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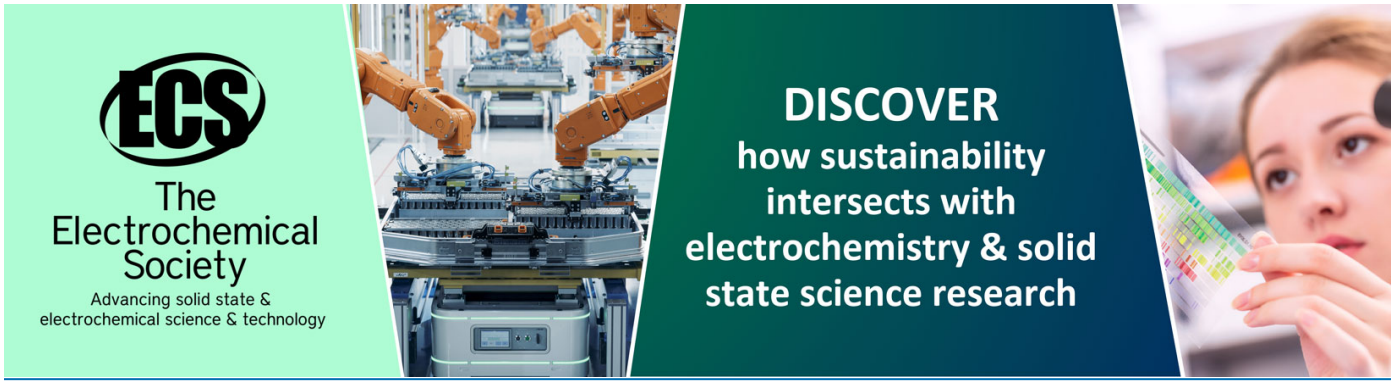

Application of electron accelerator for flue gas treatment of coal power plant to support green technology

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Abstract. Fossil fuels, which include coal, natural gas, petroleum, shale oil, and bitumen, are the main source of heat and electrical energy, but burning these fuels will emit pollutants to the environment. Most countries use coal burning power plant in generating electricity for living needs such as household electricity and industrial development. This power plant generates large quantities of pollutants (SO_X and NO_X) that create acid rain and smog leading to the water and soil degradation and they can affect living things. To meet rising worldwide energy demand, projections call for the use of coal to increase by 50 percent from 2006 - 2030, as a consequence SO_X and NO_X pollutions will rise. There are two conventional technologies to decrease air pollution from coal power plant, the first is FGD (flue gas desulfurization) based on SO2 absorption in lime or limestone slurry; and the second is SCR (selective catalytic reduction) based on NOx reduction over a catalyst to atmospheric nitrogen with ammonia as a reductant. But these technologies cannot treat different pollutants in one step process. To support green technology program, this paper describes a modern technology called EBFGT (electron beam flue gas treatment) which can treat SOx and NOx in one step process using electron accelerator. The technology and economy comparison between FGD, SCR, EBFGT as well as the existing EBFGT in the world are compiled.

1. Introduction

Industrial development in a country often challenges environmental sustainability through the damages that it caused some problems such as; high levels of air pollution, exhaustion of fishing stocks, hazard contamination in land and ocean, biodiversity loss and deforest plant, and climate change. This happens because of un-eco-friendly technology used to produce industrial products.

The source of air pollution comes from pollutants which are emitted to the atmosphere from off-gas industry, power stations, residential heating systems and vehicles. The main fuel source of this system comes from fossil fuels, which include coal, natural gas, petroleum, shale oil and bitumen. A main key in industrial development is the availability of the electricity. Ironically, a coal burning power plant will be the main source in generating electricity for most countries in the next two centuries [1,2], where it is understood that coal is the dirtiest fuels among hydrocarbons. This kind power plant not only releases pollutants of CO and CO_2 gases, but also generates large quantities of SO_X and NO_X gases to the air. Air pollution caused by particulate matter and other pollutants acts not only directly on the environment, but also by contamination of water and soil, leading to their degradation and they can affect people health and living organic through the formation of acid rain, ozone, carcinogenic and toxic substance.

To meet rising worldwide energy demand, projections call for the use of coal to increase by 50 percent from 2006 - 2030 as reported in International Energy Outlook 2016 of US Energy Information

Administration [1] as a consequence SO_X and NO_X pollutions will rise. The government of Indonesia has committed to realize the supply of electricity need of 35,000 megawatts (MW) and this program has been confirmed in the 2015-2019 National Medium-Term Development Plan (RPJMN) document. The need for 35 thousand MW has been being met mostly from coal power plants [3,4].

