Comparison of selected plasma technologies

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Contents

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1 Introduction

During fossil fuels combustion several pollutants are released to the atmosphere. Sulfur and nitrogen oxides are among the most important pollutants due to their great global emission and long range transport in the atmosphere, making the emission no more a local problem. However other pollutants like volatile organic compounds (VOCs), mercury, particulates and others are of not less importance. At present, wet flue gas desulfurization (wet-FGD) and selective catalytic reduction (SCR) are the most widely applied for SO_x and NO_x emission control. VOC are mostly removed by adsorption. The above mentioned methods are costly, single chemical stage processes which form wastewater and solid wastes (gypsum, used catalyst). Therefore, multi-component, waste free processes are of great interest to the industry.

Plasma based emission control technologies are the most promising among new generation emission control methods. Electrical discharge as well as electron beam techniques are emerging as successful methods for converting gaseous pollutants, such as SO_2, NO_x and VOCs into inert or treatable species. Various kinds of non-thermal plasma reactors have been developed. The most known are dielectric barrier discharge, corona discharge, pulse corona discharge and electron beam.

The plasma technologies are at different development stage – from laboratory scale until industrial implementations. On the other hand plasma based environmental technologies has numerous applications: inorganic and organic pollutants emission control, water treatment, sludge higienization and others.

Most emission control plasma technologies has already been tested in pilot scale, but only few industrial implementations were achieved. In this work main plasma technologies for SO_2 and NO_x removal at pilot scale were characterized and their parameters were compared. However as the operational cost is one of the most important factors in industrial scale, such cost was estimated for three plasma emission control technologies and compared with conventional methods.

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2 Plasma generation

There are known several ways of non-thermal plasmas generation in flue gas streams. Plasma can be generated either by the injection of a high energetic electron beam or the generation of a gas discharge. In discharge generated plasmas the electrons have lower mean energies than in electron beam produced plasmas, however, discharge generated plasmas give the chance to construct more compact after treatment systems for small and medium size gas streams.

As the electron beam injection is a base of electron beam flue gas treatment (EBFGT) technology, much more other technologies are based on gas discharges as: dielectric barrier discharge (DBD), corona discharge, arc and gliding arc discharge, glow discharge. The above mentioned plasma generation ways require direct contact of at least one electrode with the gas. This is not required in radio frequency and microwave discharges.

The comparison of main process parameters of selected methods of plasma generation is given in Table 1.

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Table 1. Comparison of main process parameters of selected plasma generation methods [1].

Process parameter \ Plasma technology	DBD	Corona discharge	Arc discharge	Glow discharge	Radio frequency discharge	Microwave discharge	Electron beam injection
Voltage [V]	$5\cdot10^{3}$- $2\cdot10^{4}$	10^{4} - 10^{5}	10^{2}- $5\cdot10^{2}$	10^{2} - 10^{3}	10^{2}- $5\cdot10^{2}$	10^{2}- $5\cdot10^{2}$	10^{5}- $2\cdot10^{8}$
Current [A]	10^{-3} – 10	10^{-6} -10^{-1}	10 - 100	10^{-4}- $5\cdot10^{-1}$	10^{-3}- 10^{3}	10^{-3}- 10^{3}	10^{-3}- DC
Current frequency [Hz]	10-10^{5}	DC	DC	DC	10^{3} - 10^{5}	$3\cdot10^{5}$- 10^{6}	DC-10
Gas pressure [Pa]	10^{5}- 10^{7}	10^{-1}- 10^{5}	10^{4} - 10^{7}	1- $4\cdot10^{4}$	1 - 10^{2}	10^{3}-10^{4}	1-10^{2}
Pressure drop	high	medium	medium	medium	low	low	low
Gas flow rate [Nm^{3}/h]	10^{-2} – 1	1-10^{2}	10^{-1} - 10	10- 10^{2}	10^{-2}-10	10^{-2}-1	10^{3}- 10^{5}
Plasma density	high	locally high	very high	low	high	high	very high
Electron temperature	medium	locally high	locally high	low	medium	medium	very high
Gas temperature	low	low	very high	locally high	high	medium	low
Energy transfer efficiency [%]	30 - 80	90 - 95	70 - 90	under 10%	50 - 70	30 - 60	80 - 95

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3 Comparison of selected pilot plants

Among the past or existing plasma based pilot plants for SO_2 and NO_x removal, four were selected as the most representative: electron beam flue gas treatment (Poland), electro-catalytic oxidation (USA), corona discharge (China) and pulsed corona discharge (Italy).

