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CFBC PILOT INSTALLATION WITH ADVANCED FLUE GAS PURGE SYSTEM

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Articolul prezintă rezultatele obținute în cadrul Laboratorului de Surse Regenerabile, Departamentul de Producerea şi Utilizarea Energiei - Universitatea Politehnica Bucureşti privind co-combustia biomasei şi lignitului autohton într-o instalație pilot de ardere în strat fluidizat circulant, ce integrează un sistem avansat de epurare a gazelor de ardere. Sunt analizate aspecte referitoare la efectele parametrilor de operare asupra co-combustiei biomasei şi cărbunelui. S-a constatat că temperatura în focar poate fi controlată în intervalul de 850°C - 1000°C prin varierea ratei de alimentare cu combustibil, a debitului de aer de alimentare şi a ratei de recirculare. Valorile înregistrate pentru principalii poluanți s-au menținut relativ scăzute, în perioada de funcționare staționară. De asemenea a fost analizata influența emisiilor de NO_x *şi* SO_2 *asupra degradării monoetanolaminei (MEA) folosită pentru captarea* CO_2 *precum si eficiența desulfurării cu 1%NaOH.*

Co-combustion of biomass and aboriginal lignite, was investigated at Laboratory of Renewable Energy Sources, Power Engineering Department – University Politehnica of Bucharest, in a CFBC bench installation, which integrates an advanced flue gas purge system. The effects of CFBC operating parameters on biomass and coal co-combustion are discussed. It was found that the temperatures along the furnace could be controlled in the range of 850°C– 1000°C varying the fuel feed rate, the air flow and recirculation rate. The values for the main pollutants were maintained relatively low, during the steady regime. Influence of NO_x *and* SO_2 *emissions on monoethanolamine degradation, used for* CO_2 *capture, and desulphuration efficiency using 1%NaOH is discussed.*

Keywords: combustion, fluidized bed, polluting emissions

1. Introduction

Circulating fluidized bed combustion (CFBC), in the last decade is again receiving worldwide research attention in view of its potential as an economic and environmentally acceptable technology for combustion and moreover co-combustion of any category of solid fuels from the coal class, biomass, and various types of waste.

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The technology was introduced to the market around 1980's and with progression of time, a greater understanding of the CFB technology was gained which allowed boiler manufacturers to design and construct larger CFB boilers. In Fig. 1 it is presented the scale-up Most of the CFB units reported are around 300 MW and less [1, 2] , all of them working at subcritical steam parameters and with efficiencies of 38-40%. Currently, the only capacity in operation that overcomes these limitations is Łagisza power plant, from Poland [3] but scale up to 600 – 800 MW_e is discussed [4] .

