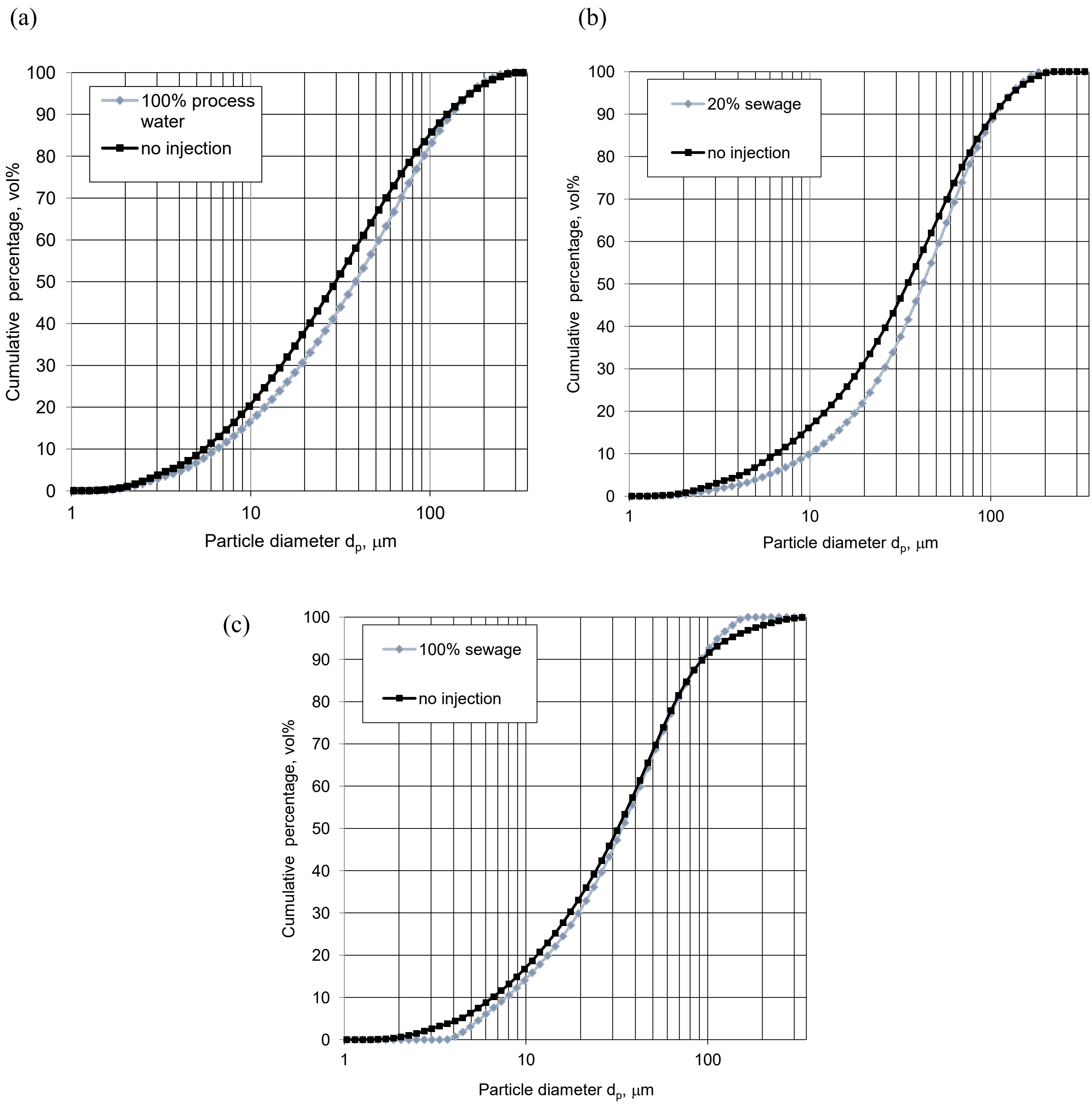


Fig. 3. Particle size distribution of dust samples from the ESP: **a** zone I, series I, **b** zone I, series II, **c** zone I, series III

Table 4. Content of chlorine, sulphate and mercury for fly ash samples from the ESP

