Assessment of Hot ESPs as Particulate Collector for Oxy-coal Combustion and CO_2 Capture

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Abstract: Considerable effort is spent on development of technologies for CO_2 capture and storage (CCS) to stabilise atmospheric levels of greenhouse gases. Oxy-coal combustion is one promising technical option for the CO_2 capture from coal-fired power generation. A 30 MWth pilot oxy-coal fired power plant has been built by Vattenfall at Schwarze Pumpe in Germany to demonstrate the CCS technology. Lignite and bituminous coals will be tested for the oxy-coal combustion and CO_2 capture. The flue gas cleaning system comprises electrostatic precipitator (ESP), scrubber and condenser. The ESP-often referred to as a cold ESP when it is placed downstream an air preheater in a conventional air fired plant-operates at a temperature below 200 ℃. Conceptual studies are in progress for a full-scale demonstration plant and an attractive option is to have the ESP operating around 350 ℃ to improve the overall thermal efficiency of the oxy-coal concept. Such an ESP is frequently referred to as a hot ESP and is placed upstream the air preheater.

This paper will review the oxy-coal combustion and CO_2 capture and discuss the advantages with an ESP operating at a high temperature. It will also review the existing experience with hot ESPs built in the 1960's and 1970's mainly in USA. Most of these plants were later converted to cold ESPs operating at a temperature of around 150 ℃. The main reason for these conversions was the so-called sodium depletion in the fly ash that caused the ESP performance to deteriorate below acceptable levels. The sodium depletion resulted in high resistivity ash and back-corona conditions. The poor performance prevented any further installations of hot ESPs.

When discussing the feasibility of hot ESPs for oxy-coal combustion consideration is paid to the fact that numerous conventional cold ESPs today reach low emissions in spite of high resistivity ash.

Keywords: Electrostatic Precipitator, ESP, Hot-side ESP, CO_2 capture, High resistivity, Sodium depletion, Na, Rapping, Oxyfuel, Oxy-coal

1 THE OXY-COAL CONCEPT

Currently there are three main technical options for CO_2 capture from stationary combustion sources, such as thermal power plants and industrial fossil fuel combustion facilities. Fig. 2 illustrates the basic principle of the three CO_2 capture technologies for power and heat generation. Vattenfall, the fourth largest European energy company, has started intensive research and development on the CO_2 capture, transport and storage (CCS) with focus on oxyfuel and post combustion CO_2 capture technologies since 2000 [1]. Recently a 30 MW_{th} oxy-coal combustion CO_2 capture pilot plant has been built at Schwarze Pumpe in Germany. It is now operated in commissioning and testing phases. Fig. 1 gives a view of the pilot plant and the major units of CO_2 capture chain included in the plant. The boiler and the ESP have been supplied by Alstom.

As indicted in Fig. 2, in the oxy-coal combustion CO_2 capture processes, the oxidant used for combustion is pure oxygen generated by the air separation unit (ASU). The coal is combusted with the pure oxygen in an atmosphere of CO_2 (instead of N_2 in conventional combustion), which is supplied by flue gas recirculation to make the flame temperature and heat transfer similar to conventional combustion in boilers. Most of the conventional knowledge and technologies could then be easily transferred or modified for the oxyfuel combustion. The particulate matter (PM) in the recirculated flue gas must be removed to protect the fan and reduce ash

load in the boiler.

