Enhancing ESP Efficiency for High Resistivity Fly Ash by Reducing the Flue Gas Temperature

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Abstract: the resistivity of fly ash after coal-fired boilers varies with the flue gas temperature. the normal esp operating temperature of around 150 ℃ is typically near the maximum resistivity of the ash. for low sulphur coals the resistivity will sharply decrease if the flue gas temperature at the esp inlet is reduced to about 100 ℃ or less. this will mean that a significantly smaller esp can be built for a given efficiency. already in the early 1970's esps were built at the liddell power station in australia purposely designed to operate at low temperature to reduce the fly ash resistivity. the full-scale design at liddell was based on pilot testing at other locations in order to verify the low temperature approach. despite successful implementation at liddell the experiences did not result in much follow-up of low temperature esp operation. the concept was revived in japan in the 1990's, resulting in several installations working at temperatures below 100 ℃ these units have a considerably reduced esp size, and the energy recovered upstream the esp is used to re-heat the flue gas after the desulphurisation system. the low temperature esp operation is now well proven and a viable alternative when burning low sulphur coals.

Keywords: Electrostatic precipitator, ESP, power plant, coal, fly ash, sulphur, resistivity, back-corona, temperature, migration velocity

1 INTRODUCTION AND BACKGROUND

Globally, the largest application for industrial particulate collection is after coal-fired boilers. In principle there are two practical alternatives of equipment to collect the fly ash, namely electrostatic precipitators (ESPs) or fabric filters (FFs). The choice between these two options is affected by the coal that will be fired in the boiler. For coal that generates fly ash that has high resistivity an ESP cannot be operated at a high specific power input since a high current passing through the ash layer on the collecting electrodes will induce back-ionisation (back-corona). Due to the low current density required to reduce the back-corona the ESP size will have to be larger to meet a given emission level. A fabric filter is not at all affected by the resistivity of the fly ash and often becomes an attractive option for such type of coals. The phenomenon of back-corona and the strategies to avoid it is traditionally an area of great interest in the field of electrostatic precipitation.

The resistivity of fly ash depends strongly on the temperature of the flue gas. The exact functional relationship depends on fly ash composition, sulphur content of the coal, flue gas moisture content, etc. It may look like the curve shown in Fig. 1 for a typical high resistivity fly ash.

The curve in Fig. 1 shows a measurement performed in the laboratory on collected fly ash, and is considered to be roughly representative of the situation inside the ESP during operation. Typically the maximum fly ash resistivity occurs between 140 ℃-160 ℃, which is close to the operating temperature of most ESPs after coal-fired boilers. The decrease in resistivity with increasing temperature above the peak is a volume property of the ash that occurs for any semi-conductor or insulator material. The decrease in resistivity for lower temperature, on the other hand, is a surface effect due to condensation of mainly moisture and SO_3 on the individual ash particles.

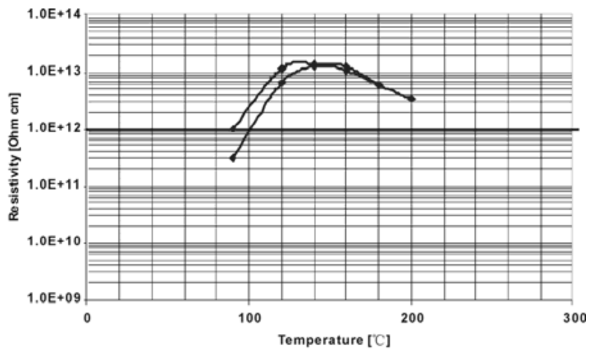

Fig. 1 Dust resistivity as function of temperature (Australian fly ash)

In the 1960's it was thought that an effective way to overcome resistivity problems in electrostatic precipitators would be to place it upstream the air preheater, letting the ESP operate at a temperature of 350 ℃-400 ℃. Under such operating conditions it was envisioned that all problems associated with high resistivity fly ash would vanish [1]. This would result in lower cost ESPs despite the higher actual gas flow and other complications associated with high temperatures. Consequently a large number of these "hot-side ESPs" were built between the late 1960's and early 1980's, mainly in the USA. However, this approach turned out as a failure for the majority of the installations due to unexpected long term effects in the dust layer. This so called “sodium depletion phenomenon” caused back-corona to re-occur after some time of operation at the elevated temperatures [2]. Thus the design of new hot-side ESPs was discontinued. Today most of the existing installations have been converted to ordinary units with the ESPs located after the air preheater at gas temperatures of around 150 ℃.