No.	Identified component	Unit	Value			
			No injection	Process water	20% sewage	100% sewage
1.	Chlorides (Cl)	mg/kg	96.7	514	748	7,952
2.	Sulphates (SO_4^{2-})	mg/kg	878	1,160	1,112	1,480
3.	Mercury (Hg)	mg/kg	0.269	0.388	0.307	0.298

though, a gradual increase in its concentration was observed during sewage injection. Since the chlorine content in the fuel was not measured, it cannot be definitively stated that this increase was caused by the sewage injection. Further research is required to clarify its cause. The authors hypothesize that this may have resulted from a temporary change in the composition of the combusted coal; however, the described study was unable to clarify this issue. It also seems unlikely that the increase was related to the transfer of chlorine to the gas phase from wastewater-derived compounds, which are primarily $CaCl_2$, $MgCl_2$, and NaCl, whose decomposition temperatures are significantly higher than those occurring in the process described. Once again, downstream of the ESP, a decrease in dust concentration (as shown in Table 3), a decrease in flue gas temperature, and an increase in water vapor content were observed.

Grain composition of dust

Grain composition analyses were performed to determine whether the injection of conditioning liquids caused changes in the grain composition of dusts precipitated in the ESP. Fly ash samples collected from the first zone of the ESP were analyzed because this is where the largest amount of dust is removed. The results are shown in Fig. 3.

In Fig. 3a, a shift in the fly ash grain composition toward larger particle sizes was noticed when water was dosed. The median diameters were 29 μm without injection and 39 μm with water injection.

A similar shift toward larger particles during the dosing of the conditioning liquid containing 20% wastewater is shown in Fig. 3b. The median diameters were 35 μm without injection and 42 μm with liquid injection.

However, as indicated in Fig. 3c, no significant change in the fly ash grain composition was observed when the conditioning liquid consisted of 100% wastewater compared with the case without any liquid injection. The median diameters were 32 μm and 35 μm, without injection and with water injection, respectively.

The obtained results confirmed the beneficial effect of liquid injection into the exhaust gases upstream of the ESP. Only in series III no significant change in grain composition was found. In order to clarify this issue, selected dust samples were additionally examined using a scanning microscope.

Chemical composition of dust

Analyses of the chemical composition of dust samples precipitated in the ESP were performed to determine how the injection of conditioning liquids containing different

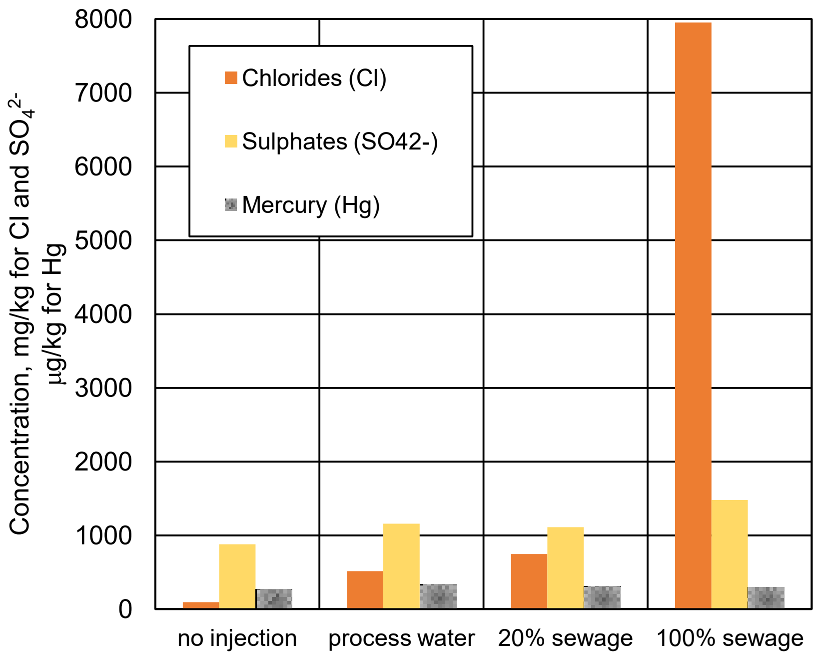


Fig. 4. Content of chlorides, sulphates and mercury for dust samples from the ESP