The problems of environmental damage and degradation of natural resources are receiving increasing attention throughout the world in recent years. Many countries have paid more attention to efficient control methods for flue gas emission [5-9]. Thus, an eco-friendly science and technology (Green Technology) that can empower and harness the existing coal power plant for the virtue of society and earth is needed. In *Encyclopedia of Ecology* [10] Green technology, also known as sustainable technology, takes into account the long- term and short-term impact something has on the environment. Green products are by definition, environmentally friendly. Energy efficiency, recycling, health and safety concerns, renewable resources, and more all go into the making of a green product or technology. Green technology is about a man, knowledge, formulated philosophy application interaction with material processing and the consequences of the products in the present and future life.

Accelerator has extraordinary potential to address this energy and environmental challenges. Accelerator according to physics is a machine to increase the kinetic energy of charged particles (electron or ions) by accelerating them in the electric field. It produces a beam of particles of the same kind, all having the same energy and travelling in the same direction. Radiation technologies applying electron accelerators for material processing are well-established processes [2,11]. There are hundreds electron accelerators in operation worldwide that are being widely used for cross-linking of tire and cable, sterilization of medical equipment, food irradiation, polymer processing, and for environmental remediation [12]. To support green technology program, this paper describes a modern technology called EBFGT (electron beam flue gas treatment) which can treat SO_x and NO_x in one step process using electron accelerator. The technology and economy comparison between FGD, SCR, EBFGT as well as the existing EBFGT in the world are compiled.

2. Flue gas treatment of coal power plant

There are two conventional technologies to reduce air pollution from coal power plant. The first conventional technologies used for reducing air pollution is wet FGD (flue gas desulfurization), based on SO_2 absorption in lime or limestone slurry; and the second is SCR (selective catalytic reduction), based on NO_x reduction over a catalyst to atmospheric nitrogen with ammonia as a reductant. Modern technology to reduce air pollution from coal power plant is electron beam flue gas treatment technology (EBFGT). This technology can treat SO_2 and NO_2 pollutants in one step process.

2.1. Working principle of EB flue gas treatment

Coal burning power plants are a type of power plant that make use of the combustion of coal in order to generate electricity. The flue gas from combustion of the coal is discharged to the air. This gas contains major components of carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), oxygen (O_2), nitrogen oxides (NO_x = NO_2 and NO) and sulfur oxides (SO_x = SO_2 and SO) with much lower concentration, and fly ash (contain trace element of heavy metals).

The scheme of the working principle of EB flue gas treatment process is depicted in Figure 1. The SO_2, and NO_x together with water vapor in the chamber are irradiated under the energetic electron beam, in the same time ammonium gas is injected into the chamber. The flue gas will react with radicals of water vapor to form sulfuric and nitric acid, then these acids undergo reaction with ammonium to produce an aerosol of ammonium sulfate and nitrate. The reaction process of the EBFGT is a very short time, where the converting of flue gas in the form of gas phase into solid phase (aerosol) is in the order of micro second.

In detail the physical and chemical processes are described as follows [13]. When flue gases are irradiated by an electron beam from an electron accelerator then these energetic electrons will interact with the gas, creating various ions and free radicals, and the primary species formed include e^-, N_2^+, N^+, O_2^+, O^+, H_2O^+, OH^+, H^+, CO_2^+, CO^+, N_2^*, O_2^*, N, O, H, OH, and CO through excitation and ionization

process. In the case of high water vapor concentration, the oxidizing radicals OH^* and HO_2^* and excited ions such as $O(^3P)$ are the most important products [13,14].