Pilot electron beam flue gas treatment plant

The electron beam flue gas treatment pilot plant was constructed in Kaweczyn Power Station in Warsaw, Poland [2]. The facility was put into operation in 1992. The plant was operated on flue gas taken from the boiler WP-120 fired by pulverized hard coal. Maximum flow rate was 20 000 Nm^3/h. The scheme of installation is presented in Figure 1.

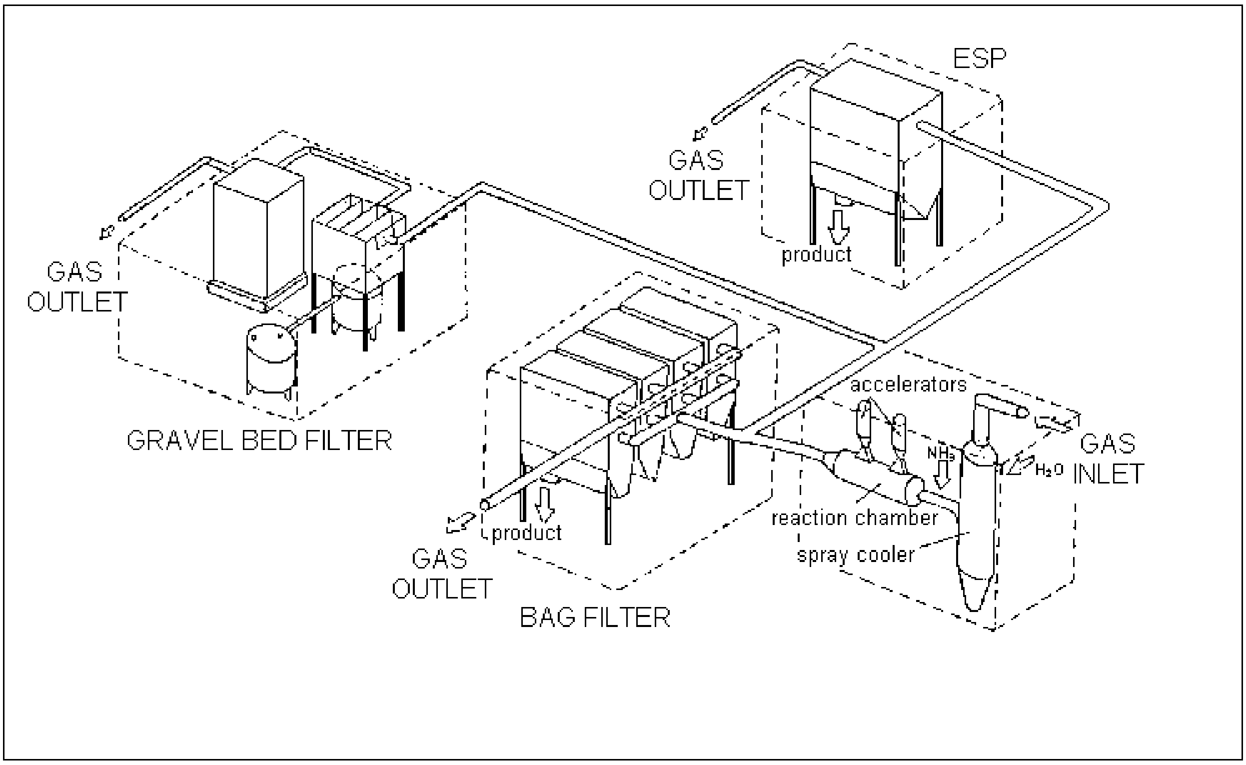

Figure 1 The scheme of Kaweczyn EBFGT pilot plant

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The flue gas inlet parameters were typical for low sulfur content hard coal fired boilers. Temperature of flue gas was in the range from 100 to 125°C depending on boiler load, while humidity was from 4 to 6%vol. Typical SO_2 concentration in flue gas was in the range 200 to 600 ppmv (about 1400 – 2100 mg/Nm^3). In several experiments, the SO_2 concentration was increased by introducing SO_2 from cylinders up to 3000 ppmv. The concentration of NO_x also depended on the loading of boiler and varied from 200 to 270 ppmv (about 500 – 700 mg/Nm^3).