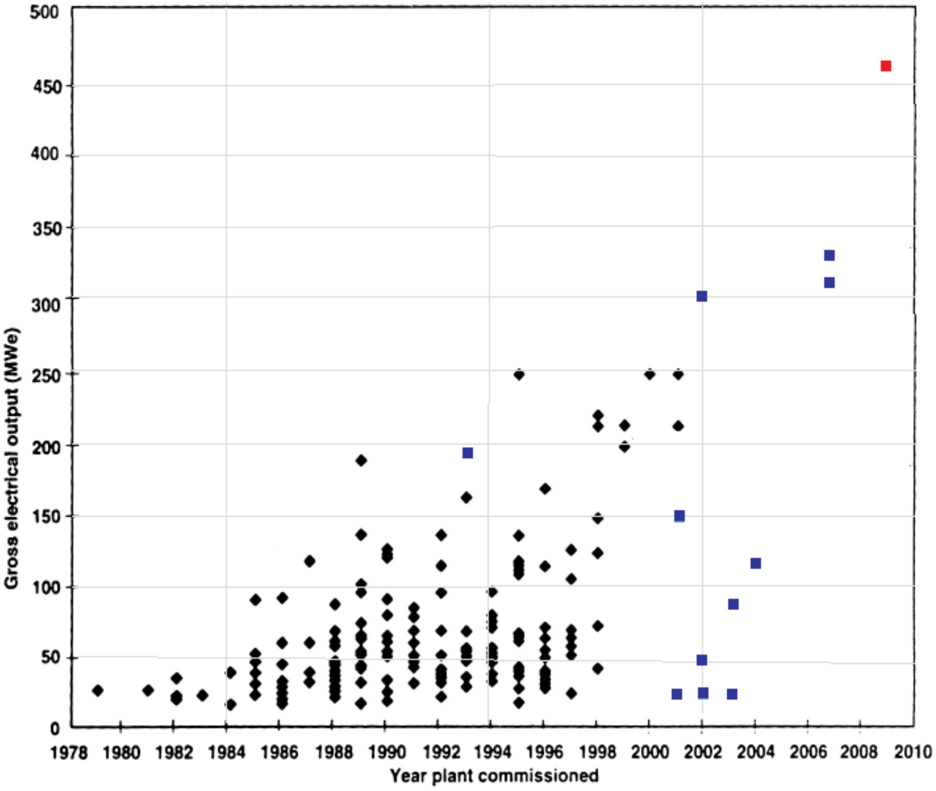

Fig. 1. CFB Boiler Scale-up Chronology

In Romania, even though the characteristics of the aboriginal coal, with a low heating value and high ash and high humidity content, are suitable for CFBC, at present, there are no CFBC boilers running. The present paper wants to underline the advantages of this technology for co-combustion of biomass waste with coal in a CFBC by presenting the results obtained in a CFBC pilot installation, with respect to NO_x, SO_2, CO_2 emission reduction from flue gases. The technology can be considered an interesting option in order to meet the values stipulated by national laws for Large Combustion Plants and the European targets regarding greenhouse emissions.

Relatively high capacity of regeneration, reduction of CO_2 emissions by saving of fossil fuels, lower NO_x and SO_x emissions (most types of biomass contain much less S and N than coal), improved combustion (due to the higher volatiles content of biomass), and lower ash content (biomass has low inert fraction), are some environmental advantages that sustain biomass as a renewable and clean fuel.

Co-combustion of pinewood waste and coal in CFBC technology, which integrates a CO_2 capture system, aims at reducing CO_2 emissions. Post-combustion carbon dioxide capture technology with monoethanolamine was integrated in the last section of flue gas cleaning stage, in order to study the effect of varying operational parameters of CFBC pilot plant installation on CO_2 capture efficiency.

2. Experimental CFBC facility

The CFBC pilot installation was designed and commissioned in the Laboratory of Renewable Energy Sources, Power Engineering Department – University Politehnica of Bucharest, and represents the only facility of this type and scale in Romania. The main particularity is the CO_2 capture system integrated in the last section of flue gas cleaning stage that uses the flue gases to heat and regenerate the rich MEA (monoethanolamine) flux.

CFBC main operating parameters are:

- Thermal load 75 kW_t
- Feed-in flow: up to 20 kg/h (depending of fuel type and particles size);
- Combustion air – up to 175 m^3/h;
- Temperature – 850°C-1000°C

The scheme of the CFBC pilot plant test unit, representing the main components of the installation, is shown in Fig. 2. The fuel, water and gas flow and as well the temperature, pressure and gas analysis sampling points are represented. The CFB bench installation is conceived as a modular structure: fuel feeding system; fan and air distributor system of primary and secondary air; natural gas burner for start-up; fluidized bed reactor; cyclone precipitator for separation of ash fraction; heat exchanger; bottom ash cooling screw; cyclone; CO_2 absorber; CO_2 scrubber; cooling system, pumps for MEA and NaOH.

Fluidizing air is introduced at the base of the fluidized bed through a nozzle distributor and used as both fluidization and combustion air. The fuel is introduced in the furnace above the air distribution plate.

