Operation of an electrostatic precipitator at a 30 MW_{th} oxyfuel plant

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1 Summary / Abstract:

The performance of a full-scale ESP was studied at the Vattenfall AB oxyfuel pilot plant in Schwarze Pumpe. The lignite-fired boiler has a 30 MW_{th} top-mounted pulverized coal burner and was operated under conventional air combustion as well as oxyfuel combustion. The ESP was operated with varying numbers of fields in service and at different current/voltage settings. Particle number size distributions downstream the ESP were established on-line in the size range 0.015-10 µm, using an electrical mobility spectrometer and an aerodynamic particle sizer. The particle size distribution at oxyfuel operation was qualitatively very similar to the results obtained for air-firing. Gravimetric measurements of total fly ash concentration showed outlet emissions below 5 mg/Nm^3 when the ESP was operated with two fields in service at oxyfuel conditions.

2 Introduction

The rapidly increasing need for electricity generation worldwide is covered to a large extent by construction of new fossil fuel power plants. This leads to a corresponding increase of CO_2 emission to the atmosphere. Significant efforts are spent in trying to reduce this emission, considering the risk of long-term temperature increase of the earth and associated climate change.

Some conventional ways exist to reduce the CO_2 emissions from fossil-fired plants, such as increased plant efficiency, co-firing with biomass, switch from coal to natural gas, etc. In addition to these relatively straightforward paths there are significant R&D initiatives ongoing in the area of CO_2 capture technologies and subsequent sequestration. Three main categories of CO_2 separation techniques are envisioned for use in commercial power plants, namely post-combustion technologies, pre-combustion technologies, and oxy-combustion [1].

In the oxy-combustion technology, or oxyfuel concept, the fuel is combusted with oxygen, resulting in a flue gas that is highly enriched in CO_2. In practice the pure oxygen generated by the air separation unit is diluted with recirculated flue gas prior to combustion, in order to obtain flame characteristics that are similar to conventional air-firing. This allows for the oxyfuel concept to utilize much of the existing technology from conventional power plants, including the flue gas cleaning equipment. The gas compression and purification plant (GPU) that takes care of the CO_2 at the end of the line requires very clean flue gas in order to work properly over extended periods of time. Thus a state-of-the-art flue gas cleaning train is of utmost importance for the success of any commercial oxyfuel plant.

In particular the dust emissions must be kept strictly under control to protect the downstream equipment, such as the GPU, but also to avoid particulate contamination of the recirculated flue gas. As for a conventional coal-fired power plant the equipment that can be used for dust separation is either a fabric filter (FF) or an electrostatic precipitator (ESP). The choice typically depends on dust properties, process conditions, economic considerations and preference of the plant operators. At an oxyfuel plant the dust cleaning equipment will typically be required to work efficiently at both oxy-firing mode as well as during conventional air-firing.

3 Vattenfall's oxyfuel pilot plant in Schwarze Pumpe

To pursue the oxyfuel concept as a possible route for future CO_2 abatement at commercial scale Vattenfall AB has commissioned a 30 MW_{th} oxyfuel pilot plant in Schwarze Pumpe, Germany [2]. The heart of the facility is the boiler, employing a single top-mounted pulverized coal burner capable of oxyfuel combustion in a number of modes as well as conventional air-firing [3]. The plant also comprises all the equipment envisioned for a future full-scale power plant, such as air separation unit (ASU), flue gas cleaning equipment and GPU. Figure 1 shows an overview of the Schwarze Pumpe oxyfuel pilot facility.

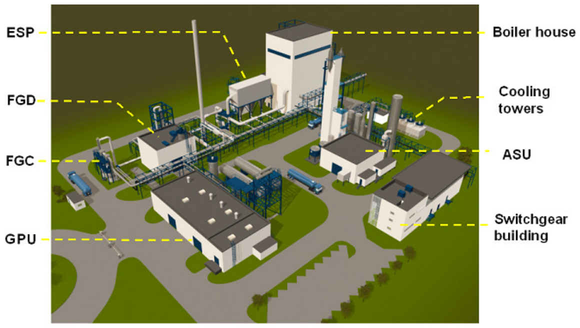

Fig. 1: Schematic overview of the oxyfuel pilot at Schwarze Pumpe.