The installation consisted of the following units as follows (see Figure 1):

- Flue gas cooling and humidification unit
- Ammonia dosage unit
- Reactor with accelerators
- Filtration units (three types was tested)
- Control and monitoring system

Complete evaporation concurrent cooling column as well as application of cooling tower with recirculation of water system was investigated. Gaseous ammonia was used as the main reagent of the process. Ammonia was stored in the steel cylinders and injected into the gas after evaporation. The system allowed to adjust ammonia stoichiometry in the range 0.4 – 1.0. Reaction vessel was constructed as 7 m long and 1.6 m diameter cylinder. Flue gas was irradiated by two electron beam accelerators ELV-3a of 50 kW power each. Accelerators were installed above the reaction vessel in series. The energy of electrons were set at 700 keV. Three types of filters were tested during pilot plant research (see Figure 1): bag filter, gravel bed filter and electrostatic precipitator. ESP was assessed as the best filtration unit for this technology.

During the pilot plant experiments very high removal efficiencies were achieved (98% for SO_2 and over 70% for NO_x). The obtained byproduct (mixture of ammonium sulphate and ammonium nitrate) was appropriate for agricultural applications as high class fertilizer.

The results of experiments in Kaweczyn Pilot Plant were the basis for design of industrial scale EBFGT plant in Electric Power Plant Pomorzany in Szczecin, Poland. After the industrial EBFGT installation was built, the pilot plant installation was disassembled in 2004/2005.

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Electro-Catalytic Oxidation (ECO)

The Electro-Catalytic Oxidation (ECO) system is an integrated air pollution control technology that achieves major reductions in the primary air pollutants of concern from coal-fired power plants: sulfur dioxide, nitrogen oxide, mercury and fine particulate matter (PM 2.5). The ECO system produces a valuable, ammonium sulfate fertilizer byproduct, reducing operating costs and minimizing landfill disposal of waste. The ECO process treats power plant flue gas in three steps to achieve multi-pollutant removal [3]:

- ECO reactor — oxidizes pollutants by DBD palsma application;
- absorber vessel — removes SO_2, NO_2, and oxidized mercury; and
- wet electrostatic precipitator (wet-ESP) - removes acid aerosols, air toxics, and fine particulate matter.

Layout of the ECO installation after www.powerspancorp.com is presented in Figure 2.