After combustion the flue gases must be cleaned of impurities that affect the CO_2 capture solvent efficiency and contributes to its degradation. The dust particles are retained by the cyclone system. After the dust removal the flue gases pass through the desulphurization unit that has a triple role: (a) to remove the SO_x contaminants, that reacts with MEA and forms stable salts, (b) to cool the flue gases and (c) to wash the dust particles from flue gases. The desulphurization unit is a direct contact heat exchanger with reactions. The flue gases are passed in counter current with the NaOH solution. The contact surface area it is increased through a layer of ceramic RASCHIG rings. The gases from the desulphurization unit are introduced at the bottom of CO_2 absorption column. The absorber column has the same characteristics as the desulphurization unit.

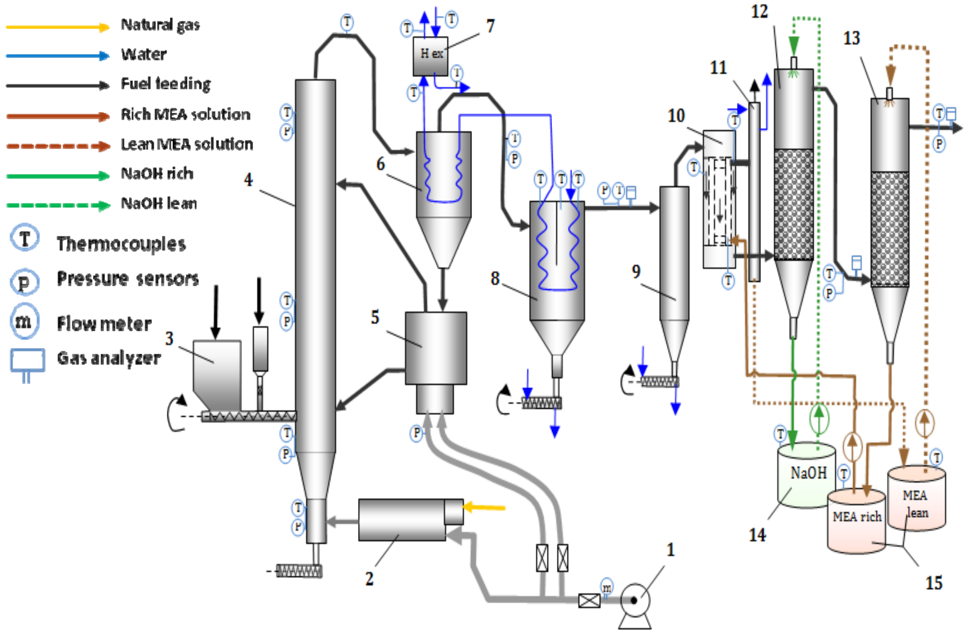

Fig. 2. Schematic diagram of experimental pilot CFBC installation

1. Blower 2. Pre-firing 3. Fuel feeding system 4. Combustion chamber 5. Recirculation system
6. Cyclone 7. H_2O-H_2O plate heat exchanger 8. Convective heat exchanger; 9. Cyclone; 10. CO_2
scrubber; 11. H_2O-MEA tubular heat exchanger; 12. Desulphurization unit 13. CO_2 Absorber
14. NaOH solution tank;15. MEA lean and reach solution tanks

The pilot plant is designed for measurements of pressure, temperature and air flow rates. The temperature variation and air flow variation values are recorded in continuous form and displayed on a synoptic board. During the experimental campaigns two samples are continuously extracted from flue gases and sent to the on-line flue gas analyzers (O_2, NO, CO_2, H_2S, SO_2, CO, NO_2, and excess air). The first flue gas composition sampling is before the desulphurization unit and the second one is after the absorber unit. Measurement points for temperature, pressure, air-flow and flue gas composition are presented in Fig. 2.

3. Fuel characterization

To assess the process, results regarding the experimental work using a mixture of two types of fuel: coal and biomass are presented. The fuel used during the experimental campaign was a mixture of pine wood and lignite.

The coal is an aboriginal coal from Schitu Golesti, having a Low Heating Value (LHV) smaller than 23865 kJ/kg. The proximate and ultimate analysis values for lignite are presented in Table 1 [5] .