The other obvious choice to solve the high resistivity problem, namely to go for lower flue gas temperatures, did not at all receive the same amount of interest as the hot-side ESPs. Possibly this was due to fear for corrosion issues when coming closer to the acid dew point, as well as doubts regarding the design of the air preheater. Despite the lack of attention for the use of a low temperature approach for improved ESP performance it came into use in at least one major installation during the 1970’s. This interesting and important plant was the Liddell power station in Australia, arguably the first installation to utilize low flue gas temperature to reduce fly ash resistivity problems in the ESP.

The Liddell plant consists of four 500 MWe boilers and each boiler was equipped with five ESPs. Three of these five ESPs, treating about 80% of the flue gas, were designed to operate at temperatures down to 90 ℃, while the two other would operate between 160 ℃ and 220 ℃. Successful performance guarantee testing of particulate emission was carried out for the low sulphur design coal in 1972.

Despite the success at Liddell no organized effort was really made by ESP vendors or utilities to pursue a similar approach for many years. However, one example in these intermediate years was the Ensted power plant in Denmark (630 MWe). Originally designed for low to medium resistivity ash from West-Canadian coals the ESP experienced emission problems after a switch to low sulphur coals from Australia in the early 1980’s. Based on the experiences from Liddell, the solution employed was to decrease the flue gas temperature to the ESP, together with the newly introduced feature of Semipulse (Intermittent Energization) [3]. It was possible to operate the air preheater in such a way that the flue gas temperature was lowered to about 105 ℃ on a continuous basis, which gave a significant performance improvement compared to the design temperature of 130 ℃. The plant was operated in the low temperature mode for more than 10 years with no operational problems or corrosion issues.

Renewed interest in low temperature ESP operation came in the mid-1990’s when Mitsubishi Heavy Industries (MHI) promoted the low temperature approach via pilot studies, and subsequently supplied a full scale ESP for a 1000 MWe plant in Japan [4,5]. This installation uses a separate non-leakage gas-gas heater (GGH) after the ordinary Ljungstrom air preheater to reduce the temperature to below 100 ℃. The energy recovered is used to reheat the flue gases downstream the wet flue gas desulphurisation unit to avoid a wet stack and visible plume. As in the Liddell case the ESP was sized much smaller than would have been the case at ordinary ESP operating temperatures, where resistivity would be very high for the low sulphur coals fired.

After MHI’s first installation at the plant Haranomachi several ESP installations operating at similar temperatures after coal-fired boilers have been built. Notable plants include Tachibanawan, Tomatoh, Maizuru, and the most recent installation Tosoh Nanyo, commissioned in early 2008. The total installed coal fired capacity using the low temperature ESP approach is to date well above 10000 MW. All of these new installations are located in Japan, and use the concept of an extra gas-gas heater before the ESP. New plants are currently in the planning stage.

In the following sections the implementation of the low temperature approach at the three sites Liddell, Ensted and Tosoh Nanyo is described in some detail. It is hoped that this will serve as useful examples, showing the potential of low temperature ESP operation. In the last section some general conclusions are presented.

2 BASIC THEORY

The basic formula describing ESP performance is the Deutsch equation, giving the outlet dust concentration, C_{out}, as function of the inlet concentration (C_{in}), gas flow (Q) and precipitator collecting area (A):

$$C_{out} = C_{in} \exp[-\omega A/Q].$$

The parameter ω has the dimension of m/s, and is referred to as the particle migration velocity (in the electric field). It can indeed be interpreted as the average velocity at which the dust particles travel towards the collecting plates, but may also be seen simply as a “performance parameter” for the ESP for the conditions at hand. The quantity A/Q that multiply ω is called the specific collecting area (SCA), which is the ESP size in m^2 of collecting area per m^3 of flue gas per second. Thus the ESP size (for given actual gas flow and emission limit) is directly proportional to $1/\omega$.

The migration velocity, ω, is a complicated function of a large number of variables, including particle size distribution, ash composition, precipitator current and voltage, flue gas temperature, actual gas flow, ESP geometry, etc. The migration velocity is also dependent on the sulphur content in the coal, which in addition is a critical parameter for the feasibility of operating an ESP at low temperature. Depending on the moisture and temperature of the flue gas, and the SO_2 to SO_3 conversion rate in the system a maximum sulphur content (e.g. 0.8%) must be specified to avoid acid condensation and corrosion.