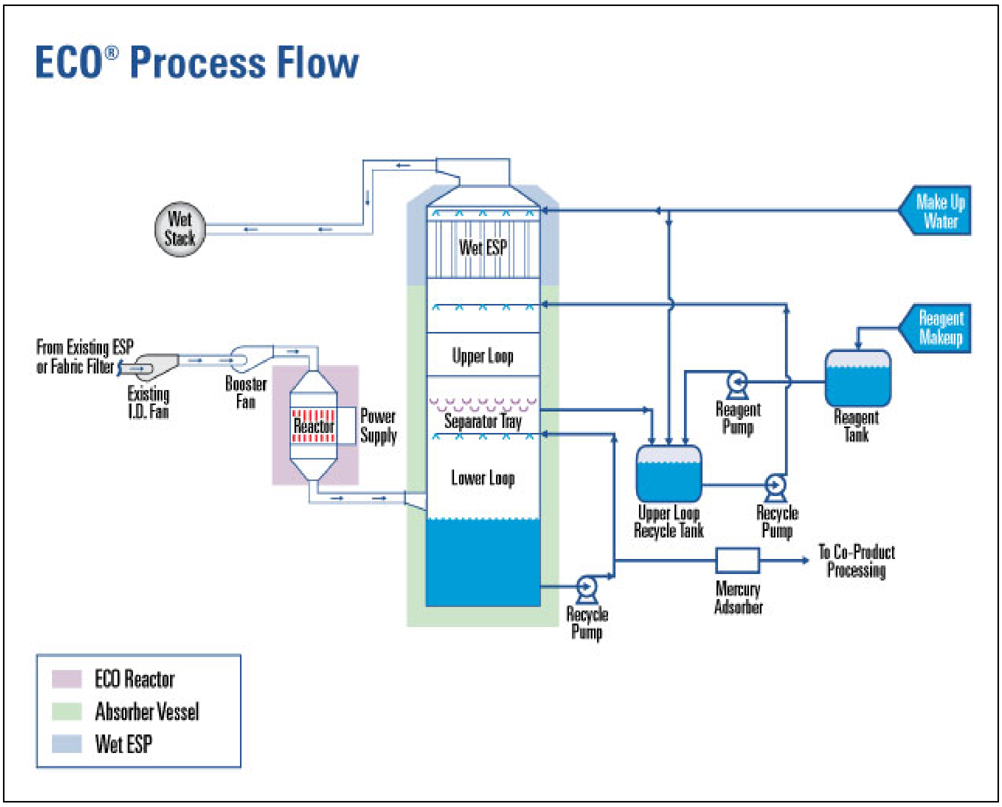

Figure 2. Layout of the ECO installation.

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The ECO pilot plant was constructed in Burger Plant in Shadyside, Ohio. Obtained removal efficiencies were respectively 95 – 99% for sulfur dioxide (SO_2), 90% for nitrogen oxide (NO_x), 80 – 90% for (Hg) and 95% for fine particulate matter (PM2.5).

The pilot experiments were followed by construction of the industrial ECO plant at Bay Shore Plant in USA.

Corona discharge

The scheme of experimental facility is shown in Figure 3 [4].

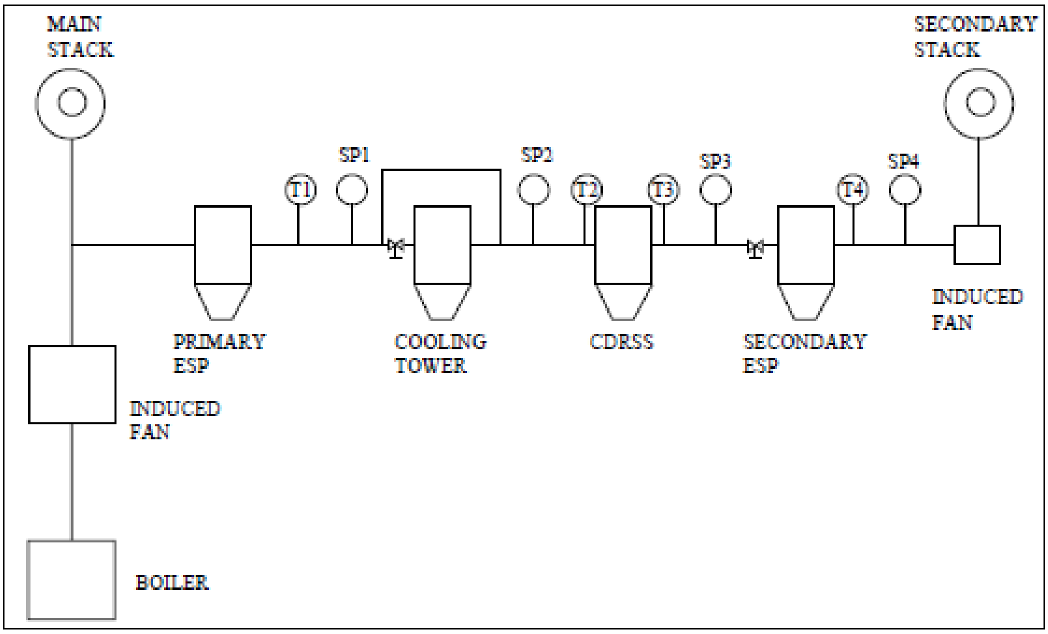

Figure 3. Scheme of pilot corona discharge facility.

A part of coal boiler flue gas (1000 – 1500 Nm^3/h) was directed to pilot facility. The test facility was composed of primary electrostatic precipitator (ESP) for dust removal, spray cooling tower, corona reactor and the secondary ESP for byproduct collections. Corona discharge reactor (of dimensions 2.1 x 1.8 x 2 m) consisted with 20 parallel flow channels with 5 corona radical injection electrodes per channel. Channel width was 10 cm and electrode length 2 m.

Similar as in previously described systems plasma generated by cathode discharges oxidizes SO_2 and NO allowing for further creation of ammonium nitrate and ammonium sulphate in reaction

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with water vapour and ammonia. The obtained removal efficiencies were respectively 90 – 99% for SO_2 and 70 – 80% for NO_x.