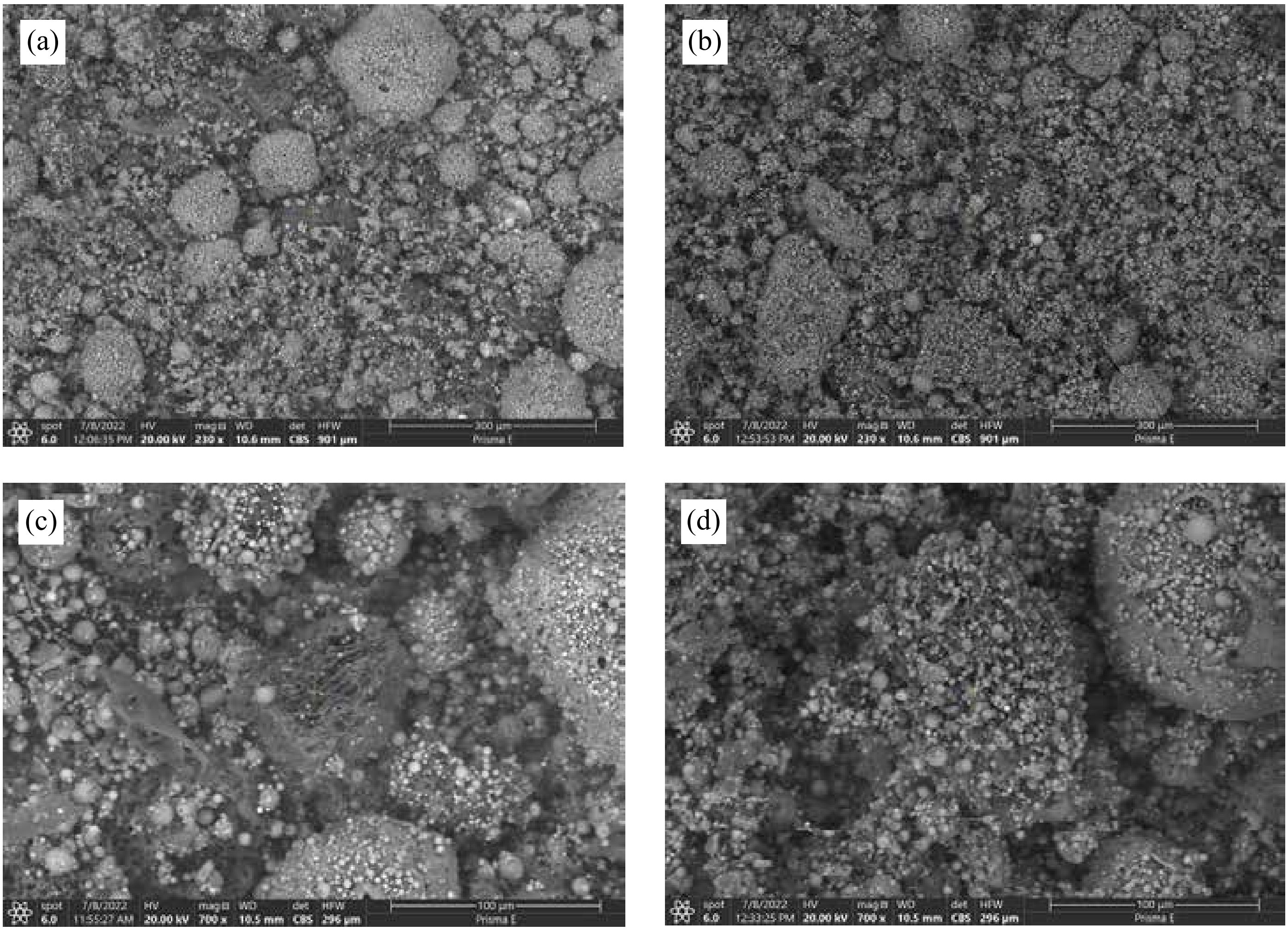


Fig. 5. Scanning electron micrographs of dust samples: **a** sample A, mag. 230x, **b** sample B, mag. 230x, **c** sample A, mag. 700x, **d** sample B, mag. 700x

proportions of sewage affects their properties. This is important because fly ash from the ESP is used as an additive in the production of cement or other construction products. In this context, the chlorine content is crucial and should not exceed 0.1% by mass.