The experimental pine sawdust came from a wood processing factory. The proximate and ultimate analysis values for pine sawdust are given in Table 1. The values are taken from literature [6] . The particle size of pine dust was between 0.5 mm to 5 mm.

Table 1

The proximate and ultimate analysis of fuels used in experimental campaign

Fuel data		M.U.	Fuel		
			Lignite	Pine wood	Equivalent fuel
Particle size		[mm]	<4	0.5-5	-
Low heating value		[kJ/kg]	13.6	17.96	14.472
Proximate Analysis	Fix carbon	[%]	24.63	14.4	22.584
	Volatile Matter		53.50	74.9	57.78
	Moisture		12.6	10.3	12.14
	Ash		9.27	0.4	7.496
Ultimate Analysis	C		65.21	46.3	61.428
	H		5.69	5.54	5.66
	O		26.84	47.64	31
	N		0.96	0.5	0.868
	S		1.3	0.02	1.044

The pine wood ignites and burns easier than coal, due to the high volatile matter. The high volatile matter content is also expected to affect the combustion process and temperature distribution in the riser. Moreover, the low density of pine wood complicates its processing, transportation, storage, feeding system and firing. The biomass / coal mass ratio used was ¼. The main restriction in using low density biomass is imposed by the feeding system (Archimedes screw) that has a fixed volumetric flow. The maximum biomass / coal ratio achievable in our installation is 1.

4. Results and discussions

Romanian lignite and pine sawdust was burned in the CFB pilot installation. Different variable have been studied: combustion temperature (850°C-1000°C), fluidizing velocity (2-4 m/s), excess air (1.5-3). The influence of SO_x, NO_x and O_2 emissions from flue gases on CO_2 capture efficiency are discussed.

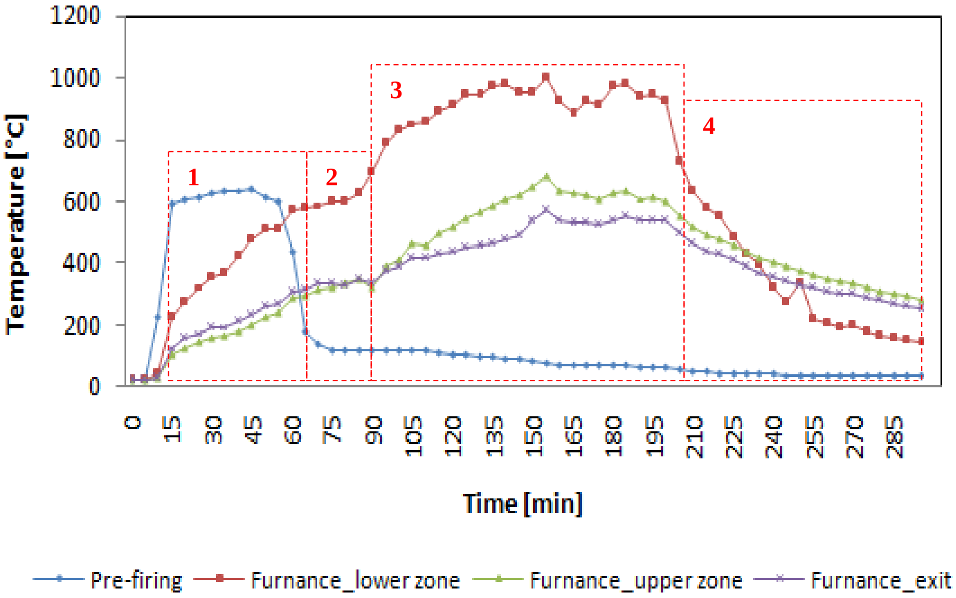

Fig. 3. Furnace temperature profile of lignite and pinewood co-combustion

Section 2 shows the fast decreasing of "pre-firing" temperature and, when the burner was shut down, and the slow increasing of the rest of the monitored temperature in the furnace. In this section the fuel feeding was maintained lower than 5 kg/h in order to obtain a stable combustion.