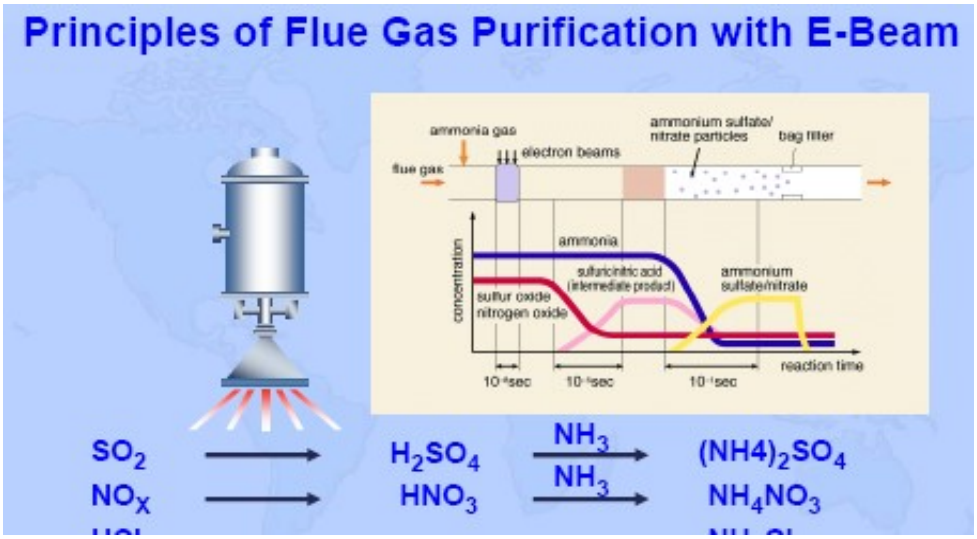

Figure 1. The scheme of working principle of EB flue gas treatment process.

In EBFGT technology, ammonium (NH_3) must be present as an additive to aid removal of the Sulfur and Nitrogen oxides. The SO_2, NO, NO_2, and NH_3 present cannot compete with the reactions because of very low concentrations, but react with N, O, OH, and HO_2 radicals. There can be several pathways of the SO_2 oxidation depending on the condition. The most important pathways are radio-chemical reaction and thermal reactions. Radio-thermal reactions proceed through radical oxidation of SO_2 and HSO_3, which creates ammonium sulfate in the following steps [15,16]:

$$SO_2 + OH^* + M \rightarrow HSO_3 + M ,$$

$$HSO_3 + O_2 \rightarrow SO_3 + HO_2^* ,$$

$$SO_3 + H_2O \rightarrow H_2SO_4 ,$$

$$H_2SO_4 + 2NH_3 \rightarrow (NH_4)_2SO_4 .$$

The thermal reaction is based on the following process:

$$SO_2 + 2NH_3 \rightarrow (NH_3)_2SO_2 ,$$

$$(NH_3)_2SO_2 \rightarrow (O_2, H_2O) \rightarrow (NH_4)_2SO_4 ,$$

The total yield of SO_2 removal consists of the yields of thermal and radio-thermal reactions, and can be written as follows [17,18]:

$$\eta SO_2 = \eta_t(\varphi, T) + \eta_r(D, \alpha NH_3, T) \qquad (1)$$

There are also several pathways of NO oxidation known. In the case of EBFGT the most common are as follows [16]:

$$NO + O(^3P) + M \rightarrow NO_2 + M ,$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M ,$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M ,$$

$$NO + O_3 + M \rightarrow NO_2 + O_2 + M ,$$

$$NO + HO_2^* + M \rightarrow NO_2 + OH^* + M.$$

After the oxidation NO_2 is converted to nitric acid in the reaction with OH^* according to the reaction:

$$NO_2 + OH^* + M \rightarrow HNO_3 + M$$

Then HNO_3 reacts with NH_3, giving ammonium nitrate that can be written:

$$HNO_3 + NH_3 \rightarrow NH_4NO_3$$

NO is partly reduced to atmospheric nitrogen.

The yield of the thermal reaction (η_t) depends on the temperature and humidity, and decreases with the temperature increase. The yield of the radio-thermal reaction (η_r) depends on the dose, temperature, and ammonia stoichiometry. The main parameter in NOx removal is the dose. Ammonia, as mentioned above, is to neutralize acids formed in reactions, with aerosol of ammonium sulfate and nitrate being the final products of the reaction.

2.2. The technological description of EB flue gas treatment system

The process mechanism described in section 2.1, studied in laboratory conditions, was a basis for the technical implementation of the technology. However, in real conditions, dose distribution, gas flow patterns, and gas temperature are important from the technological point of view [19]. These parameters influence the electrons energy transfer, mass, and heat transfer before, after, and in the process vessel. Therefore all these parameters should be taken into account in order to achieve maximal removal efficiency of SO_x and NO_x. This section will describe some parameters that should be full filed in each process steps taken from BEDP of 20000 Nm^3/h Flue Gas Processing System of Coal Fired Plant Using Electron Beam Machine [20].

The schematic diagram of the technology of EBFGT system is depicted in Figure 2. There are six main components of the EBFGT system such as ID-Fan to overcome the entire pressure losses of the system, Spray cooler to cool the flue gas, Ammonium system to neutralize the sulfate and nitric acids, E-Beam system as a radiation source of the energetic electron beam to make excitation and ionization of gas molecules, Process vessel for the irradiation process of the flue gas and NH3, ESP (electrostatic precipitator) to capture the by-products.