Averaged fly ash samples collected from beneath the ESP were analyzed for their chlorine, sulfate, and mercury contents. The results of these analyses are shown in Table 4.

During Series I, no significant change in the chemical composition of the fly ash was observed due to the injection of process water.

When the 20% sewage solution was injected into the flue gas duct upstream of the ESP, no effect on the mercury content in the ash was detected. However, the levels of sulphates and chlorine in the fly ash increased. This phenomenon is generally attributed to the high chlorine content in the injected liquid (4,245 mg/dm³). Since fly ash is used as an additive in concrete mixes, the chlorine concentration should remain below 0.1%.

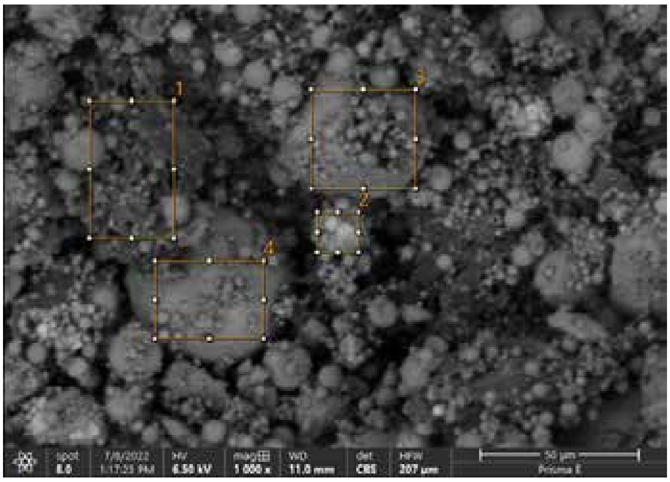
During Series III, when 100% sewage was injected, again, again no effect on mercury levels in the fly ash was observed. But, similar to the previous case, the concentrations of sulfates and chlorine in the fly ash increased, this time due to an even higher chlorine content in the wastewater (18,530 mg/dm³).

A summary of the obtained results is presented in Fig. 4. It is evident that the permissible chlorine concentration in dust samples from the ESP was exceeded when 100% sewage was injected. This indicates the need to limit the proportion of sewage in the applied conditioning liquid if the operator wishes to maintain the utility properties of the fly ash. In this context, other methods for addressing the problem of excessive chloride concentrations in fly ash may also be considered. For example, chloride removal from the wastewater or post-treatment of the ash precipitated in the dust collector could be applied. However, both approaches would require substantial additional costs and are unlikely to be economically justified. Thus, when disposal of at least part of the problematic wastewater is required, the only reasonable solution is to inject a quantity that does not cause the chloride content in the collected ash to exceed permissible limits. Changes in the concentration of other analyzed components were either insignificant (Hg) or did not affect the utility properties of the dust (SO_4^{2-}).

Morphology of dust

The main objective of examining the morphology of dust collected during the study was to verify literature reports on the formation of so-called monolayers on the surface of dust particles exposed to injected sewage (Gostomczyk 2007). According to Gostomczyk (2007), salts (chlorides, sulphates) contained in sewage can alter the properties of the collected dust, for example by changing its resistivity. To investigate this,

(a)



(b)