The boiler is firing local Lusatian lignite that is dried and pre-pulverized at a nearby briquette factory. The main fuel source has a low sulphur and ash content, but also lignite with higher sulphur and ash concentrations from other nearby mines has been tested at different campaigns. It is also planned that in the future some imported hard coals will be brought to site and tested in the pilot plant.

The ESP, which is situated immediately downstream the boiler, treats the entire flue gas flow before approximately 2/3 of the gas volume is diverted back to the boiler to dilute the pure oxygen before entering the burner. The ESP has three electrical fields in the direction of gas flow, and is of the standard Alstom FPA design with spiral discharge electrodes and bottom rapping of the collecting plates. Although the height of the collecting plates is limited to five meters the size and layout of the precipitator may anyhow be considered as realistic for evaluation purposes. An external view of the ESP is shown in the photograph furnished in Figure 2.

Fig. 2: Photograph of the three-field ESP at Schwarze Pumpe.

The picture in Figure 2 is taken towards the outlet funnel of the ESP and the boiler house can be seen in the background to the left. Inside the enclosed area below the ESP it is possible to access the three dust hoppers to collect individual ash samples from each of the three fields.

4 Investigation of ESP dust collection performance at air- and oxy-firing

Compared to the vast knowledge base regarding ESP performance at conventional coal-fired plants very little is known about electrostatic precipitation at oxy-coal combustion. Some investigations of bench-scale character have been performed, but they offer limited insight on what to expect at a full-scale oxyfuel plant [4-5].

In September 2009 a test campaign with focus on the ESP performance was carried out at the Schwarze Pumpe oxyfuel pilot plant, as a joint effort by Vattenfall, Alstom and the Linnaeus University. The first part of the test campaign concerned gravimetric dust measurements at oxyfuel operation to establish the overall ESP performance. The fly ash concentration in the flue gas was measured at the ESP inlet and outlet, allowing the total dust collection efficiency to be determined at various electrical settings. In the second part of the investigation particle size distributions were measured at the ESP outlet at both oxyfuel operation and conventional air-firing. This comparison is of interest since many studies indicate that coal combustion in O_2/CO_2 atmosphere at various ratios may lead to changes in the fine particle fraction [6-7]. Today there is significant focus on the human health aspects of exposure to very fine particles that can penetrate deep into the lungs – for example PM 2.5 (airborne particulate matter below 2.5 µm diameter).

4.1 Gravimetric measurements of total dust concentration at the ESP inlet and outlet

The first objective for the ESP investigation at Schwarze Pumpe was to determine the overall collection efficiency during oxy-firing for a set of different ESP settings. Isokinetic gravimetrical samplings of fly ash were performed in the ducts upstream and downstream the ESP. Each measurement consisted of three repeated samplings, after which the new ESP setting was selected and allowed to stabilize overnight.

Four different ESP set-points were investigated during four days, while the boiler was running stable at oxy-firing 24 hours per day the entire week. More precisely, the burner was operated in so-called “Expert Mode A”. This means that the pure oxygen from the ASU and the recirculated flue gas are mixed directly in the flame zone (as opposed to pre-mixed mode) and that the oxygen is evenly divided between the lances in the burner [3]. Compared to air-firing, where the dried lignite results in a flue gas moisture content around 9% by volume, the oxy-firing gives approximately 35% moisture. This is due to the recirculation of flue gas that results in an enrichment of moisture as well as other gas components (like SO_2).

For all four test series the ESP was operated with two of its three fields in service. The main reason was that the measurement accuracy of a gravimetric sampling would not be enough for the low emission levels at three-field operation. Future planned test campaigns with high-ash lignite or hard coal may, however, require that all three fields are energized.