Fig.1 View of Vattenfall's oxy-coal combustion pilot plant (30 MWth) with a whole CO_2 capture chain currently operated in Germany

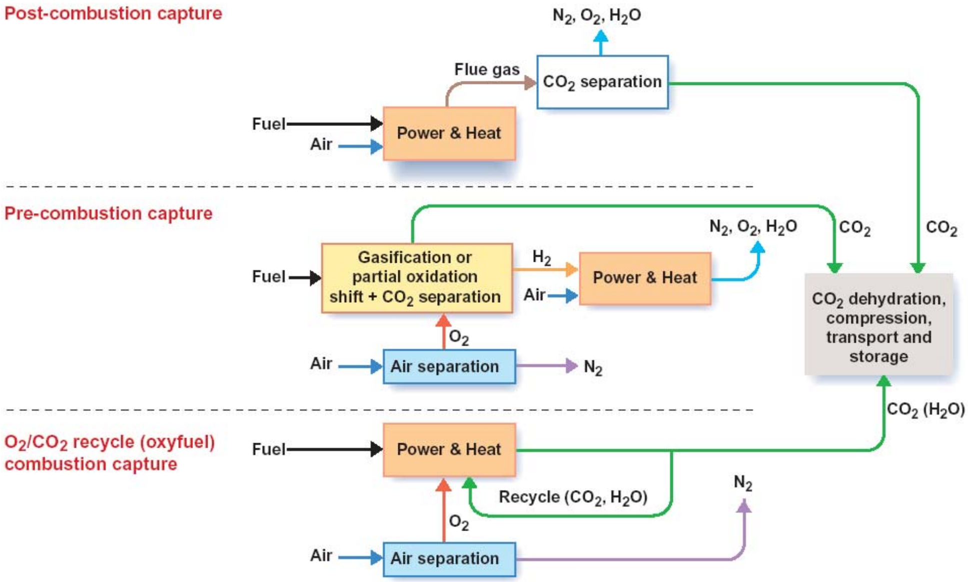

Fig. 2 CO_2 capture principle of three technologies applied for fossil fuel power/heat generation

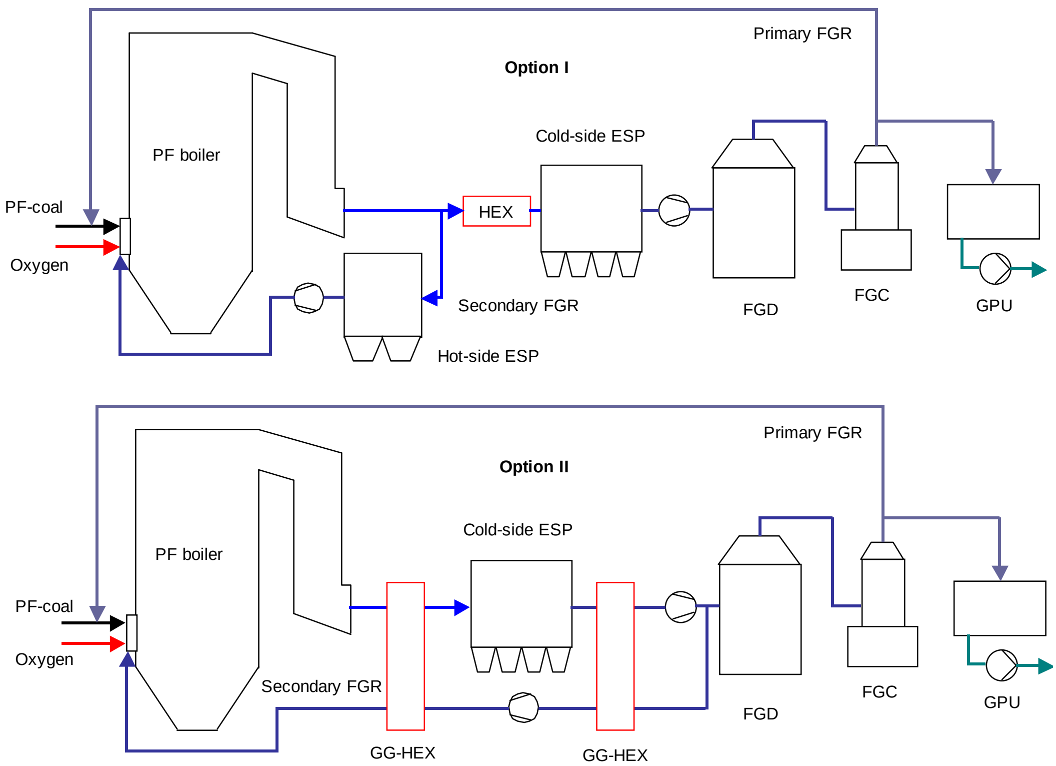

Fig. 3 Major options for participate matter removal in oxy-coal combustion of PF utility boiler