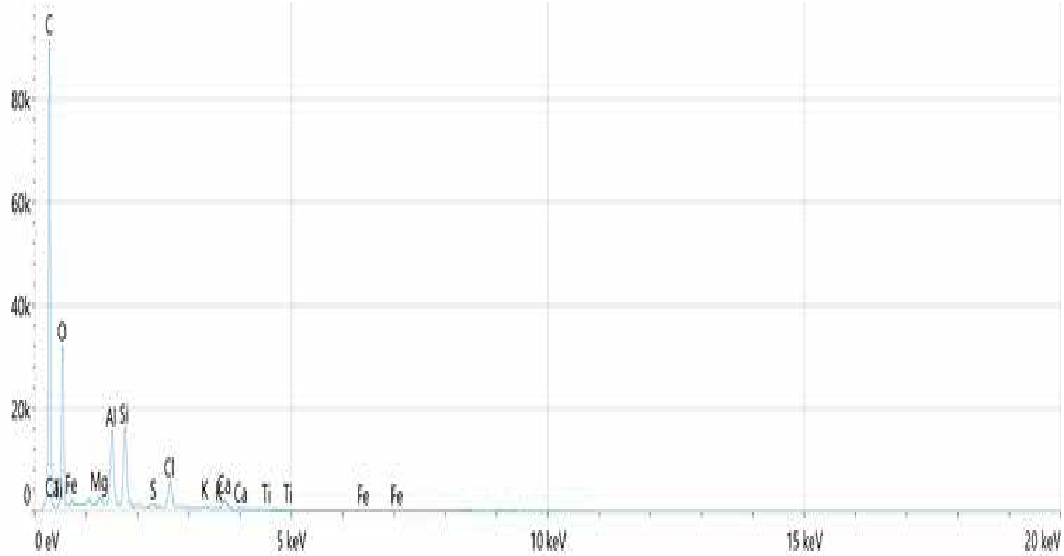


Fig. 6. Results of analyses on a scanning microscope: a sample B, mag. 1000x, b results of analysis of zone no. 1

dust samples collected from beneath the ESP were analyzed using a scanning electron microscope: one sample without sewage dosing (sample A) and one with 100% sewage dosing (sample B). Photographs of both samples were taken at various magnifications, and the particle surfaces were examined to determine the chlorine content, as chlorine was the component with the highest concentration in the injected sewage. The results are presented in Fig. 5.

A qualitative analysis of the photographs in Fig. 5 did not show any significant differences in the morphology of the tested dust samples. The appearance is typical of particles originating from coal combustion in a pulverized-fuel boiler, showing substantial variation in both particle shape and size. The elemental composition of individual particles indicates, among other things, the presence of unburned coal particles (e.g., the particle in the center of Fig. 5 c) and an increased chlorine content in sample B. Figure 6 presents photographs of the tested samples along with an example of chemical analysis results for one of the marked regions.

In the analyzed case, sample B (Fig. 6) showed a chlorine mass fraction ranging from 0.6% to 8.5% in zone 3 and zone 1, respectively, whereas the analysis of sample A did not reveal any chlorine.

The tests performed did not show the presence of a specific layer (monolayer) on the surface of particles exposed to sewage. However, this does not change the fact that the positive effect of conditioning liquid injection on ESP operation was confirmed. Further investigations into the mechanisms governing the deposition of sewage-derived compounds on dust particles are still required, but such studies will likely need to be conducted under well-controlled laboratory conditions.

Summary and conclusions

Challenges associated with reducing harmful emissions and limiting the release of wastewater from industrial processes have prompted the search for technically and cost-effective solutions. One sector facing such challenges is the energy industry based on fossil fuels. Installations burning fossil fuels (including coal) will remain in operation for several decades during the transitional to renewable energy sources; therefore, minimizing their environmental impact is essential. This article proposes a solution that involves injecting the mixture of wastewater from the WFGD absorber into the flue gas stream upstream of the electrostatic precipitator. This approach enables partial disposal of wastewater while simultaneously improving ESP efficiency.

During the tests, treated wastewater originating from WFGD, process water, or their mixtures were injected into a flue gas stream of 125,000 Nm^3/h. It was observed that the conditioning liquid evaporated at the injection point, resulting in a temperature reduction at the ESP inlet. No increase in the concentration of standard pollutants, particularly SO_2, HCl, HF, and NH_3, was detected downstream of the ESP. The reason for the increase in HCl concentration observed during Series III remains unclear.