Pulsed corona discharge

The corona induced simultaneous removal of NO_x and SO_2 from flue gas is based on the application of narrow voltage pulses to an electrode structure similar to that of an electrostatic precipitator. The free electrons of the corona discharge, having energy up to 20 eV, originate active radicals which lead to the transformation of NO_x and SO_2 into their acids which can be neutralized to salt particulate by adding to the gas a basic compound such as ammonia and calcium hydroxide, that is a common reaction scheme for all plasma based technologies. However the aim of application of pulsed discharge was to increase the energy efficiency of pollutants removal.

The pilot plant on pulsed corona discharge process was constructed by scientists from Thermal Nuclear Research Center, Pisa, Italy [5]. The scheme of the facility is shown in Figure 4. The process has been investigated with a test rig installed in the slipstream of the flue gas duct of a coal-fired thermal power plant.

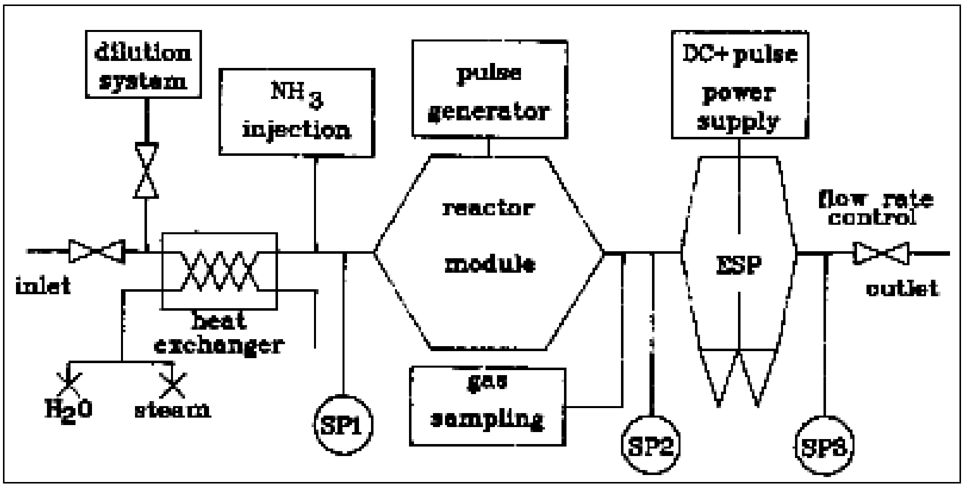

Figure 4. The scheme of pulsed corona discharge pilot plant.

The comparison of main parameters of described plasma pilot plants is given in Table 2.

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Table 2. Comparison of main parameters of selected plasma pilot plants.

	EBFGT (Poland)	ECO (USA)	Corona discharge (China)	Pulsed corona discharge (Italy)
Gas flow rate, [Nm^3/h]	20 000	2500 – 5000	1000 – 1500	1000
Beam or dicharge Power, [W]	50 000 * 2 accelerators	100 000	800	20 000
NO_x inlet concentration, [ppmv]	250	250 – 500	53 – 93	400 – 530
SO_2 inlet concentration, [ppmv]	500	2000	800	400 – 530
Ammonia stoichiometry, [-]	0.8 – 0.9	n.a.	0.88 – 1.3	0.7 – 0.8
Inlet gas temperature, [^oC]	120	150 – 180	62 – 80	70 – 100
SO_2 removal efficiency, [%]	>95	95 – 99	90 – 99	80
NO_x removal efficiency, [%]	>75	90	70 – 80	50 – 60

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4 Upscalling of the selected technologies

Plasma based pollution control technologies are one of the most promising technologies of new generation. At the moment only one of them – EBFGT was implemented in the industrial scale. However the pilot plant research are a base for further implementations. The decision about application of certain technology is undertaken by the investor basing on the numerous technological, economical and marketing aspects. Beside them the cost of the certain technology operation is one of the most important factors. Basing on the available literature data the annual operational costs of three plasma based technologies (electron beam, corona discharge and pulsed corona discharge) were estimated and compared with conventional FGD+SCR system. The calculations were made according to SUENTP [6] procedure described by J.-S. Chang and S.J. Kim. The results are presented in Figure 5.