The main purpose of oxyfuel combustion for CO_2 capture is to generate a flue gas consisting mainly of CO_2 and water vapour. The part of the flue gas that is not recircultated, nominally 25%-30%, is taken to the CO_2 capture system. After flue gas desulphurisation (FGD) and condensation (FGC), a highly concentrated CO_2 stream could be obtained from the coal combustion with relatively low cost and energy consumption. Actually the non-CO_2 components generated from oxy-coal combustion are not only water vapour. Some non-CO_2 components, e.g. sulphur oxides, nitrogen oxides and other acidic gases, are also concentrated like CO_2 during the oxy-coal combustion. They should be kept to acceptable levels in order to meet the requirements of flue gas recirculation for boiler operation and for the CO_2 quality specifications for downstream processes. In general, the PM is removed by electrostatic precipitator (ESP), sulphur oxides are reduced by FGD, and finally non-condensable gases like N_2, O_2, Ar, etc. are separated from the CO_2 stream during the CO_2 processing (CO_2 plant).

In this paper the PM issues related to flue gas cleaning for oxy-coal combustion and CO_2 capture will be addressed - in particular the technical option for PM removal by using a so-called hot-side ESP. The expression hot-side or hot ESPs refer to ESPs placed upstream the air preheater in conventional air fired plants. The flue gas temperature is then in the range 300 ℃-400℃. The denomination cold-side or cold ESP that operates in the 130 ℃-180 ℃ range is used to characterise the conditions when the ESP is placed downstream of the air preheater.

Generally three are two major options for PM removal from flue gas in an oxy-coal combustion CO_2 capture for pulverised fuel (PF) utility boilers as shown in Fig. 3. Option I is using a hot ESP. Option II is similar to conventional configuration of PM removal for emission control and comprises a cold ESP. The main advantages of the hot ESP, option I, are:

(1) Avoid the gas-gas heat exchangers (GG-HEX) in option II. This could reduce the costs for equipment and heat losses because there is no need to cool down and re-heat the flue gas.

(2) Avoid the condensation of sulphuric acid during the flue gas recirculation. The corrosion potential of the boiler system could be reduced because the recirculation and the high temperature imply that higher concentrations of SO_3 could be tolerated.

(3) The cold ESP used for the non-circulated flue gas can have a much smaller cross section than for option II.

The main drawback of using the hot ESP concept according to option I is that the additional cold ESP may increase the total investment and operation costs for PM removal. It should be emphasised that it is not proven, and not very likely, that the collecting efficiency of a hot ESP is able to meet the final requirement for downstream CO_2 processing in an economical way. Here a very low dust concentration level in the 1 mg/Nm^3-10 mg/Nm^3 range is requested. Option II can therefore not comprise a hot ESP. In addition the performance characteristic of a hot (or cold) ESP under oxy-coal combustion conditions is not yet very well known. Hot ESPs, mainly used in USA during the 1970's-1990's, experienced a lot of problems as discussed in next section. As a consequence virtually no new hot ESPs have been built after PF boilers during the last decades. The question now is if a hot ESP in spite of the experience can be a technical viable alternative and weather it will be cost-efficient for oxy-coal combustion. Conceptual studies for a full-scale demonstration plant using a hot ESP are in progress according to option I.