In all cases, the injection of conditioning liquid resulted in a reduction in dust concentration downstream of the ESP, with the largest decrease of 38% recorded during series II. The values measured during the injection were well below the expected emission limit of 25 mg/m³ (under reference conditions) for the tested unit. This provides plant operators with flexibly when handling variable coal parameters, which increasingly occur in current market conditions. The described studies were short-term in nature due to the operating regime of the peak-load boiler. Further research is necessary to determine the long-term effects of the injection system on ESP performance, including potential risks of corrosion or dust collection problems. However, such risks appear primarily depended on appropriate injection control to prevent condensation of the injected liquid within the ESP. In the described installation, this was ensured by an automatic control system equipped with an algorithm for calculating the acid dew point temperature. The control logic maintained a safe temperature margin above this level: if the exhaust gas temperature downstream of the system dropped below this margin, injection was automatically limited, and if the temperature fell below the calculated acid dew point, the injection system shut down. No other operational problems, such as potential injection nozzle clogging, were observed, though periodic air-blowing, inspection, and maintenance of the nozzle system are planned.

The parameters of the fly ash collected in the ESP depended on the composition of the injected conditioning liquid. Injecting process water had little effect on the chemical composition of the fly ash. However, injecting liquids containing treated sewage increased the concentrations of sulfites and chlorine in the ash. In the case of injecting 100% treated sewage, the permissible chlorine content in ash (<0.1%) was exceeded due to the high chlorine concentration in the supplied wastewater. Therefore, optimization of process parameters is necessary to prevent unacceptable deterioration of the ash quality, which has commercial importance.

Conditioning flue gases by liquid injection improves ESP operation without requiring extensive and costly upgrades, making it particularly beneficial for existing energy facilities that must maintain low emission levels while limiting expenditures. Moreover, the injection system allows for the reduction of other pollutants, such as NO_x and mercury through the use of appropriately formulated liquids (Świerczok et al. 2020, Jędrusik et al. 2021), which will be investigated in future studies on the described installation. The results also indicate that injecting treated sewage into the flue gas duct upstream of the ESP enables its removal in amounts tailored to site-specific conditions. This approach may eliminate the need to extend the sewage treatment system or install evaporators, thereby facilitating compliance with national regulations and BAT conclusions.

A direct cost comparison between the proposed method and alternative wastewater disposal solutions is difficult because alternatives typically require separate systems, including evaporators, dryers, and product-handling lines, to manage the residual solids. In contrast, the system described in this study does not generate an additional waste stream, as contaminants are incorporated into the fly ash collected in the ESP. Additionally, the presented process utilizes waste heat contained in the flue gases, heat that would otherwise be lost, to evaporate the injected liquid. According to the author's best knowledge and supported directly by literature data (Tong and Elimelech 2016, Hill and Heermann, 2014), the investment cost of the described installation is several times lower than that of an evaporator-based system. Nevertheless, these estimates cannot be considered universal, as the optimal solution depends on the specific characteristics of each facility.

References

Amann, M., Kiesewetter, G., Schöpp, W., Klimont, Z., Winiwarter, W., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Gomez-Sabriana, A., Heyes, Ch., Purohit, P., Borken-Kleefeld, J., Wagner, F., Sander, R., Fagerli, H., Nyiri, A., Cozzi, L., Pavarini, C. (2020). Reducing global air pollution: the scope for further policy interventions. *Philosophical Transaction Royal Society,* A 378: 20190331. http://dx.doi.org/10.1098/rsta.2019.0331

Baldrey K. E. et al. (1997). Duke Energy's Operating Experience with ADA-ES Flue Gas Conditioning Technology on a Cold-Side ESP. Power–Gen'97 International Conference, December 9-11, Dallas.

Battles R. L., Lentz M. J. and Wright R. A. (1998). SO_3 Flue Gas Conditioning System with Catalytic Converter Temperature Control by Injection of Water. Pat. USA No 5 791 268

Brown J. R. (1998), Pure Air's Advanced Flue Gas Desulfurization Clean Coal Project, *Environmental Progress*, Vol 17, nr 3, pp. 173-182.

Chenghang, Z., Shen, Z., Yan, P., Zhu, W., Chang, Q., Gao, X., Luo, Z., Ni, M., Cen, K. (2017). Particle removal enhancement in a high-temperature electrostatic precipitator for glass furnace, *Powder Technology*, 319, pp.154–162. doi: 10.1016/j.powtec.2017.06.017.