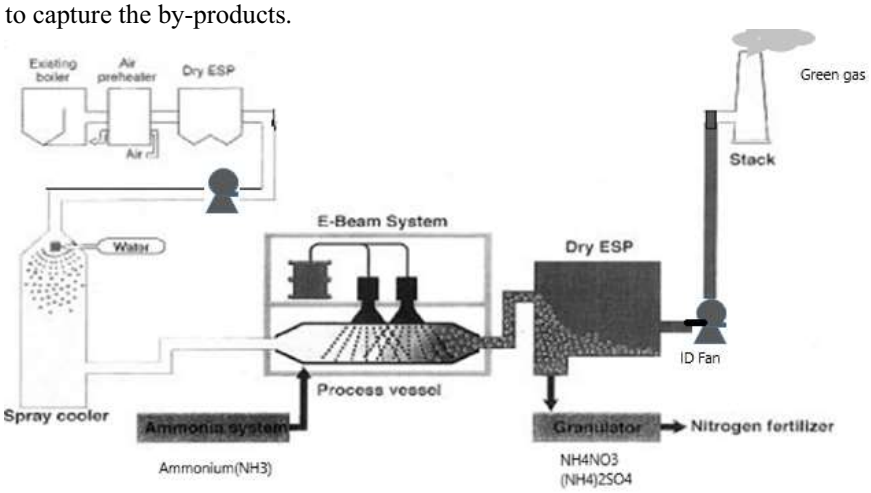

Figure 2. The schematic diagram of the technology of EBFGT system.

2.2.1. Pre-treatment of particulate. Before the flue gas going into the EB-FGT process, the flue gas that contains particulates, SO_2, and NO_x from the plant must pass the existing electrostatic precipitator (ESP)

such that fly ash is efficiently removed**.** This step is very important in order to optimize the removal efficiency of SO_x and NO_x from the coal power plant.

2.2.2. Humidification step. The flue gas after passing the ESP at a temperature of 125 ℃ then it passes through an evaporative spray cooler to achieve around 65 ℃. In adiabatic cooling with the water vapour content up to 11.5% in volume of the flue gas before passing into process vessel. These temperature value and the water vapour content are the best parameters of reaction process for flue gas treatment in order to optimize the removal efficiency of SO_x and NO_x from the coal power plant. Atomized water is injected into flue gas stream in each spray cooler using single fluid water nozzles by the hydraulic pump. The spray cooler is operated with a dry bottom, therefore all of the water injected into the flue gas is evaporated.

2.2.3. Ammonia injection. After the humidification step the flue gas flows into the process vessel (irradiation chamber), at the inlet side to the process vessel the gaseous ammonia reagent is added to the flue gas via nozzles mounted at the site of duct. NH_3 is injected upstream of the irradiation chamber. A hydrous ammonia is stored in storage tank. The ammonia storage facility should be placed inside the independent building. The ammonia is then vaporized using electrical heating. To ensure good distribution in the flue gas duct, ammonia is distributed using a multi-nozzle assembly configured as a grid in the flue gas duct. The temperature of flue gas at this point is approximately 65°C. The ammonia is used to neutralize the sulfuric and nitric acids, and to form the solid particle aerosol.

2.2.4. Irradiation process. After humidification, lowering of the temperature and adding of ammonium, flue gases are guided to the process vessel (reaction chamber), where irradiation by energetic electron beam takes place. In the process vessel flue gases containing SO_2, NO_x and ammonia are irradiated by high energy electron beam generated by an electron accelerator which is installed over the process vessel with respect to the gas stream flow. The electrons are introduced into the process vessel via thin 50 μm titanium foil. The length and width of the process vessel depend on electron beam scanning, the height of the process vessel depends on electron energy. The electron beam can be scanned up to 120 cm length and 20 cm width using the magnetic scanning coil.

The penetration of energetic electron in matter is influenced by the density of mater. Figure 3 shows the penetration of energetic electron in water for different electron energy. The height of process vessel can be determined from the optimum penetration of the electron energy. For electron energy of 0.8 MeV used to irradiate the air with density of 0.001225 g/cm^3, then the maximum penetration range is about 3.5 m. Nevertheless for flue gas with density of 0.001372 g/cm^3, then the maximum penetration range is about 2.5 m. A radiation dosage of 2~10 kGy was chosen for various removal rates of SO_2 and NOx based on the experimental data of some references [9,21-23]. The E-beam units are enclosed in a concrete structure to ensure no radiation is emitted to the external surroundings. The flue gas rate that can be process is determined by how much the removal rates of SO_2 and NO_2, and the power of electron accelerator as written in the following equation:

$$P(kW) = [M(kg/jam) \times D(kGy)] \div (3600\ \eta) \qquad (2)$$

Where P is the electron beam power, M is the flue gas rate, D is absorbed dose, η is utilization efficiency. The removal efficiency of SO_x and NO_x depends on the absorb dose as depicted in Figure 4. A high dose is required for NO_x removal, while SO_x is removed in proper conditions, at low energy consumption.

