Experimental studies on WFGD sewage injection upstream of electrostatic precipitator

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Summary

The paper presents a method of utilization of cleaned sewage from flue gas wet desulfurization treatment plant. For this purpose a sewage injection system has been designed and installed at the inlet of an ESP. For a horizontal flue gas duct, the designated operational parameters of the sewage injection system, such as the permissible drop of temperature, evaporation time of the sewage drops, and the length of zone to complete evaporation have been determined. Preliminary studies have shown that an injection of about 2.5 m^3/h of liquid sewage caused the flue gas temperature to decrease of about 17-20°C, without disturbing the operational parameters of ESP. An increase of ESP-precipitated dust particles modal diameter from 16 to 88 μm after sewage injection has been noticed, whereas the characteristic chemical parameters of the dust have not been altered. The experimental work on the dust collection efficiency and dust emission, using this test installation, will further be continued.

1. Introduction

Polish power generation industry is based mainly on the combustion of hard and brown coals that requires removal of dust (fly ash) particles as well as nitrogen and sulfur oxides from flue gases. Present Polish allowable emission limits are 20 mg/m^3_{stp} for particles and 200 mg/m^3_{stp} for SO_2 that requires implementation of new high efficient devices for the reduction of these pollutants. Usually electrostatic precipitators (ESP) and wet flue gas desulfurization (WFGD) systems are used for this goal. However, WFGD installations generate a large amount of liquid sewage requiring further accurate cleaning.

One of the methods of liquid sewage utilization may be the usage of the sewage as a gas conditioning medium, injected upstream of electrostatic precipitator (ESP). Flue gas conditioning for electrostatic precipitation by means of water or chemical compounds is well known and often applied to mitigate problems with the collection of high-resistivity dust [1, 2]. Flue gas conditioning by humidification and cooling results in a decrease of flue gas volume and the reduction of dust resistivity that improves collection efficiency of ESP. The hitherto carried-out studies on the effect of flue gas cooling and humidification on ESP collection efficiency have shown a significant increase of the collection efficiency [3, 4].

Current Polish Emission Standards limit the yearly-averaged mercury concentration in ambient air to 0.04 $\mu g/m^3$. Therefore, taking into account the expected more stringent EU requirements, cutting further the allowable air pollution limits, also for small emission sources (below 50 MW_t), it is necessary to develop new methods and devices for the reduction of emission of mercury and respirable particles by industrial installations, mainly coal fired power plants, which will meet the new regulations (PM10 and PM2.5). In near future, it will be the most difficult task for Polish power industry, based on the combustion of coal, which is the main source of emission of those pollutants, to reduce the emission. The content of mercury in polish coals ranges from 30 to over 1000 μg/kg, and furthermore, the greater is the content of ash in coal, the higher is the percentage of mercury in it.

From the results of former studies on different methods of reduction of mercury, which had been tested in American power industry, it can be concluded that the following solutions are the most promising:

- activated carbon injection into flue gas [5],
- mercury removal in ESP by injection of active sorbents (reagents) [6, 7],
- wet flue gas desulfurization supported by different additional oxidizing substances [8, 9],
- flue gas cleaning by a sorbent covering fabric filter (FF) material [8, 10].

At this time, the most advanced method of mercury removal is activated carbon injected into flue gasses upstream of ESP or ahead of FF [5, 11]. The most frequently used sorbents are activated carbon, $Ca(OH)_2$, $CaSiO_3$ and modified fly ash. However, all of the sorbents have reduced collection efficiency of mercury at temperatures above 200°C.

Moreover, the consumption of activated carbon in this process significantly increases costs of the production of electrical energy. According to [11, 12], for a coal containing of about 0.1ppm$_v$ of mercury, by the cost of activated carbon of ca. 1.0 $/kg the costs of production of electric energy should be higher of about 0.0004 $/kWh. It was also estimated that the total costs of removal of 1 kg of mercury from flue gas would be about 30 000-85 000$. For a power unit of 250 MW$_e$ having yearly emission of mercury of 65 kg, the reduction of mercury emission by 50% would result in a cost from 1 to 3 mln$.