In section 3, of the figure above, the fuel feed rate was increased and kept between 10 and 15 kg/h. The result was an increase of the temperature in the furnace, in the separation cyclone and in the recirculation loop. During the tests the dense bed temperature was controlled in the range of 850°C– 1000°C varying the fuel feed rate (10-15 kg/h) and the air flow (100-200 m^3/h). The variation observed in the second part of section 3 are due to variation of the fuel feed rate and air flow.

In section 4 the fuel feeding was stopped and the temperature in the installation started to decrease slowly.

The furnace temperature can be effectively controlled by changing the solids loading in the upper furnace by varying the primary/secondary air ratio, by varying the gas velocity and fuel feeding rate. However, high gas velocity rates should be avoided because the residence time in the furnace of particle is reduced. This will permit volatile and un burned particle to escape before complete combustion is achieved.

During the experimental campaigns two flue gas samples were continuously extracted and sent to a gas analyzer that contains six gas sensors: O_2, NO, CO_2, H_2S, SO_2, CO, NO_2 and an IR sensor for CO_2 direct measurements. The flue gas The obtained values were analyzed in order to obtain information regarding the influence of the operating condition on flue gas emissions.

NO_x refers to oxides of nitrogen. These generally include nitrogen monoxide, also known as nitric oxide (NO), and nitrogen dioxide (NO_2). Among these, nitric oxide is the major product of coal and biomass combustion. During combustion, the nitrogen of the combustion air is oxidized to thermal NO_2, but its contribution is significant when the temperature in the furnace is above 1540°C [7] In circulating fluidized bed the NO_2 contribution to NO_x we observed it is less than 10% as the temperature are maintained between 800 and 1000°C.

During steady operation of the CFBC pilot installation NO_x emissions are < 300 due to low furnace temperatures and particle recirculation combustion. The values presented are calculated based on dry flue gas samples and with O_{2ref} =7%, as the instructional manual recommends [8] Most of the NO_x is formed in the lower portion of the furnace, with NO_x emissions increasing with fuel volatile content [1] , furnace temperature and O_2 level, and decreasing with an increase in the amount of char available in the fuel [9] .

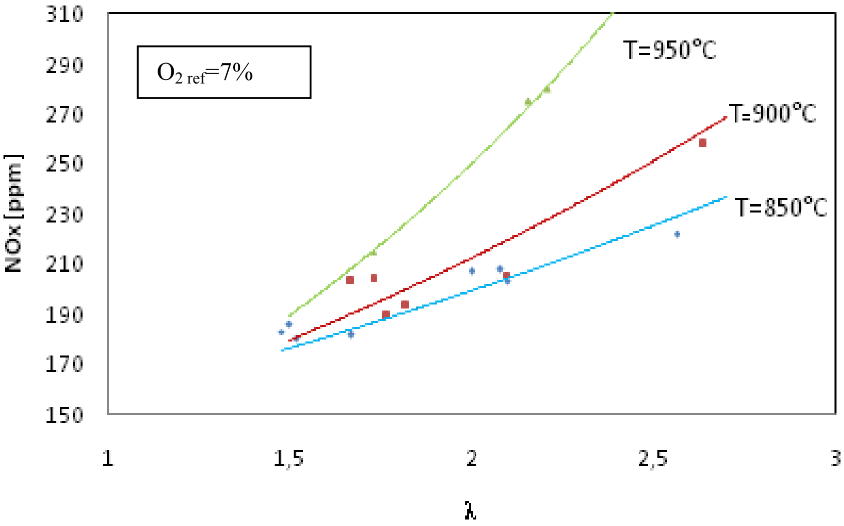

Fig. 4. The emission of NO_x during co-combustion of lignite and pine wood

In Fig. 4 it can be clearly seen that the values for NO_x concentration increases with excess air ration as well as with the bed temperature. The effect of bed temperature can be explained by its effect on the chemical reaction rate which leads to a change on reactions of formation and destruction of NO_x. The strong effect of bed temperature on NO_x emission is primarily the results of the reduced char content in the bed at higher temperature, which lower the degree of nitrogen oxide reduction into molecular nitrogen.