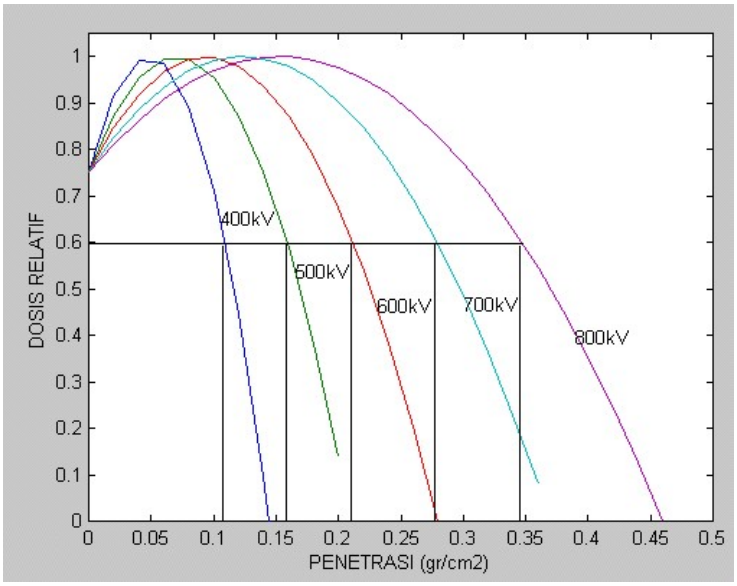

Figure 3. Penetration depth of electron in water for different energy.

2.2.5. By-product collection. After the irradiation process, the flue gas is passed through the by-product collection system. A dry ESP of special design is needed to capture the by-product with the particulate emission of less than 30 mg/Nm^3. Typically, the by-product will contain 88% of ammonium sulfate, 10% of ammonium nitrate and 2% inert solids (fly ash).

2.2.6. Cleaned gas. The treated flue gas stream leaving the ESP will be guided to the exhausting stack. All the ducts connecting the equipment are part of the flue gas system. 1 set of ID fan provides the sufficient draft to overcome the entire pressure losses of the system. The flue gas leaving the stack contains much less SO_2 and NO_x.

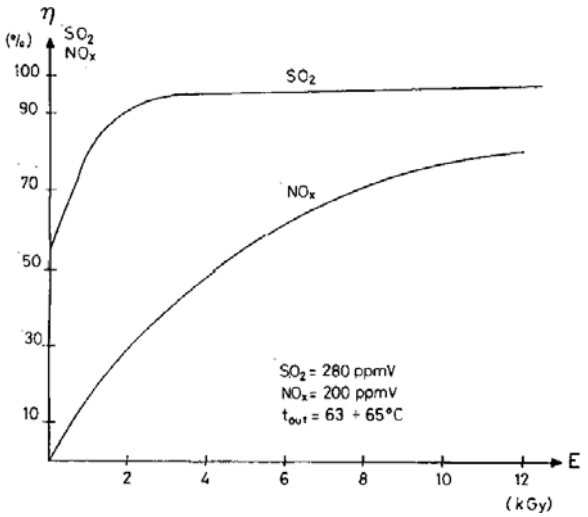

Figure 4. SO_2 and NO_x removal efficiency vs. dose. The results obtained by the pilot plant experiments and theoretical calculations.

3. Application and technology of electron accelerator for flue gas treatment

3.1. Application of EBFGT from laboratory to industrial scale

In the early 1970 Japanese scientists [24] used an electron beam from a linear accelerator with the energy of 2-12 MeV and the power of 1.2 kW to do an experiment of SO_2 removal from a flue gas sample in laboratory scale. In this demonstration, a dose of 50 kGy at flue gas temperature of 100 °C was used to convert SO_2 into an aerosol of sulfuric acid droplets which were easily removed. Since then many research institutes in Japan sited in Tokyo, Takasaki, Ebara, JAERI have set up laboratory scale of flue gas treatment using electron electrostatic accelerator with different energy and power of the accelerators [24,25]. Research institutes in Tokyo used the energy of 1 MeV and the power of 12 kW, in Takasaki used the energy of 0.3 MeV and the power of 15 kW, in Ebara used the energy of 0.3-0.75 MeV and the power of 30 kW, in JAERI used the energy of 1.5 MeV and the power of 30 kW. By using the varieties data of the irradiation process parameters of flue gas from laboratory scales, in the 1977-1978, Ebara Co. of Japan built a pilot plant to convert not only SO_2 but also NO_x in one step process using a higher power electron accelerator. It employed an electron accelerator with energy of 0.75 MeV and power of 45 kW to led the conversion of SO_2 and NO_x into a dry product containing $(NH4)_2SO_4$ and NH_4NO_3 which could be used as a fertilizer.