The different ESP settings selected for each day are summarized in Table 1. In all cases the same set point was selected for both the front and the rear field. Two of the settings employed continuous charging, while the other two operated at pulsed mode with charging ratio 1:3. Pulsed operation is mainly used for high resistivity applications, but may also be used to lower the ESP energy consumption. The specific average current density comes from the imposed pulse current limit divided by the charging ratio and the collecting area.

Date	ESP setting	Inlet dust	Outlet dust
8/9	1:3 150µA/m^2	6.6 g/Nm^3	4.4 mg/Nm^3
9/9	1:1 450µA/m^2	6.8 g/Nm^3	3.2 mg/Nm^3
10/9	1:3 60µA/m^2	6.2 g/Nm^3	5.6 mg/Nm^3
11/9	1:1 110µA/m^2	7.4 g/Nm^3	4.8 mg/Nm^3

Table 1: Summary of results from gravimetric measurements at the ESP inlet and outlet. All dust concentrations refer to dry basis.

The measured fly ash concentrations at the ESP inlet and outlet, listed in Table 1, shows clearly that the collection efficiency is in excess of 99.9% for all electrical settings. Furthermore it can be seen that the dust emission is decreasing when the ESP current input is raised. This is the normal behaviour for the ash-type at hand (low resistivity), although a somewhat stronger relation between current input and emission would perhaps be more typical.

The ESP operating average voltage, which follows from the current set-point, spanned from around 30 kV at the 10/9 setting to around 60 kV for the highest current input at the 9/9 setting. Typically the recorded voltages were about 5 kV higher in the front field compared to the rear field, due to the higher dust load and associated space charge effect. The flue gas temperature at the ESP was between 170 °C and 180 °C for all tests.

The measured outlet emissions according to Table 1 may be plotted against the corresponding ESP power consumption at each test point. This is done in Figure 3.

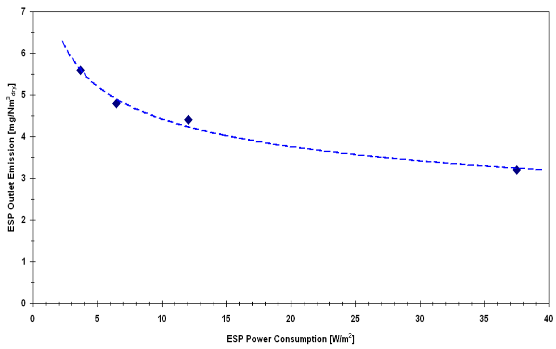

Fig. 3: Dust emission from the ESP as function of specific power consumption.

Frequent coal and ash samples were collected during the measurement campaign and later sent for analysis. Some data for a typical coal sample are listed in Table 2 for reference purposes. It can be seen that the Lusatian lignite has low ash content and a relatively low sulphur content. Due to the pre-dying it has a moisture content more representative of a bituminous coal.

	Sample 1	Sample 2
Total moisture	9.5%	9.2%
Ash (d.m.)	5.7%	5.7%
Sulphur (d.m.)	0.82%	0.79%
SiO_2 in coal ash	16%	13%
Al_2O_3 in coal ash	4.1%	4.1%
Fe_2O_3 in coal ash	20%	21%
CaO in coal ash	17%	17%
MgO in coal ash	9.0%	9.1%
SO_3 in coal ash	22%	21%

Table 2. Selected data for the pre-dried Lusatian lignite fired during the test campaign.

It is obvious from Table 2 that the coal ash composition is rather unusual. For most coal types silica and alumina constitute the majority of the ash, while the present ash is dominated by iron, calcium and magnesium. In addition there is a very high content of "SO_3" in the ash. In actuality it is not likely that the sulphur in the ash is present in this form, but rather represents sulphur that has reacted with the calcium during the pre-ashing stage in the laboratory.