2 EXPERIENCE WITH HOT ESPS FOR AIR FIRING

ESPs after coal fired boilers, located upstream the air preheaters have been used extensively in USA. The flue gas temperatures are typically around 350 ℃. The idea was to overcome the problem of high resistivity for certain fly ashes from coals with low sulphur content. Resistivities of a number of US fly ashes were measured and it showed that at 350 ℃ the resistivities were two decades lower than at 150℃-180 ℃ – see Fig. 4. This figure is shown as Fig. 4 in ref. [2]. When high resistivity conditions prevail on the collecting plates it reduces the collecting efficiency due to back-corona generation and sometimes due to frequent sparking (implying low power input). Back-corona or back-ionisation occurs when the product of current and resistivity causes a too high electric field in the ash layer (Ohm's law). If an ESP was sized and designed for low or medium resistivity the guaranteed emission could not be obtained if high resistivity ash was present. From Fig. 4 is can be seen that there were good reasons to believe that at temperatures around 350 ℃ the resistivity should be moderate even for a relatively low sodium content in the ash, so that back-corona was avoided. Hot ESPs after more than 150 boilers in USA were built and operated based on these premises. It should be noted that the emission guarantees in those days were substantially higher than today's standard. However, unexpectedly the perfor-mance deteriorated by time and also mechanical problems occurred. Almost all of these ESPs are today rebuilt and placed downstream the air preheaters, i.e. operating at temperatures in the range of 130℃-170 ℃. The mechanical problems for hot ESPs have in principle been solved while the performance issue was difficult to manage even if the root cause of the malfunction became known. As a consequence customers rejected any new installations following this concept.

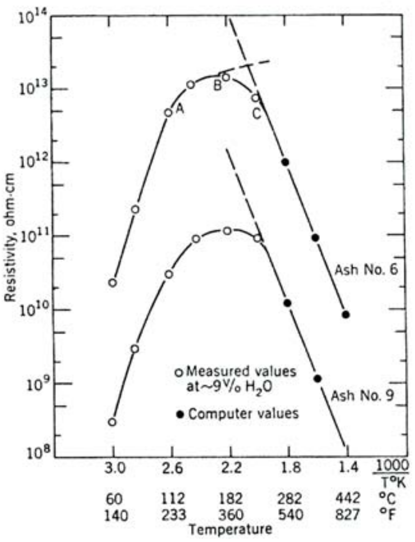

Fig. 4 Resistivity as function of temperature for two fly ashes. No.6 has 0.25% Na_2O and No.9 has 2.31% Na_2O [2]

Severe deterioration by time of performance in some plants took only a few weeks to develop, whereas in other plants it could take several months. The main remedy for the problem was to clean the ESP manually with water or high-pressure air. This caused loss of production during several days. Special investigations started, when the hot ESPs did not meet the expectations, and comprised long-term laboratory tests and full-scale investigations [2-4]. The tests showed that there is a migration of sodium ions, Na^+, in the ash layer on the collecting plates towards the negative discharge electrodes when the ash is exposed to an electric field and a penetrating current. The ash layer close to the plates lost Na^+ ions and as a result the resistivity increased in that part of the layer. Refs. [2-4] have demonstrated that reduced amount of Na will increase the resistivity. The low Na ash was found close to the collecting electrode. The phenomenon is known as sodium depletion. The corona current also had to penetrate the high resistivity part of the ash layer to reach the plate and back-corona was generated. A high resistivity ash is more difficult to dislodge from the collecting plates due to the electrical holding forces. Ref. [5] states that high rapping acceleration in the plates is necessary for efficient cleaning. The inner low Na ash layer remained on the collecting plates once it had developed in the hot ESPs where the performance had deteriorated, as it was very difficult to rap off. Rapping or cleaning of the collecting plates is therefore a key issue for high resistivity conditions. Fig. 4 illustrates that a Na_2O content of 0.25% in the ash has a much higher resistivity than a fly ash with 2.31%. Ref. [3] clearly shows that sodium is the major constituent in fly ash deciding the resistivity at high temperatures. The problems with the hot ESPs occurred when relatively low Na_2O contents, mostly <1%, were present in the coal ash. Laboratory measurements showed that the sodium content could be as low as 0.1% in the inner ash layer after the depletion process. It should be said that the resistivity diagram in Fig. 4 does not cover any long-term effects like sodium depletion. Carefulness with resistivity measurements must be taken. A few hot ESP plants have been built outside USA. Alstom built a hot ESP for a plant in Japan in the late 70's. The design coal had 1% Na_2O and the ESP met the guarantees after long time exposure.