MEA, used for CO_2 capture from flue gases interacts with NO_x and forms stable salts that leads to monoethanolamine degradation. According to Chapel et al. [10] , for NO_x it is the NO_2 which leads to the formation of heat stable salts that fortunately, as mentioned above, is mostly less than 10% of the overall NO_x content in flue gases.

The values for CO are maintained between 100 and 350 ppm. Due to high volatile matter of the pinewood waste the CO emissions level are than coal combustion only. This can be noticed in the variation of the CO emission level when the fuel feed rate and air flow is constant, due to the heterogeneity of the fuel mixture.

The values for SO_2 in the O_{2ref} = 7 % by volume, in dried flue gas, during co-combustion of pine wood and lignite coal is maintained between 300 and 550 ppm (780-1300 mg/m^3) before SO_2 desulphurization system. SO_2 emission increases in proportion to the amount of coal burned and with the increase of combustion efficiency. Since the sulphur content of the pine wood is negligible, most of the emissions are due to the sulphur contained in the coal. Therefore SO_2 emission would decrease with increasing of the pine bark share in the fuel mixture. Because biomass fuels contain relatively large amounts of calcium, potassium and sodium, some SO_2 might be absorbed by CaO and MgO in the biomass ash to some extent [11] .

In order to avoid MEA desulphuration (values lower than 10 mg/m^3 are recommended as acceptable [12]), and to meet the values stipulated by the national legislation, wet sodium hydroxide (NaOH) method was chosen to remove the SO_2 emissions from flue gases. The scrubber is integrated in the final part of the gas cleaning stage; after dust separation and before CO_2 capture absorber. The NaOH based flue gas desulphurization process is a simple method with high efficiency. The reactions that occur during desulphuration process are [13] :

$$2NaOH(liq)+SO_2(gas)\rightarrow Na_2SO_3(precipitate)+H_2O(liq.) \tag{1}$$

$$Na_2SO_3(liq.)+{}^1\!/_2\,O_2(gas)\rightarrow Na_2SO_4(precipitate) \tag{2}$$

Two very important aspects should be considered when NaOH solution it is used for desulphuration: (1) achieving a good solvent dispersion in scrubber's cross section and (2) and realizing a good contact between flue gases and the solvents. Both requirements are achieved using a packing layer. RASCHIG rings layer was introduced in the scrubber in the case of this study.

In our experiment, 1% NaOH solution was used. The operation of the desulphuration unit was always maintained at high L/G ratio and alkaline pH. For emissions lower than 500 mg/m^3 the efficiency measured by the flue gas analyser (accuracy of ±5% vol. for +100...+2000ppm SO_x), was close to 100% and even for values in the range of 500-1000 mg/m3 the efficiency was about 99%.

Prepared by-products resulted from the desulphuration process can used as home laundry detergent, paper production , in laboratory as drying agent and for removing traces of water from organic solutions [13] .

As we said before, the experimental pilot installation integrates in the last section of flue gas cleaning stage the post-combustion CO_2 capture system. Currently CO_2 capture system uses MEA. According to Austgen and co-workers [9], the following reactions occur in the aqueous MEA-CO_2 system:

Water ionization:

$$2H_2O \longleftrightarrow H_3O^+ + OH^- \tag{3}$$

Dissolved CO_2 hydrolysis and ionization:

$$CO_2 + 2H_2O \longleftrightarrow H_3O^+ + HCO_3^- \tag{4}$$

Bicarbonate dissociation:

$$HCO_3^- + H_2O \longleftrightarrow H_3O^+ + CO_3^{2-} \tag{5}$$

MEA+ (protonate MEA) dissociation:

$$\mathrm{C_2H_8NO^+} + \left(\mathrm{MEAH^+}\right) + \mathrm{H_2O} \longleftrightarrow \mathrm{H_3O^+} + \mathrm{C_2H_7NO\ (MEA)} \tag{6}$$

