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Research article

Pilot plant for electron beam treatment of flue gases from heavy fuel oil fired boiler

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ABSTRACT

The pilot scale electron beam flue gas treatment (EBFGT) plant was constructed at Saudi Aramco's Refinery in Jiddah, Saudi Arabia. The plant was designed to treat 2000 Nm^3/h of flue gas emitted from a heavy fuel oil fired boiler. A unique mobile electron accelerator unit (600 keV, 20 kW) made by EB TECH Co., Ltd., Korea was used as a beam source. The pilot plant operation proved the high potential of the technology for simultaneous control of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions. The obtained removal efficiencies reached 98.5% for SO_2 and 83.1% for NO_x. Two types of byproduct collection devices – cartridge bag filter and electrostatic precipitator – were tested. The obtained byproduct was a high quality fertilizer that can be used directly or as a substrate for NPK blends manufacturing. The soluble part of the byproduct was almost pure ammonium sulfate (98% to 99%) with some amount of ammonium nitrate. The content of heavy metals in the byproduct was very low and lower than the allowed standards by two orders of magnitude. The results of the research are the basis for the design of a full industrial scale EBFGT plant for treatment of flue gas from heavy fuel oil combustion.

1. Introduction

World economic growth is connected with energy consumption increase. The combustion of fossil fuels, including coal, natural gas, petroleum, shale oil and bitumen, are still the primary source of energy. According to International Energy Agency data [1], in 2013 68% of world's electricity was generated with use of coal (41.3%), natural gas (21.9%) and oil (4.8%). Such an energy generation structure is responsible for emitting a large amount of pollutants into the atmosphere. The most important among them are oxides of sulfur (SO_x) and nitrogen (NO_x). The uncontrolled emission of these pollutants affects human health and causes serious environmental problems; for example, degradation of forests caused by acid rains. In response, the limits regarding pollutants emission control in the fossil fuels combustion processes are becoming stricter day by day.

There are various technologies available for flue gas treatment, however, at present, wet flue gas desulfurization (wet-FGD) and selective catalytic reduction (SCR) are most often applied for SO_x and NO_x emission control [2,3]. This two-step ($deSO_2 + deNO_x$) system is complicated, energy consuming and requires large area for installation set up. Moreover the process generates considerable amounts of waste, both solid (gypsum, waste catalyst) and liquid (wastewater). Cost analyses performed for different countries have shown that investment and operational costs of application of air pollution control technologies are very high [4].

Therefore, dry, multi-component, waste free processes are of great interest to the industry. The most promising technologies fulfilling the above criteria are plasma-based technologies that are under intensive development in recent times [5]. There can be different ways of plasma generation for gas depollution purposes: direct by electric discharges in the gas or injection of high energy electron beam and indirect as low temperature oxidation with ozone [6,7]. Among them, electron beam flue gas treatment (EBFGT) technology is one of the most advanced and matured technologies. In this technology, the energy consumption for a molecule transformation is the lowest and electron beam penetration range is the longest.

EBFGT is a dry scrubbing process of simultaneous SO_2 and NO_x removal, where no wastes except the usable byproduct are generated. In the process flue gases are irradiated with fast electrons of 0.8 to 1.2 MeV energy, that initiates a series of chemical reactions leading to oxidation of SO_2 to SO_3 and NO to NO_2 and further formation of ammonium sulfate and ammonium nitrate with ammonia used as a substrate [8,9]. The solid ammonium salts created in the process are collected and used as an agricultural fertilizer. The technology is efficient against

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pollutants removal, flexible against initial process conditions (flue gas flow rate, pollutants concentration, gas humidity, etc.) and easy to control.

The first research on the EBFGT process was performed in Japan in the 1970s. In the beginning, the process was invented for SO_2 removal from ore sintering plants, however, soon the possibility of simultaneous removal of both of SO_2 and NO_x was recognized. Intensive process developments have been undertaken for the next twenty years in many countries such as Germany, USA, Japan, China and Poland [10]. A breakthrough regarding process engineering was achieved at EPS Kaweczyn Pilot Plant in Poland, where longitudinal, two stage gas irradiation and reaction vessel windows protected by air curtain were applied [11]. Moreover three different byproduct collection systems – bag filter, gravel bag filter and electrostatic precipitator – were tested. Many patents on the process engineering were granted. On the basis of the pilot scale research results, three demonstrational industrial EBFGT plants have been constructed at Chengdu [12], Hangzhou (China), and Szczecin (Poland) [13]. All of the plants were designed for treatment of flue gas from coal fired boilers.

Polish installation is, currently, the only operational industrial scale EBFGT plant in the world. The facility purifies 100,000 to 270,000 Nm^3/h of flue gas from two Benson boilers of 100 MW_{th} each. The temperature of flue gas is up to 140 °C and inlet concentration of pollutants about 2000 mg/Nm^3 of SO_2 and 400 to 600 mg/Nm^3 of NO_x with low dust concentration (after upstream applied high efficiency electrostatic precipitator). The operation of Polish EBFGT installation at Pomorzany has proven high efficiency of simultaneous removal of both pollutants on the big industrial scale. The experiences gathered during operation of this industrial demonstration plant might be used in design of other facilities of this kind. The installations based on the technology are competitive to conventional ones from economical and technical points of view.