The oxidation of mercury considerably improves mercury collection efficiency. Some researches have considered the injection of chlorine into boiler. However, such injection has a negative effect on the furnace and other elements of combustion and gas cleaning installation, increasing their corrosion that makes this method less attractive.

Taking into account all the above mentioned problems, one should expect that power plants will look after low-cost and high-effective technologies of mercury emission control. One of such technologies is that which utilizes cleaned sewage from flue gas wet de-sulphurization treatment plant, with the addition of small amount of properly selected mercury oxidants. Preliminary tests indicated that this technology is a cheaper and more effective solution for the reduction of mercury emission into atmosphere. The Hg^{2+} ions, after reaction with an oxidant, form solid HgO particles, which can be easily removed by ESP together with fly ash particles.

In this paper, a novel design of experimental installation for the utilization of WFGD liquid sewage for flue gas conditioning in an ESP is presented. This solution has an important impact on ecology, especially when a large amount of chlorides, sulfates and heavy metals are contained in the sewage. One of the important advantages of this installation is its ability to the reduction of emission of mercury, which is released during the coal-combustion process.

2. Experimental installation description.

The investigated wet de-sulphurization treatment plant (WFGD) is able to clean form 500 000 to 1 600 000 m^3/h damp flue gasses, having a temperature between 120 and 140°C. Sewage generated in the de-sulphurization process is lead to a sewage-treatment plant comprising of the following sections:

- heavy metals neutralization and precipitation,
- flocculation and separation of particles,
- de-watering of sewage sludge,
- final monitoring of cleaned sewage.

The sewage at the outlet of this installation has the following parameters: pH=8.5; chlorides content about 30 000 mg/dcm^3; sulfates contents ca. 2000 mg/dcm^3. However, the content of mercury and other heavy metals compounds does not meet the clean-water regulations. In order to utilize the liquid sewage, a special technology installation, schematically shown in Fig 1, has been designed.

The liquid sewage is injected into flue gas prior to entry to ESP, in horizontal part of the flue gas ducts of cross section of 5.0×2.7 m and length of 7.0 m.

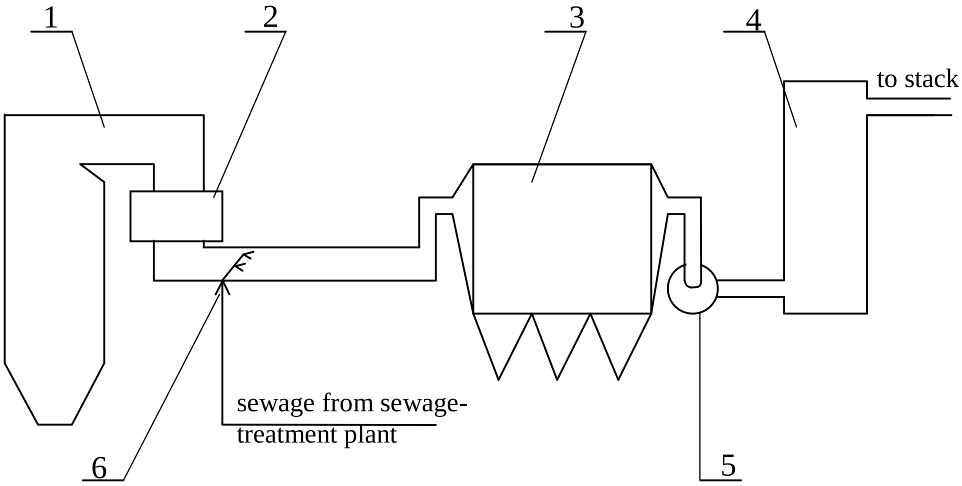

Fig. 1. Diagram of liquid sewage injection system upstream of the inlet to ESP: 1 – boiler, 2 – air preheater, 3 –ESP, 4 –wet scrubber, 5 – fan, 6 – injection system

In Fig. 2 are shown injection pipes assembled in the inlet flue gas duct prior to ESP

Fig. 2. Injection pipes (lances) inside flue gas duct

The installation comprises of liquid sewage feeding system and injection system. In the gas dust are fixed two injection pipes with 12 twin-fluid nozzles. Air needed for injection is heated in a channel heater.