Based on the success of the Ebara pilot plant, then many pilot plants of flue gas treatment by using "Ebara process" were built in many places of many countries. Frank [25] has reported the project of flue gas treatment an using electron beam in the period of 1972- 1994, and the pilot plant of industrial applications of electron beam flue gas treatment can be found in many references [5-9,13,22,23]. Besides the Ebara pilot plant, there were three small scale pilot plants built in Japan, in Fujisawa the pilot plant used electron accelerator with the energy of 500 keV and the power of 15 kW to treat flue gas of 1500 Nm^3/h, in Matsudo the pilot plant used electron accelerator with the energy of 900 keV and the power 15 kW to treat flue gas of 1000 Nm^3/h. Two small scale pilot plants in Karlsruhe, Germany were built, the first plant used low energy electron accelerator with the energy of 220 keV and power of 22 kW to treat the flue gas of 100-1000 m^3/h, the second plant used low energy electron accelerator with the energy of 300 keV and power of 36 kW to treat the flue gas of 100-1000 Nm^3/h.

A large scale pilot plant located Indianapolis, USA was equipped with two electron beam accelerators (0.8 MeV, 80 kW) and had a flue gas rate capacity of 8000-24000 Nm^3/h, with gas containing 1000 ppm SO_2 and 400 ppm NO_x. Also, the large scale pilot plant located in Tokyo it was used two electron accelerators with the energy of 500 keV and the power of 12.5 kW to treat flue gas of 12000 Nm^3/h. Another large scale pilot plant located in Karlshue, Germany used two electron accelerators (0.3 MeV, 90 kW) to treat 10000–20000 Nm^3/h flue gas containing 50–500pm SO_2 and 300–500 ppm NOx. The small scale pilot plant in Warsaw, Poland used electron accelerator with the energy of 1 MeV and the power of 20 kW to treat the flue gas of 400 m^3/h. The large scale pilot plant in Kaweczyn, Poland [23] used two electron accelerator with the energy of 700 keV and the power of 50 kW to treat the flue gas of 20000 Nm^3/h.

Demonstrations of EBFGT have shown the effectiveness and efficiency of electron accelerator technology in treating flue gas emissions with high-efficiency removal of NO_X and SO_X. To install the industrial size plant, the problems finding in a pilot plant must be overcome by re-engineering design of a component of EBFGT that caused the problem. The first problem came from corrosive flue gases into a Ti electron window of the accelerator. The Ti electron window had a function to separate vacuum and irradiation process chambers. The second problem was the sticky final product of fertilizer. In this industrial installation, new engineering solutions were applied: 1) the double window was applied to protect the Ti window of the accelerator from the corrosive flue gas atmosphere, and the air curtain protects a secondary window from such effects as well, 2) atomized water was injected into the flue gas stream in each spray cooler using single fluid water nozzles by the hydraulic pump in order to get high enthalpy water in the humidification of flue gas, 3) ammonia injection was distributed using a multi-nozzle assembly configured as a grid in the flue gas duct to ensure good distribution in the flue gas duct.

The obtained results have confirmed the physicochemistry of the process described earlier. These new solutions led to improvements in economic and technical feasibility and final industrial scale plant construction.

The industrial size plant of EBFGT has been built in Nagoya Japan [22]. The Nishi-Nagoya plant uses three electron accelerators with the energy of 800 keV and the power of 36 kW to treat flue gas of 520,000 Nm3/h to treat heavy oil of 2.5% Sulfur. Other industrial sizes of EBFGT are located in Pomorzany, Poland and in Chengdu China. The flue gas treatment industrial installation is located at the Pomorzany electric power plant in Szczecin, Poland [6]. The installation treats flue gases from two Benson boilers of 65 MWe and 100 MWth each. The maximum flow rate of the gases is 270000 Nm3/h and the total beam power exceeds 1 MW. There are two reaction chambers with nominal flow gas rates of 135000 Nm3/h. Each chamber is irradiated by two accelerators (260 kW, 700 keV) installed in series. The applied dose is in the range of 7–12 kGy. The removal of SO_2 approaches 80–90% in this dose range, and that of NOx is 50–60% (Figure 4). The by-product is collected by the electrostatic precipitator and shipped to the fertilizer plant. EBFGT has been constructed by Ebara Corporation in Chengdu, China [9] for treatment of 300,000 Nm3/h of the flue gas. The power of accelerators applied is 320 kW, this EBFGT is mostly for treatment of the SO_X. The reported removal efficiency is 80% for SO_X and 20% for NOx. Table 1 shows the compilation of industrial scale of EBFGT installed in the world. The biggest EBFGT is in Pomorzany, Poland and in Chengdu, China.