Many of the hot ESPs built in USA in the 1960's and 1970's had small sizes and they were most likely designed for low or medium resistivities based on resistivity curves. This is described e.g. in ref. [6] where SCA values (Specific Collecting Area, m^3 of gas per second per m^2 of collecting area) ranging from less than 20 up to 80 are shown. Such SCA values might have been adequate for cold side ESPs without resistivity problems at that time. When comparing SCA values one must take the spacing between the collecting plates into account. Most likely ref. [6] refer to 10 inch spacing between the plates

Suggestions to improve the ESP performances were numerous, for example more efficient rapping, sodium conditioning, pulsing, regular switch of high voltage polarity, etc. Users of hot ESPs finally chose to rebuild the ductwork for the ESP to operate downstream the air preheater.

3 USAGE OF COLD ESPS FOR HIGH RESISTIVITY CONDITIONS

ESPs are still a commonly used device for high resistivity fly ash. In Europe and Asia they are for many users the preferred equipment instead of fabric filters (FFs). New coal fired plants under construction in Europe for low sulphur export coals have emission guarantees in the range of 10 mg/Nm^3. The SCA values are becoming very large compared to e.g. the hot ESPs used in USA. The specified coals often comprise low sodium contents. For many of the coals the sodium content is around 0.1% or even lower. Commonly used SCA values for high resistivity ashes and low emissions often exceeds 200 but some extreme ESPs have SCA values > 300, i.e. 4-10 times larger than the US plants. The SCA values are for these references based on 300 mm spacing. Many customers preference is still an ESP despite the large ESP size needed due to low emissions and high resistivity ashes.

During the US investigations it was proven that the sodium depletion occurs also at low temperatures, i.e. cold ESPs will also be subjected to sodium depletion [2]. However, with the low sodium content in many fly ashes the phenomenon may not have been detected or investigated. The time dependency for sodium depletion might also vary between hot and cold operation for various reasons making observations difficult for cold ESPs. From the vast number of successful installations, the sizing and design of cold ESPs must already from the beginning implicitly have considered the effect of sodium depletion. Important features for the ESPs working successfully with high resistivity ashes are

(1) Well-designed geometry to achieve even current distribution along the collecting plates [7].

(2) Heavy-duty rapping that implies bottom rapping with hammers [5].

(3) Advanced and properly optimised control system for energization of the ESP [8].

Most of the European and Asian installations for low emissions are made with the so-called European design where above features are incorporated to a great extent. As a side remark, it can be mentioned that the choice of filter in USA today for high resistivity ashes has become FFs. For cold ESPs the choice between FF and ESP is a question of installation and operating cost, as well as customer preference.

4 CONSIDERATIONS FOR USING HOT ESPS FOR OXY-COAL COMBUSTION

From the previous sections it can be anticipated that an adequately designed and sized hot ESP can be considered for oxy-fuel firing from a technical view point, at least when moderate emission levels can be accepted for the recirculation flue gases. If much lower emissions were requested, the feasibility would need to be investigated in much more detail. The cost for a hot ESP concept compared to other alternatives might still be an obstacle. The prerequisites to build a reliable and efficient hot ESP must besides an appropriate size and sound mechanical design follow the advices previously mentioned: geometry designed for high resistivities, efficient rapping, and advanced controls. For coals comprising low sodium content a size has to be based on experience with similar coals from cold ESP plants due to lack of data from hot ESPs. A conservative approach would be to take achieved migration velocities at cold ESPs for low Na coals and extrapolate them to hot ESPs. One has to take into account that due to lower density of the flue gas the electrical properties are weakened as the temperature increases, which reduces the collecting efficiency for the ESP somewhat. This decrease in performance will be counteracted by the higher water content during oxy-coal firing. The higher moisture content strengthens the electrical properties of the flue gas.