Ciesielczuk, T., Rosik-Dulewska, Cz. (2023). Decomposition dynamics of cooking-oil-soaked waste paper in media with low inorganic nitrogen content, *Archives of Environmental Protection*, Vol. 49 no. 1 pp. 85–93. DOI 10.24425/aep.2023.144741

Durham M. D. et al. (1998). 2nd Generation Flue Gas Conditioning for Enhanced ESP Performance on Low-Sulphur Coal. Power–Gen'98 International Conference, December 9, Orlando Florida.

EU Decisions Commission Implementing Decision (EU) 2017/1442 of 31 July 2017 establishing best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for large combustion plants (notified under document C(2017) 5225), in Polish

EU Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010, on industrial emissions (integrated pollution prevention and control), Official J Europ Union, (2010), L 334/17).

Gostomczyk M. A. (2007). New technologies and techniques for flue gas desulphurization. *Energetyka Cieplna i Zawodowa*. nr 1, pp. 45-47 (in Polish).

Hilborn J. W. (1993). Traditional Versus Non-traditional Flue Gas Conditioning for Electrostatic Precipitators. Proc. 10th Particulate Control Symposium and 5th ICESP, Vol. 2, April 5-8, Washington DC.

Hill H., Heermann M. (2014) Zero Liquid Discharge Effluent Guidelines Compliance Strategies for Coal-Fired Power Plants' FGD Wastewater, Presented at Power-Gen, International Conference, December 7-11, Orlando.

Jędrusik M., Łuszkiewicz D., **Świerczok** A. (2021) Methods to reduce mercury and ni-trogen oxides emissions from coal combustion processes. In: Environmental emissions / ed. Richard Viskup. London : IntechOpen, pp. 1-23. doi: 10.5772/intechopen.92342

Katz J. (1981) *The art of electrostatic precipitation*. S&S Printing Company, INC Pittsburgh, Pennsylvania.

Klyta, J., Janoszka, K., Czaplicka, M., Rachwał, T. (2023). Co-combustion of wood pellet and waste in residential heating boilers – comparison of carbonaceous compound emission, *Archives of Environmental Protection*, Vol. 49 no. 3 pp. 100–106. DOI 10.24425/aep.2023.147332

Krigmont H. V., Coe E. L. (1990). Experience in Conditioning Electrostatic Precipitators. In: 4th International Conference on Electrostatic precipitation, Beijing, China, pp 597-609.

Lund C. R., Selby M., Cottingham C. (1998). Dual FGC Solving ESP Performance Problems. Proc. 7th ICESP, Sep. 20-25, Kyongju, Korea.

MME&IN Regulation, Regulation of the minister of maritime economy and inland navigation of 12 July 2019, on substances particularly harmful to the aquatic environment and on the conditions to be met when discharging sewage into waters or soil, as well as when discharging rainwater or meltwater into waters or into water facilities, in Polish.

Navarrete, B., Alonso-Fariñas, B., Lupión, M., Cañadas, L. (2015). Effect of Flue Gas Conditioning on the Cohesive Forces in Fly Ash Layers in Electrostatic Precipitation. *Environmental Progress & Sustainable Energy*, Vol.34, No.5. doi: 10.1002/ep12133

Parker K. R. et all (1997) *Applied Electrostatic Precipitation*. Blackie Academic & Professional, London.

Pilco-Nuñez, A., Hinostroza-Antonio, E., Diaz-Bravo, P., Palacios-Salvador, W., Solis-Toledo, R., Baldeon-Romero, J. (2024), Removal of microplastics by electrocoagulation, *Archives of Environmental Protection*, Vol. 50 no. 4 pp. 64–71. DOI 10.24425/aep.2024.152896

Porle K., Bradburn K., Bader P. (1996). FGC as a Means for Cost – Effective ESPs for Low Sulphur Coals. Proc. 6th ICESP, 18-21 June, Budapest

Primus, A., Buntner, D., Rosik-Dulewska, Cz., Chmielniak, T. (2024). Energy efficiency of waste gasification plants in the national municipal waste management system, *Archives of Environmental Protection*, Vol. 50 no. 4 pp. 93–103. DOI 10.24425/aep.2024.152899

Schwab J. J. and Hawks R. L. (2000). Detached Plume Abatement Method. Pat. USA No 6 060 030.