Apart of the successful construction of the industrial plant in Pomorzany, the technology is still under development. The research on the applicability of the technology for VOC [14,15] and mercury [16] removal are in progress. Efforts to increase the energy efficiency of EBFGT process by fine water droplets dispersion in the reactor were undertaken [17]. New possibilities of process implementation are sought. Among them, the very promising area of EBFGT technology implementation is purification of flue gas from heavy oil fired boilers.

Coal and natural gas are the most often used fossil fuels, however, the prices of fossil fuels will follow increasing trend and the reserves of clean fuel like gas will become depleted. Heavy fuel oil is essentially industrial fuel used in industrial boilers containing up to 4.0% of sulfur. This fuel, as a byproduct of crude oil processing, is produced in the refineries in large quantities; however, the combustion of this fuel results in high emission of SO_x and NO_x and requires application of emission control devices. On the other hand, heavy oil is far cheaper than fuel gas, which is a valuable substrate for chemical industries. In this way the combustion of heavy oil with the use of flue gas treatment methods is economically justified.

A laboratory study on EBFGT application on flue gas from combustion of high sulfur heavy oils was performed at the Institute of Nuclear Chemistry and Technology in Poland [18]. Three grades of heavy fuel oil were tested. During the research, high removal efficiencies – up to 98% for SO_2 and 82% for NO_x – were obtained under optimal process conditions. It was found, that the technology is fully applicable for treatment of flue gas from liquid fuel combustion and main dependences for process optimization were elaborated.

Following the results of laboratory research, it was decided to undertake the pilot plant scale research to demonstrate the ability of the technology for operation in a larger scale at the harsh industrial conditions. The research was performed in cooperation between the Institute of Nuclear Chemistry and Technology (Poland), Saudi Aramco (Saudi Arabia) and EB TECH (South Korea). The tests were performed at the Jiddah Refinery (Saudi Arabia) and were based on the use of unique mobile electron beam accelerator that was constructed by EB TECH. This paper presents the construction of the Jiddah EBFGT pilot plant and results of the research.

2. Pilot plant description

The pilot scale EBFGT plant was constructed in the boiler area of the Jiddah Refinery. The simplified lay out chart of the plant is shown in Fig. 1. The flue gas from the boiler was directed to the cooling and humidification unit and then was irradiated in the reaction chamber. A near stoichiometric amount of ammonia was added to the treated gas upstream reaction chamber. After irradiation, the gas was directed to the byproduct separation unit consisting of a cyclone and cartridge bag filter or a cyclone and electrostatic precipitator in the second part of the research. Purified flue gas was released to the atmosphere by a separate stack. The gas flow rate was controlled by an ID fan rotation speed regulation. The construction of particular units is presented below.

2.1. Flue gas inlet

The pilot plant was supplied by a part of exhaust gas from the CE 31 VPH-12 W boiler manufactured by Mitsubishi (Japan) marked F 1001. The boiler may be fired by fuel heavy oil or fuel gas. During the research heavy fuel oil was combusted. The main properties of this fuel are presented in Table 1.

The pilot plant inlet was attached to the boiler outlet upstream of the power plant stack. A flap type valve was installed at the gas inlet to the plant.

2.2. Flue gas conditioning unit

Flue gas temperature at the pilot facility inlet was about 310 °C, therefore, the gas conditioning unit was applied for gas cooling down. Flue gas from the installation inlet was directed to the cooling device by uninsulated 315 mm diameter steel ducts. These ducts served as a pipe heat exchanger lowering the gas temperature before reaching the main cooling device.

A countercurrent water spray scrubber was applied as a main cooling and humidification device. This device was also designed for dust removal as no other dust collection system was applied in the installation inlet. The water was circulating in a closed loop. Water spraying nozzles were installed under the demister located in the upper part of the column, beneath the gas outlet. Water coming out from the cooling device was filtered to prevent nozzle plugging. In order to stabilize water temperature, a water cooler in the cooling loop was applied.

The ducts after the conditioning unit were heat insulated to avoid further gas cooling and water condensation in the ducts.

2.3. Ammonia dosing unit

Ammonia was delivered and stored in liquid form in steel cylinders and evaporated during the experiments. A battery of cylinders was used to ensure the proper amount of this reagent. Ammonia was injected into the duct via two nozzles upstream of the reaction vessel. In order to prevent particulate deposition that might lead to nozzle plugging, compressed air was used for ammonia spraying. The amount of injected ammonia was manually controlled via a rotameter with a needle valve.

2.4. Process unit

Electron accelerator ELV-0.6 M made by EB TECH was applied for flue gas irradiation. The main parameters of this accelerator are: beam energy 400 to 700 keV, maximum beam current 33 mA, and maximum beam power 20 kW. The scanner window length was 640 mm. The accelerator with radiation shielding, cooling, ventilation and other