The performance of an ESP operating under oxy-coal conditions is not very well known at this stage. There are investigations [9,10] showing that the amount of submicron or ultrafine particles could increase somewhat compared to conventional air firing. Furthermore, as the flue gas is recirculated it is likely that the fine fraction of the ash will be enriched during oxy-coal combustion. Fine particles need longer treatment time in the ESP than coarse particles for the same collection efficiency. It is anticipated that the pilot tests with the cold ESP at Schwarze Pumpe will be a good guidance in this respect. Together with general knowledge of high resistivity fly ashes the proper size of a hot ESP for oxy-coal firing can then be estimated for cost comparisons with other alternatives.

A hot ESP for oxy-coal combustion does not need to be sized for extremely low emissions. The level would rather be decided from the fan perspective and could result in e.g. 300 mg/Nm^3. It is assumed that such an emission can be achieved without any excessive risk. One drawback with a hot ESP compared to a cold ESP according to option I (Fig.3) is that the actual gas flow is higher due to the temperature. Furthermore, a hot ESP is somewhat more expensive per volume compared to a cold ESP. The total cost might still be attractive compared to one cold ESP because the cold ESP has to be designed for a low emission for the full gas flow.

The ESP in option I, treating the non-circulated flue gas, operate at a high moisture content and moderate gas flow during oxy-coal mode. However, if the plant should occasionally operate with air firing and normal moisture, e.g. during start-up of the system, the cold ESP has to be sized according to demands for the downstream FGD and to emission limits set by the authorities. The ESP might then have to be sized for high resistivity conditions resulting in a large SCA. In order to use a reasonable size of such an ESP the boiler load during air firing must be limited compared to oxy-coal firing.

A cold ESP according to option II has to treat the whole gas flow. However, during oxy-fuel conditions there is still the advantage of high moisture content in the flue gas compared to air firing. Boiler load limitations during air firing may have to be considered also for option II.

5 SUMMARY

Vattenfall is performing a conceptual study for the utilisation of a full-scale hot ESP, operating around 350 ºC for oxy-coal firing. Advantages would be a better thermal efficiency and that the corrosion risks would be reduced compared to other alternatives. The concept implies that a large portion of the gas flow from the boiler is recirculated and the PM must therefore be collected to protect the fan and the boiler.

Hot ESPs placed upstream the air preheater became common in USA from the late 60’s. With a hot ESP it was believed that the high resistivity problem of certain fly ashes could be avoided. However, numerous problems arose and among them an inherent phenomenon that became known as sodium depletion was identified. Sodium ions were moving away from the inner layer of the fly ash on the collecting plates and by time developed a high resistivity ash layer. This layer generated back-corona conditions that gradually reduced the ESP performance. Today, almost all hot ESPs in USA have been rebuilt and placed downstream the air preheater. In Europe and Asia cold ESPs are commonly used for high resistivity ashes and low emissions can be achieved. The ESP sizes (SCA values) are however substantially larger than the US ESPs and consequently more costly.

By applying experience and technology used for high resistivity ashes in cold ESPs it is believed that hot ESPs can be attractive technical solutions for oxy-coal combustion. A conceptual study for a full-scale plant is ongoing. Vattenfall is now running an oxy-coal pilot plant in Germany, including a cold ESP. Based on results from the pilot investigations and general knowledge about hot ESPs during air firing the hot ESP concept for the recirculation gases will be evaluated both technically and economically.

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