4.2 On-line particle size distribution measurements downstream the ESP

For on-line particle size characterisation the flue gas immediately downstream the ESP was sampled from the duct using a dilution probe sampling system [8]. The probe tip was oriented towards the gas flow to obtain close to isokinetic conditions. The sampled flue gas is then diluted with dry filtered air in two steps. The primary dilution takes place close to the probe tip, after which the gas is further diluted in an ejector placed outside the duct. The final dilution ratio of the gas is carefully monitored before being distributed into two streams and brought to the SMPS instrument and the APS instrument, respectively.

The SMPS instrument (Scanning Mobility Particle Sizer) is based on how the particles move in an electric field after being charged. It is suitable for the particle size interval of ~0.01 µm to ~1.0 µm, and have a time resolution in the order of 60 s. The APS instrument (Aerodynamic Particle Sizer) accelerates the particles in a gas flow at a nozzle exit and measures the time they need to travel a certain distance. Since the force on a particle from the fast flowing gas is dependent on its aerodynamic diameter the particles may be classified by their size if their density is known (or assumed). The APS instrument works in the size range of ~0.5 µm to ~20 µm with a very fast time resolution of only a few seconds. More information about the sampling equipment and instruments can be found in reference 8. A photograph of the entire experimental set-up at the ESP outlet duct is shown in Figure 4.

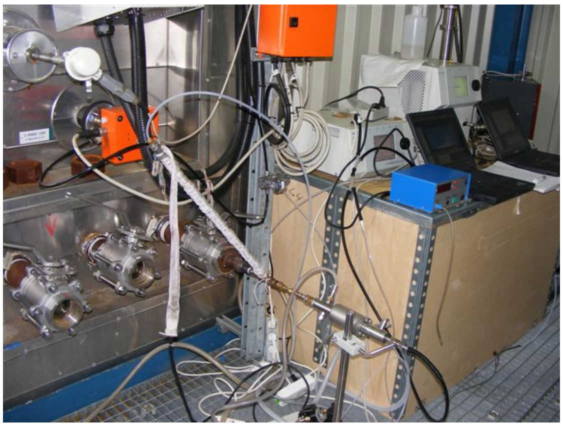

Fig. 4: Ongoing particle size measurement at the ESP outlet.

For processing of the SMPS and APS data, spherical particles of density 1.0 kg/dm^3 has been assumed. Furthermore the size range presented from the APS instrument has been limited to maximum 10 µm since losses in the sampling system for larger particles is expected to be very large. Even for particles with a diameter around 5 µm the internal losses within the sampling system have been shown to be significant [9].

The fuel and the operation of the boiler were intended to generate identical process conditions as during the gravimetric measurements described in Section 4.1 above. The burner was operated at the same load in "Expert Mode A", and coal samples collected showed clearly that neither the fuel itself nor the mineral composition of the ash had changed appreciably. However, due to some problems with the air separation unit only a limited number of ESP settings could be investigated at oxyfuel conditions before the unit was switched to air-firing.

The testing continued in air-firing mode, and after reaching stable boiler operation the same points (ESP settings) as for oxy-firing were repeated. After finishing these test points some further variation of the ESP settings could be tried in order to obtain further information on how the operation of an ESP affects the particle emission.

A comparison of the size-resolved particulate emission downstream the ESP for oxy-firing and for air-firing, respectively, is shown in Figure 5. The ESP was operated with two fields in service (as during the gravimetric measurements described in Section 4.1), and for the specific test series shown in Figure 5 the current input was limited to 110 µA/m^2.

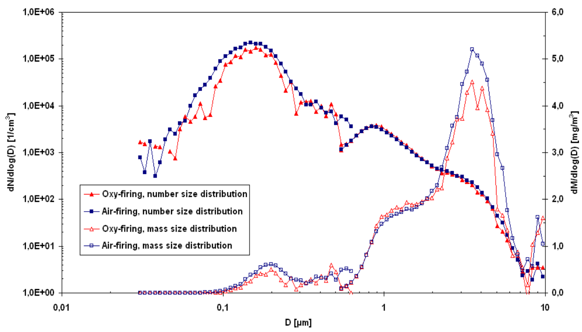

Fig. 5: Particle number size distributions and mass size distributions downstream the ESP for oxyfuel and air-firing conditions.