The cleaned liquid sewage from the WFGD treatment plant injected to the duct prior to ESP cools down the flue gas in the process of complete evaporation of the liquid. It is necessary to notice that the cooling process should keep the flue gas temperature about 20-40°C above the water dew point.

3. Estimation of injection installation operational parameters

The spray apparatus used for the humidification of flue gas leaving a boiler can be considered as a direct, non-membrane heat exchanger operating in a setup: hot gasses – sprayed liquid. The useable (active) volume, in which the sprayed liquid evaporates completely, can be determined from the following equation:

$$V_{ap} = Q/\left(k_V \Delta t_{avg}\right) \qquad (1)$$

where:

Q – the heat flux transferred from gas phase to the sprayed liquid, W,

k_v – the volume coefficient of heat penetration, W/(m^3·K),

Δt_{avg} – average temperature difference (heat penetration motive module), °C.

The heat flux transferred from hot gasses to the sprayed liquid, Q, is calculated from the equation:

$$Q = \frac{\dot{m}_c}{3600}\left(I''_{p.w.} - t'_c \cdot c_{p.c.}\right) \qquad (2)$$

in which:

$c_{p.c}$ – is the liquid specific heat, J/(kg·K),

$I''_{p.w.}$ – is water vapor enthalpy corresponding to the temperature of flues gas phase t''_{sp}, J/kg (of dry gas),

$\dot{m}_c$ – is the mass flow rate of sprayed liquid, kg/h,

t'_c – is the initial temperature of the liquid, °C.

Water vapor enthalpy $I''_{p.w.}$ is described by the relationship:

$$I''_{p.w.} = 1.97 \cdot t_{2g} + 2493 \tag{3}$$

The length of heat exchanger zone (evaporation zone) in a horizontal flue gas duct is:

$$L_{ap} = \frac{V_{ap}}{F_{ap}} = \frac{V_{ap}}{a \cdot b} \tag{4}$$

where:

a, b – are the cross section dimensions of the flue gas duct, m,

F_{ap} – is the cross-section area of the flue gas duct, m^2.

Volume coefficient of heat penetration of non-membrane heat exchanger, in this specific case for the horizontal flue gas duct, is:

$$k_v = \alpha\left(116.5 + 525\frac{\dot{m}_c}{\dot{m}_g}\right)\left(1 + \frac{t_{avg.g}}{1000}\right) \tag{5}$$

where:

α – is an experimental coefficient of proportionality (for a counter-current phase flow α=1, and for co-flow phase α=2),

$\dot{m}_g$ –is the mass flow rate of gaseous phase, kg/h,

$t_{avg.g}$ – is an arithmetic average temperature of gas in the duct, ºC.

The average temperature difference (heat penetration motive module) in an apparatus is described by the equation:

$$\Delta t_{avg} = \frac{t_{1g} - t_{2g}}{\ln\dfrac{t_{1g} - t_M}{t_{2g} - t_M}} \tag{6}$$

where:

t_{1g} – initial temperature of the flue gas, ºC,

t_{2g} – final temperature of the flue gas, ºC,

t_M – wet thermometer temperature, ºC.

The average flue gas temperature in the liquid evaporation zone may be calculated as:

$$t_{avg.g} = \frac{t_{1g} + t_{2g}}{2} \tag{7}$$

Gas phase temperature after its humidification in the flue gas duct can be determined from the regression equation, derived by the authors of this paper, based on a set of experimental data obtained for the liquid evaporation operational parameters specific to the investigated installation:

$$t_{2g} = t_{1g}^{\ 1.1563} \cdot x_{1g}^{\ 0.01148} \cdot I_{1g}^{\ -0.01372} \cdot \dot{m}_c^{\ -0.13843} \cdot w_{1g}^{\ 0.13087} \tag{8}$$

Input data for an example calculation of sewage evaporation apparatus are:

- mass flow rate of hot flue gas (raw) $\dot{m}_g$ = 520 000 kg/h
- flue gas density at a temperature before injection plane: $\rho_{\iota g}$ =0.8543 kg/m^3 ,
- sewage mass flow rate before evaporator $\dot{m}_c$ = 2525 kg/h,
- sewage density: ρ_c = 1010 kg/m^3,
- flue gas temperature before evaporator (apparatus) : t_{1g} = 140°C,
- humidity of flue gas before evaporator apparatus: x_{1g} =0.037 kg/kg (of dry flue gas),
- enthalpy of raw flue gas (before apparatus) I_{1g} = 243.85 kg (of dry flue gas),
- flue gas velocity in the gas duct: w_{1g} = 12.45 m/s.

The results of calculation are

- heat flux: Q=1836×10^3 W,
- coefficient of heat penetration: k_v=2388 W/m^{3}K,
- average temperature difference: Δt_{avg}=111.75°C,
- useable volume: V_{ap}=69.0 m^3,
- length of evaporation zone: L_{ap}=5.11 m

The calculations have shown that the cross-section of a horizontal duct should be 5.0 × 2.7 m and its length of 5.11 m in order to evaporate the sewage flowing from WFGD with mass flow rate of 2525 kg/h, completely after its injection into flue gas. In the experimental installation under investigation, the length of the duct is about 7.0 m.

The considered experimental installation of sewage injection has been assembled on a real power plant upstream of an electrostatic precipitator. The primary parameters for that installation will be as follows: temperature of flue gasses after injection zone (and complete evaporation of sewages in flue gas) should be 127.7°C; flue gas humidity will be 0.042 kg/kg$_{\text{dry gas}}$; and evaporation time for drops with maximal diameter of 140 μm will be ca. 0.41 s.

4. Sewage injection upstream of ESP – primary results

The presented technological installation (Fig. 1) is an original solution for utilization of cleaned liquid sewage from WFGD. The installation has been built at the entrance to a two-sectional, electrostatic precipitator (ESP) with three serial zones. Its basic parameters are as follows: active length of electric field 3 × 3.5m; active height 14 m; gas duct width 300 mm; and designed efficiency of 99.86%. The ESP is provided to clean flue gasses from a steam boiler co-fired with hard coal and biomass (up to 10%).

There are two inlet gas ducts and four outlet gas ducts. Measurements were carried out on the left ESP section and basic flue gas parameters are listed in Table 1.

Table 1. The results of the measurement gas flow before the ESP

	Parameter	Symbol	Unit	W/o inject.	With inject.
Boiler	Boiler capacity	Q_B	MW	140	140
	Steam temperature	T_s	°C	292	292
	Steam volume	V_s	t/h	422	422
Measuring plane	Flue gas temperature	t_{sp}	°C	133	113
	Stat. pressure	p_{st}	hPa	-18.0	-17.0
	Oxygen	u_{O2}	%	8.7	8.5
	Humidity	X	kg/kg	0.030	0.042
	Flue gas cross section	A	m^2	13.5	13.5
	Flue gas velocity	w	m/s	9.06	9.42
	Flue gas flow rate (actual)	$\dot{V}_a$	m^3/h	440 316	457 860
	Flue gas flow rate (STP))	$\dot{V}_{stp}$	m^3/h	291 107	297 868
	Flue gas flow rate (STP dry gas))	$\dot{V}_{stp,d.g.}$	m^3/h	277 163	280 900

During the operation of experimental installation, sewage has been injected into two ducts of raw flue gas by means of 2 × 2 lances with a total flow rate of 5-6 m^3/h. The flue gas temperature had stabilized at a level of 113°C after an hour of sewage injection, without disturbing the operation of ESP.

Samples of fly ash precipitated in ESP were taken before and during the test runs in order to determine the fly ash electric resistivity, its chemical composition and size distribution. Fig. 4 presents the size distribution of fly ash collected from the first collection zone of the ESP during the tests with and also without sewage injection. It can be noticed from the characteristics shown in Figs. 4a and 4b that sewage injection into flue gas significantly influences the size distribution of fly ash particles.