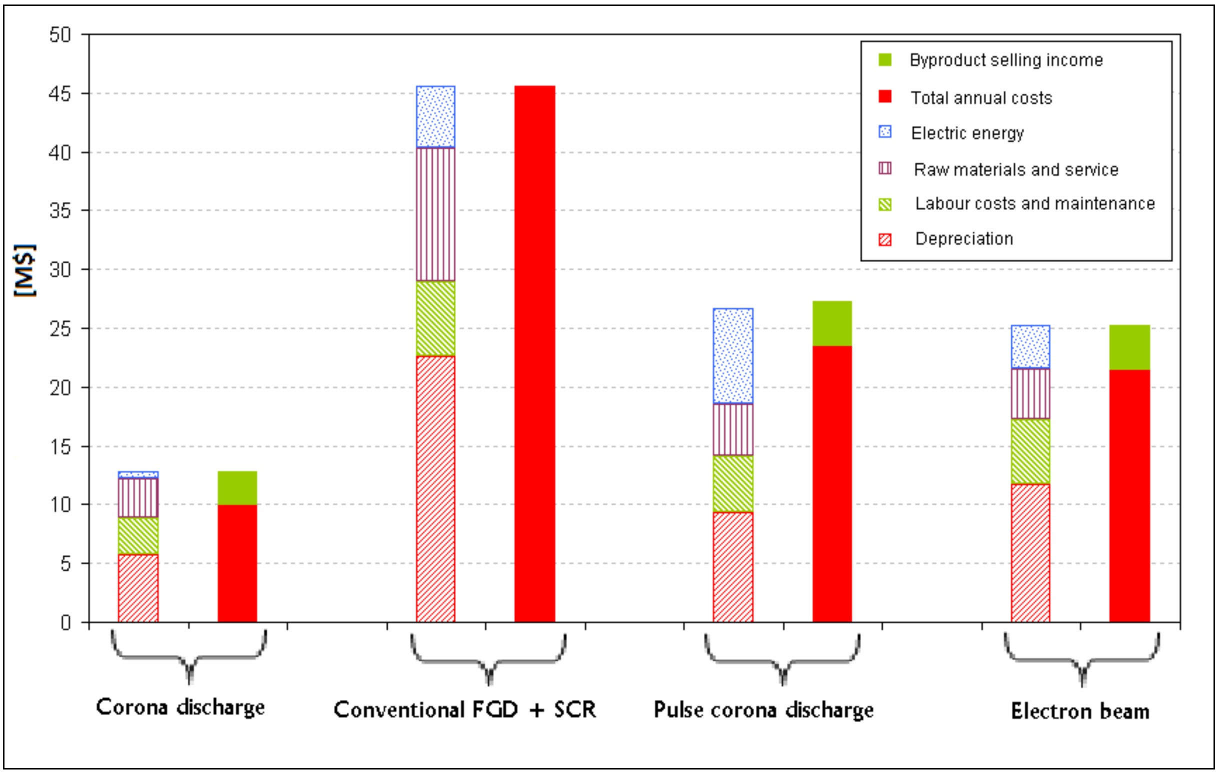

Figure 5. Annual operational costs of selected plasma technologies for 500 MW unit

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The obtained results shows, that plasma based technologies are economically competitive towards conventional ones. However the differences between them (as in the case of electron beam and pulsed corona discharge) may be low.

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5 Conclusions

1. Four, the most representative, plasma based pilot plants for SO_2 and NO_x removal were described and compared: electron beam flue gas treatment (located in Poland), electro-catalytic oxidation (located in USA), corona discharge (located in China) and pulsed corona discharge (located in Italy).

2. The flow rate of the pilot plants varies from 1 000 Nm^3/h (pulsed corona discharge) until 20 000 Nm^3/h (EBFGT) and the inlet pollutants concentration varies in the range 400 – 2000 ppmv (for SO_2) and 50 – 530 ppmv (for NO_x). In all cases high removal rates are noticed, mostly over 95% for SO_2 and over 70% for NO_x. The lowest removal efficiency were noticed in the case of pulsed corona discharge.

3. The estimation of annual operational costs of conventional and plasma technologies show, that plasma based technologies are economically competitive towards conventional ones. However apart of the economical factors, the technical and marketing factors play also important role in the process of technology selection.

4. The plasma based emission control technologies are one of the most promising among modern multipollutant control technologies. The case of electron beam flue gas treatment showed their applicability in industry. Therefore new implementations of plasma based technologies are feasible.

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