From the figure it can be seen that the size distributions from oxy-firing (red triangles) and air-firing (blue squares) are almost identical. The number size distribution peaks at about 0.1 µm for both combustion schemes, while the mass size distribution (derived from the number distribution assuming 1.0 kg/dm^3) has its maximum at a particle diameter of ~4 µm.

An estimate of the total particle emission can be obtained from the size distribution by integration of the curve in the entire range. For the data in Figure 5 this results in 4.1 mg/Nm$^3_{dry}$ and 3.5 mg/Nm$^3_{dry}$ for oxy-firing and air-firing, respectively. The result from oxy-firing compares favourably with the gravimetric measurement performed 11/9 with the same ESP setting (4.8 mg/Nm$^3_{dry}$ as per Table 1). This is despite the fact that the size spectrum is likely truncated to some extent for particle diameters above 5 µm, due to losses in the sampling system [9].

The particle size spectra that can be obtained from the SMPS and APS instruments may also be used to study how various electrical settings of the ESP affect the emission. This was done especially during the air-firing conditions, where the opportunity was given to vary the power input and number of fields in service within a relatively wide envelope. An example is given in Figure 6 that shows the size resolved emission for three different ESP current levels, all with two fields in operation.

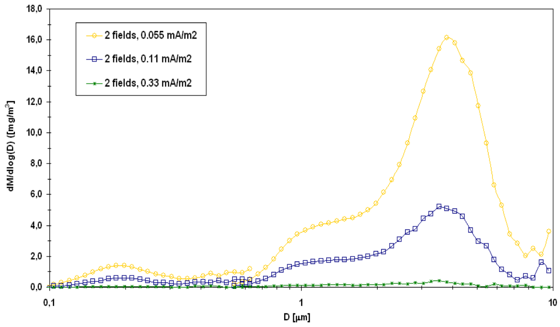

Fig. 6: Particle size resolved emission from the ESP at three different current densities for air-firing conditions.

It can be seen that the total emission goes down significantly when the current input is increased from 55 µA/m^2 (yellow circles) via 110 µA/m^2 (blue squares) to 330 µA/m^2 (green stars). At the maximum current of 330 µA/m^2 the estimated total emission (integral under the curve) is as low as 0.3 mg/Nm^3. This is significantly lower than what was measured by gravimetric sampling at oxyfuel conditions for a similar (higher) current input – The testing on 9/9 from Table 1. Given the similarity in particle emission between oxy-firing and air-firing demonstrated in Figure 5 it is not very likely that the big discrepancy stems from different firing schemes. More likely is perhaps that neglected losses in the sampling system start to become important, or that the gravimetric measurement technique has difficulty to measure the low emissions resulting from a high ESP power input.

5 Conclusions

The oxyfuel concept is a promising route for future CO_2 capture at fossil-fired power plants. The technology will utilize existing air pollution control equipment to clean the CO_2-rich flue gas prior to the gas compression and purification plant.

In the present study the performance of a conventional, commercially supplied, ESP has been studied at Vattenfall's oxyfuel pilot plant in Schwarze Pumpe. For the low sulphur Lusatian lignite fired during the test campaign it was shown that the ESP collection efficiency was very satisfactory for both air-firing and oxy-firing. Collection efficiencies in excess of 99.9% were reached, even when only two of the three ESP fields were in operation. This corresponds to a total particulate emission below 5 mg/Nm^3 on dry basis.

Particle size distribution measurements in the range 0.015 µm to 10 µm were performed for both oxy-firing and air-firing. This showed that the size distribution and total amount of particulate matter emitted from the ESP was virtually independent of the firing scheme. Size distribution curves established during air-firing for various ESP settings showed a strong decrease in emission for higher current input and when additional fields were engaged.

Acknowledgements

The authors wish to thank the personnel at the Schwarze Pumpe pilot plant for their kind assistance during the campaign. In particular we like to thank Mr. Manfred Stübe for helping with all practical aspects and preparations at site before and during the measurements.

6 Literature

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