Tabel 1. Pilot and Industrial scale of EBFGT installed in the world.

Plant site	**Specification of EBFGT**				
	Electron accelerator (E and P)	Flow rate of flue gas	Number process vessel	Process vessel posiition	Flue gas
Indianapolis USA (1984-1988)	800 keV & 80 kW	24,000 Nm^3/jam	2	Horizontal	SO_2 & NO_2
Karlsruhe Jerman (1985-1989)	300 keV & 90 kW	20,000 Nm^3/jam	2	Horizontal	SO_2 & NO_2
Kaweczyn Poland (1990)	700keV & 50kW	20,000 Nm^3/jam	2	Longitudinal	SO_2 & NO_2
Nishi-Nagoya Japan (1999)	800 keV & 36 kW	520,000 Nm^3/jam	3	Horizontal	SO_2 from heavy oil sulfur of 2.5%
Chengdu China (1999)	800keV & 160 kW	300,000 Nm^3/jam	2	Horizontal	SO_2 from heavy sulfur coal
Pomorzany Poland (2000)	700 keV & 260 kW	270,000 Nm^3/jam	2	Horizontal	SO_2 & NO_2

3.2. Electron accelerator technology for EBFGT

From Table 1 and the equation (2), the power of the electron accelerator used for EBFGT is mostly dependent on the flue gas rate, and its removal efficiency. The utilization efficiency depends on the efficiency of the used electron accelerator and the designed reaction chamber. The higher the flue gas rate, the higher the accelerator power needed. There are many accelerator technologies to be used for EBFGT such as Cockcroft Walton, Dynamitron, Linac, UHF, and DC transformer. These are the most economical accelerator units with high energy efficiency, and their preferability for applications of EBFGT considering the fact that the double windows technology must be used and the density of flue gas is close to 1.25 kg/Nm3. The most popular accelerators, due to the electron energy requirements (up to 1 MeV) to assure good penetration and high power accelerator, were transformer accelerator. The transformer accelerator met the criteria for EBFGT because it provides high power, and high electrical efficiency. The present achievement of accelerator technology for radiation processing illustrates in Table 2.

Table 2. Accelerators technology for radiation processing.

Accelerator type	Direct DC	UHF 100-200 MHz	Linear 1.3 - 5.7 GHz
Beam current	< 1,5 A	< 100 mA	< 100 mA
Energy range	0.1-5 MeV	0.3-10 MeV	2-10 MeV
Beam power	500 kW	700 kW	100 kW
Efficiency	60-80 %	25-50 %	10-20 %

Zimek [26] reported the criteria and selection of the electron accelerator for the application of radiation processing in environmental protection in Technical Meeting on Radiation Processing of Gaseous and Liquid Effluents conducted in Sofia, Bulgaria, 7–10 September 2004. The chosen accelerator must be based on three basic criteria selections, namely 1) Fundamental accelerator parameters (Electron energy, Average beam power); 2) Terms of accelerator purchase (Price, Producer, Terms of delivery and installation, Warranty conditions, and Exploitation cost); 3) Auxiliary accelerator parameters (Scan performances, Auxiliary parameters, Measures and control, Main components and systems, Auxiliary components and systems, and Accelerator external supply service). Higher number of accelerators build by certain accelerator producer may significantly reduce the cost of accelerator manufacturing. Here are the selected electron accelerators for radiation processing illustrates Table 3 [26].

High power accelerators have been developed to meet specific demands of environmental application and high throughput processes to increase the capacity and reduced unit cost of operation. The technological developments of accelerator is based on new constructions and components. The substantial improvement could be achieved by support of R&D study of accelerator technology by governmental and international institutions. New developments in the field of electron beam accelerators have been reported by PAVAC Industries, Canada. Future use of the electron beam treatment of flue gases technology is predicted. Reliable and moderately priced accelerators are a key factor for progress in the field. Guidelines for feasibility studies have been elaborated [11]. A new planned unit at the Svilosa Power Plant, Bulgaria with capacity 580 MWt (four coal fired boilers) will be constructed. This plant will treat flue gas with a flow rate of 600,000 Nm^3/h and the estimation of installation construction cost is equal to 26 million euros [27].