Shanthakumar S., Singh D.N., and Phadke R.C. (2009). The Effect of Dual Flue Gas Conditioning on Fly Ash Characteristics, *Journal of Testing and Evaluation*, Vol. 37, No. 6.

Shuangchen, M., Jin, Ch., Gongda, Ch., Weijing, Y., Sijie, Z. (2016) Research on desulfurization wastewater evaporation: Present and future perspectives. *Renewable and Sustainable Energy Reviews,* 58, pp. 1143-1151. doi: 10.1016/j.rser.2015.12.252.

Starzomska, A., Strużewska, J. (2024). A six-year measurement-based analysis of traffic-related particulate matter pollution in urban areas: the case of Warsaw, Poland (2016-2021), *Archives of Environmental Protection*, Vol. 50 no. 2 pp. 75–84. DOI.10.24425/aep.2024.150554

Świerczok A., Jędrusik M., Łuszkiewicz D. (2020). Reduction of mercury emissions from combustion processes using electrostatic precipitators. *Journal of Electrostatics,* 104, pp. 1-5. doi:10.1016/j.elstat.2020.103421

Tong, T., Elimelech, M. (2016). The Global Rise of Zero Liquid Discharge for Wastewater Management: Drivers, Technologies, and Future Directions, *Environmental Science & Technology,* 50, pp. 6846−6855, DOI: 10.1021/acs.est.6b01000

Wang, Ch., Miao, X., Fang, M., Chen, Y., Jin, T. (2024). The improvement of Beijing ambient air quality resulting from the upgrade of vehicle emission standards, *Archives of Environmental Protection*, Vol. 50 no. 3 pp. 109–121. DOI:10.24425/aep.2024.151690

Wolska, M., Kabsch-Korbutowicz, M., Solipiwko-Pieścik, A. (2024). Assessing the feasibility of using ultrafiltration to recirculate backwash water in a surface water treatment plant, *Archives of Environmental Protection*, Vol. 50 no. 2 pp. 3–13. DOI.10.24425/aep.2024.150547

Ograniczenie misji pyłów przy wykorzystaniu ścieków z absorbera mokrego odsiarczania spalin jako przykład wdrożenia strategii zerowego zrzutu cieczy

Streszczenie: W dalszym ciągu bardzo istotne są działania mające na celu ograniczenie szkodliwego oddziaływania przemysłu na środowisko. W artykule przedstawiono rozwiązanie umożliwiające jednoczesne ograniczenie emisji pyłów i usuwanie ścieków z miejskiej elektrociepłowni. Zaprezentowano wyniki przeprowadzonych badań wtrysku oczyszczonych ścieków (lub ich mieszaniny z wodą) z instalacji mokrego odsiarczania spalin (IMOS) przed elektrofiltrem (EF), do oczyszczania spalin z kotła pyłowego opalanego węglem kamiennym. Instalacja wykorzystuje ciepło odpadowe spalin do eliminacji wtryskiwanej cieczy poprzez jej całkowite odparowanie. Jednocześnie przyczynia się do zwiększenia skuteczności EF poprzez kondycjonowanie spalin. Badania przeprowadzono na instalacji o wydajności wtrysku cieczy maksymalnie 6 m³/h do strumienia objętości spalin o średniej wartości ok. 125 000 Nm³/h. W trakcie badań potwierdzono zupełne odparowywanie cieczy kondycjonującej. Nie stwierdzono wzrostu stężenia zanieczyszczeń w spalinach, w szczególności SO_2, HCl, HF, NH_3, przy temperaturach w jakich przebiegał wtrysk (ok. 200°C). Z kolei zaobserwowano spadek stężenia pyłu za elektrofiltrem po wtrysku cieczy kondycjonującej. Uzyskane wyniki wskazują, że przedstawiona instalacja umożliwia eliminację częściowego strumienia ścieków z IMOS. Ponadto przyczynia się do poprawy skuteczności pracy elektrofiltra bez konieczności jego głębokiej i kosztownej modernizacji, co jest szczególnie istotne dla istniejących obiektów przemysłowych.