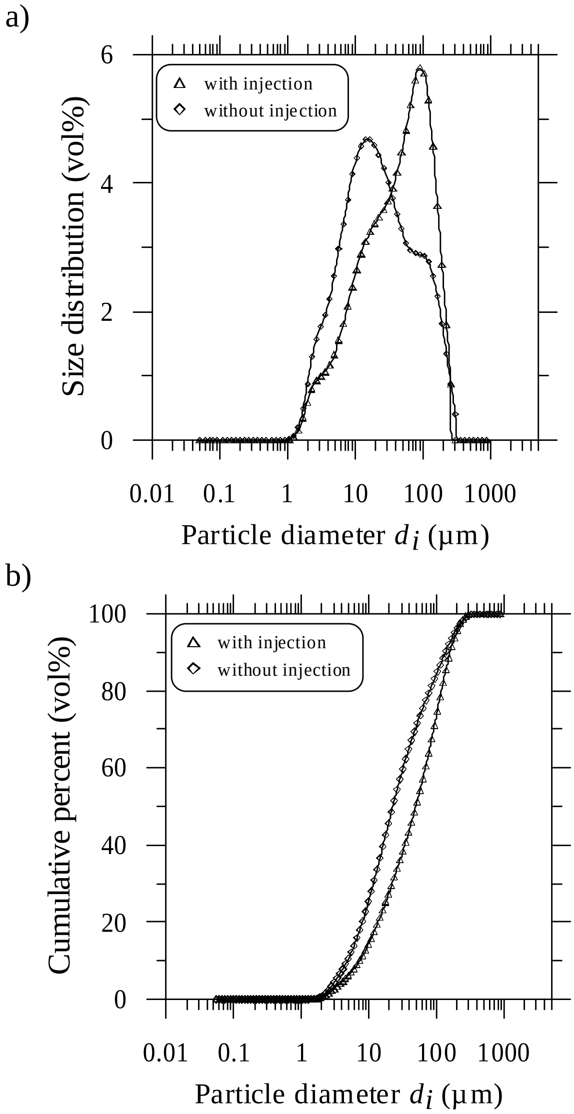

Fig. 4. Fly ash size distribution of samples taken from ESP first zone of precipitator; a) volume size distribution, b) cumulative volume size distribution.

The fly ash collected from the first zone of ESP has more coarse particles when sewage injection is applied. The modal diameter of the particles increases from d_{max}=16 µm to d_{max}=88 µm for the samples from the ESP operating without and with sewage injection, respectively. Similarly, the median diameter increases from d_{50}=24 µm to d_{50}=52 µm.

Table 2 shows selected results of physicochemical analysis of fly ash for these two cases. The fly ash samples were analyzed by X-ray fluorescence method in order to determine their elemental composition. Also fly ash samples were tested for its electric resistivity measured at a temperature of 20°C.

Table 2. Fly ash samples chemical composition and electric resistivity

Parameter	Unit	Intake point		
		gas duct (w/o injection)	gas duct (with injection)	hopper (with injection)
Fe_2O_3	%	3.71	3.62	3.42
SO_3	%	0.69	0.94	0.68
CaO	%	1.88	5.06	3.15
SiO_2	%	47.68	43.78	49.18
Al_2O_3	%	32.00	25.69	29.71
Na_2O	%	2.91	2.17	2.80
MgO	%	2.41	3.80	3.17
K_2O	%	2.22	2.89	2.78
TiO_2	%	0.82	0.73	0.74
P_2O_5	%	-	-	-
Unburned carbon	%	5.10	8.24	3.86
Resistivity	Ω·cm	7.1×10^8	6.8×10^8	7.0×10^8

The analysis has not shown significant differences of the fly ash chemical composition when sewage injection was applied and without it. The average content of fly ash primary components, i.e., aluminosilicates Al_2O_3 & SiO_2 is in the range of 25÷32% and 44÷49%, respectively, which are typical values for fly ash after PC boilers. The content of alkaline earth metals CaO + MgO in fly ash samples has been between 4 and 8%, and the content of alkaline oxides $K_2O + Na_2O$ of about 5%. The first two components contribute to an increase in resistivity of fly ash, but their total percentage in the tested samples was too low to influence the resistivity significantly. On the other hand, the content of alkaline oxides above 2% favors an increase in bulk conductivity of fly ash. The results of measurements of fly ash resistivity in laboratory tests have not shown any influence of the sewage injection into flue gas upstream of ESP on the resistivity of precipitated particles. Likewise, alkaline earth metals CaO + MgO and alkaline oxides $K_2O + Na_2O$ are of similar percentage in the tested fly ash samples like in PC boiler fly ash.