MEACOO- reversion to bicarbonate

$$C_3H_6NO_3^-(MEACOO^-) + H_2O \longleftrightarrow C_2H_7NO(MEA) + HCO_3^- \tag{7}$$

CO_2 is measured both from O_2 measured values using formula 1 and by using a non-dispersive infrared sensor module for direct measurements.

$$CO_2 = CO_{2\max} \cdot \frac{21\% - O_2\%}{21\%} \tag{8}$$

$CO_{2\,\max}$ is a fuel specific constant and depends on fuel type. For lignite, the value recommended [8] for $CO_{2\max}$, when lignite it is burned, is 18.5. In the formula presented above 21% represent the content of oxygen in the air, in % and O_2 represents the measured oxygen content, in %. The measurement range of CO_2 measured values with the infrared sensor were between 7-12%.

The CO_2 absorption with 30 wt% MEA solution was around 60%. It was noticed that high NO_x, SO_2 emissions (when desulphurization unit was not running), and O_2 concentrations, contribute to monoethanolamine increase viscosity and degradability, decreasing its efficiency and requiring the replacement of the solution. There have been previous studies on reaction of alkanolamines with O_2, SO_2, CO [14-16] [15] . Most of these studies were conducted under laboratory conditions, with pure gases. However, in flue gases from a fossil fuel power plant the process becomes much more complicated due to the presence of a mixture of CO_2, O_2, CO, SO_x, NO_x, fly ash and other constituents. There are chemical degradation reactions that do not occur in laboratory experiments with pure gases. The degradation problem in this case remains poorly understood, particularly under conditions that are common to power plants. These problems are objective of further research activities at University Politehnica of Bucharest.

Another aspect that influences the MEA efficiency is the temperature. The temperatures in the absorption column were kept around 45-50°C and in the desorption column were in the range of 100-120°C. The desulphurization unit has as well, the role of cooling the flue gases to 40-60°C. Outside these range the absorption efficiency is very low, less than 30%.

5. Conclusions

Co-combustion of local coal and biomass was investigated in an experimental pilot CFBC in order to evaluate its combustion characteristics and flue gases emissions.

The results show that high combustion efficiencies and good emissions level control could be achieved by choosing appropriate operating conditions. During the tests performed the dense bed temperature was controlled in the range of 850°C– 1000°C varying the fuel feed rate (10-15 kg/h) and the air flow (100-200 m^3/h).

Circulating fluidized bed boilers presents the advantage of low NOx emissions. As well the NO_2 contribution to NO_x we observed it is less than 10% as the temperature are maintained between 800 and 1000°C. During steady operation of the CFBC pilot installation NO_x emissions are inherently low (< 300 ppm) due to low furnace temperatures and particle recirculation combustion.

The values for the CO emissions are maintained between 100 and 350 ppm. Due to high volatile matter of the pinewood waste the CO emissions level are slightly lower than coal combustion only. This can be noticed in the variation of the CO emission level, when the fuel feed rate and air flow is constant, due to the heterogeneity of the fuel mixture.

The SO_2 emissions during the tests of co-combustion of pine wood and local lignite coal were between 300 and 550 ppm (800-1500 mg/m^3). 1% NaOH solution, high L/G rates and alkaline pH was observed to be a efficient solution for desulphuration. For values of the SO presented in the flue gases close to 99%.

The by –products resulted from wet NaOH desulphuration method can be used in different processes and applications after a relatively simple preliminary treatment.

For the presented scheme, the CO_2 absorption with 30 wt% MEA solution was around 60 %. High L/G were required to achieve this value. It was noticed that high dust particles, NO_x, SO_2 emissions (when desulphurization unit was not running), and O_2 concentrations, contribute to monoethanolamine increasing viscosity and degradability, decreasing its efficiency and requiring the replacement of the solution.

The results obtained in our experimental bench plant allowed obtaining the necessary data regarding co-combustion of coal and biomass proper operation conditions in a CFB.

Acknowledgements

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