4. The comparison of EB and conventional method

4.1. Technological comparison of flue gas treatment methods

Although several attempts have been made the electron beam flue gas treatment method is the first that was applied for simultaneous removal of sulfur and nitrogen oxides in the industrial scale. Conventional technology was only applied to specific flue gas such as FGD for removal SO_2 and SCR or NSCR for

removal NO_2. The removal of SO_2 and NO_x from flue gas is normally realized by a combination of de-SO_2 and de-NO_x methods. The removal efficiency of both systems, that is, electron beam flue gas treatment (EBFGT) and combined wet flue gas desulfurization and selective catalytic reduction, is comparable.

Table 3. Selected accelerators for radiation processing (basic parameters).

Manufacturer	Accelerator type	Energy [MeV]	Current [mA]	Power [kW]	Price* [M$]	Cost [$/W]
IBA, Belgium	UHF	10	15	150	6.1	40.7
RDI, U.S.A.	DC	5	50	250	4.9	19.6
NHV, Japan	DC	5	30	150	5.0	33.3
Vivirad,France$^+$	DC	5	200	1000	4.4	4.4
INP, Russia	UHF	5	10	50	1.2	24.0
INP, Russia	DC	1	500	400	2.0	5.0

The desulfurization efficiency is up to 95% and SCR efficiency is around 70-80% where the efficiency of the SNCR is much lower. In SCR system, ammonia gas reacts with NO_x flue gas through catalytic assistant to form harmless nitrogen and water. The limitation of SCR systems is too sensitive to contamination and plugging resulting from normal operation or abnormal events. This is because most catalyst on the market is of porous construction. In FGD system, SO_2 flue gas reacts with lime or lime slurry in scrubbing vessel to form calcium sulfite or gypsum with further chemical process. The highest SO removal efficiencies (greater than 90%) are achieved by wet scrubbers and the lowest (less than 80%) by dry scrubbers. The weakness of the FGD system is that it requires a large area to store lime for the process and lagoon to store the by-product of calcium sulfite in the form of slurry.

4.2. Economical comparison of flue gas treatment method

Among the most attractive characteristics of electron accelerators for environmental applications is their electrical efficiency and the by-product of high-quality fertilizer. The by-product is sold commercially. Although it doesn't cover the costs of plant operation (all the flue gas treatment facilities are non-profit) it may lower these costs. In addition, the plant may save money reducing the emission penalties.

Table 4. The costs of various emission control methods for a retrofit 120 MWe unit.

Emission control method	Investment cost ($US/kWe)	Annual operational cost ($US/MWe)
Wet flue gas desulfurization	120	3000
Selective catalytic reduction	110	4600
Wet FGD + SCR	230	7600
Electron beam FGT	160	7350

Tyminski and Pawelec [28] has reported the economic evaluation of electron beam flue gas treatment. They considered estimation cost, investment costs of the plant, and operational costs of the plant in their calculation. According to their economic evaluation as the following. The investment costs of retrofit wet FGD installations are usually 80 – 120 $US/kWe depending on size and local conditions. It is worth to notice, that this kind of pollution control facility is installed mostly in large power plants of size above 500 MWe. So in the case of smaller installations (about 120 – 250 MWe) the investment cost should arise. On the otherhand the retrofit SCR installations' investment costs are 59 – 112 $US/kWe depending on the plant size and difficulty and scope of retrofit [29]. For new facilities such costs are 45 – 60 $US/kWe. The investment costs of these two emission control methods seem to be lower, then for electron beam plant. But the cost of both installations taking together is 140 – 230 $US/kWe. For small plants of boiler size 120 – 250 MWe this cost will be about 200 – 230 $US/kWe, that is considerably more than 160 $US/kWe for electron beam technology. The cost of combined wet

FGD and SCR system is estimated for 270 – 474 $US/kWe for the units of 300 – 50 MWe. In the case of annual operational costs the wet FGD methods cover about 2500 – 3000 $US/MWe, while SCR methods cover 3800 – 4600 $US/MWe [30]. That means, that removal of both pollutants by a conventional methods costs annually 6300 – 7600 $US/MWe. The comparison of the costs of various emission control methods for a 120 MWe unit is presented in Table 4.

5. Conclusion

The EBFGT is a new proven technology that has the ability for efficient removal of SO_2 and NO_x simultaneously of flue gases from coal combustion processes. This technology is more attractive than the conventional technologies because it needs small area, has high electrical efficiency and produces by-product of fertilizer. Although the costs of this prototype and retrofit installation are relatively high, they are comparable with conventional technologies. Further development of EBFGT can significantly reduce both the investment and operational costs of the plant, especially by reducing the electron accelerator cost. It is expected that the progress in the new development of the electron accelerator technology will answer it.

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