5. Summary

An experimental installation for sewage injection into flue gas prior to entry into ESP was used for the utilization of cleaned sewage from WFGD. The tested installation has met the expected assumptions regarding its operation.

It may be concluded that:

- sewage injection effectively contributes to fly ash particles agglomeration that results in increased collection efficiency of ESP.
- basic chemical composition and resistivity of fly ash have not been changed after sewage injections into flue gasses upstream of ESP.

These preliminary results needs further studies for their verification, especially the dependence of fly ash size distributions and ESP collection efficiencies on different operational parameters of ESP and the injection installation. The studies and tests of the experimental sewage injection installation will be continued in order to optimize its operational parameters and to reduce sewage cleaning requirements, or even, in particular cases, entirely eliminate the sewage cleaning.

References

[1] Cain J.D., Cushing K.M., Altman R.F., *Improvements in Predicting the Effects of Sulphur Trioxide Vapor on Fly Ash Resistivity*. Procee. 8th ICESP May 14-17, 2001, Vol. 2, Birmingham, Alabama, USA,

[2] Parker K.R., *Applied Electrostatic Precipitation*, Blackie Academic & Prof., London 1997

[3] Jędrusik M., *Electrostatic precipitators - development of selected technologies increasing the effectiveness of dust removal*, Wroclaw University of Technology Publishing House, Wrocław 2008 (in Polish)

[4] Jędrusik M., Jędrusik J., *Exploitation experience of the cooperation of an electrostatic precipitator and a*

desulphurization installation. Procee. of 6th International Conference on Electrostatic Precipitation, Budapest, Hungary, 18-21 June 1996

[5] Levy E.K., Kiely C.: *Investigation of fly ash and activated carbon obtained from pulverized coal boilers*, Annual Report, September 1, 2004 to September 1, 2005

[6] Li Y., Daukoru M., Suriyawong A., Biswas P.: *Mercury Emission Control in Coal Combustion Systems Using Potassium Iodide: Bench-Scale and Pilot-Scale Studies*, Energy & Fuels, 2009, 23, pp. 236-243

[7] Smolík, J.; Schwarz, J.; Dzumbová, L.; Veselý, V.; Sýkorová, I.; et. al *Particulate emissions from fluidized bed combustion of lignite with mineral sorbents* . Journal of Aerosol Science, Volume: 31, Supplement 1, September 2000, pp. 670-671

[8] Naik Chitralkumar V.; Krishnakumar Balaji; Niksa Stephen, *Predicting Hg emissions rates from utility gas cleaning systems*, Fuel, Vol.: 89, Issue: 4, April, 2010, pp. 859-867

[9] Stergaršek Andrej; Horvat Milena; Kotnik Joze; Tratnik Janja; Frkal Peter; Kocman David et. al; *The role of flue gas desulphurisation in mercury speciation and distribution in a lignite burning power plant*, Fuel, Vol: 87, Issue: 17-18, December, 2008, pp. 3504-3512

[10] Cao Yan; Cheng Chin-Min; Chen Chien-Wei; Liu Mingchong; Wang Chiawei; Pan Wei-Ping, *Abatement of mercury emissions in the coal combustion process equipped with a Fabric Filter Baghouse,* Fuel, Vol: 87, Issue: 15-16, November, 2008, pp. 3322-3330

[11] C.E. Romero et al. *Modification of boiler operating conditions for mercury emissions reductions in coal-fired utility boilers,* Fuel 85 (2006) 204–212

[12] Pavlish J. H., et all: *Status review of mercury control options for coal-fired power plants*, Fuel Proces. Technol., 2003, 82, 89–165