It should be clear that the Deutsch equation is a highly idealized formula. Among other things it assumes the same ω-value for each particle, independent of its size, and includes no non-ideal effects like rapping losses or dust re-entrainment. In fact, the real precipitation process is so complex that purely theoretical models of the ESP operation have never been really successful. Electrostatic precipitation is therefore an experimental science, where prediction models must be based on empirical experience in conjunction with theoretical considerations.

One way to somewhat compensate for the dependence of ω on the particle size and make it less dependent on the SCA value is to use the modified Deutsch equation, also known as the Matts-Öhnfeldt equation [6]:

$$C_{out} = C_{in} \exp[-(\omega_k A/Q)^k].$$

Here k is an ad hoc parameter to compensate for a finite particle size distribution of the dust. For fly ash it has turned out that a k-value of around 0.5 is suitable to get a robust equation for size predictions and performance evaluations. Since this paper only concerns coal fired boilers the modified migration velocity, ω_k, will be used throughout as the relevant ESP performance parameter. A k-value of 0.5 is then implied in the modified Deutsch equation.

In this paper the focus will be on ω_k as a function of flue gas temperature. When discussing the dependence of a multivariable function like ω_k of only one single parameter all other variables would ideally be kept constant. This is however not theoretically possible due to internal temperature related dependencies among the variables themselves. Another comparison philosophy, which is possibly more relevant, is to optimize the ESP operation for each new test condition (temperature). However, it is very difficult to know that optimized performance is indeed achieved, and all parameters may not be practically possible to adjust. In the test descriptions below an attempt is made to explain briefly how other parameters were treated while investigating different flue gas temperatures.

3 RESULTS OF LOW TEMPERATURE ESP OPERATION IN AUSTRALIA

In 1966 Fläkt (now Alstom) and the Electricity Commission of New South Wales (which later adopted the trading name Pacific Power) performed pilot testing to prepare the ESP specifications for the upcoming Liddell power plant.

The tests were carried out using an Alstom three-field pilot ESP connected to a slipstream after boiler #4 at the Pyrmont power station in Sydney, Australia. The boiler was a 50 MWe pulverized coal boiler manufactured by International Combustion in 1955. For the tests 5000 tons of Bayswater coal, which was considered as a main fuel source for Liddell, had been excavated and transported to site. The flue gas temperature of the slipstream could be cooled by means of a heat exchanger, or heated using electrical heaters or by extracting flue gas upstream the economizer. A temperature range from about 90 ℃ up to 280 ℃ was achieved during the course of the test campaign.

The ESP performance for the difficult low sulphur Bayswater coal was found to be strongly temperature dependent. This is illustrated in Fig. 2, where relative migration velocities for the temperature range have been plotted.

During the testing at Pyrmont the pilot ESP was mostly run at a voltage close to the sparking threshold and continuous charging was used (the Semipulse concept was not developed until about 15 years later). The gas velocity through the pilot ESP was kept constant at about 0.55 m/s, and the boiler was running stable close to maximum load.

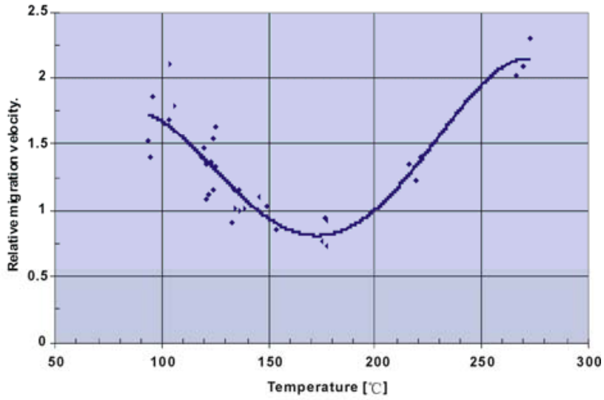

Fig. 2 Relative migration velocity for the pilot ESP tests at Pyrmont as function of temperature (fly ash from Bayswater coal)

As can be seen in Fig. 2, ω_k at 90 ℃ is almost twice as high as compared to e.g. 150 ℃. For the design of an ESP this would translate in the first approximation to a corresponding reduction of the ESP size to half. If also the reduced actual gas flow at the lower temperature is considered one would arrive at a further reduced ESP size.

The pilot study at Pyrmont, was made available to all prospective tenders for the 4×500 MW Liddell project. The contract for all four boilers went to Combustion Engineering, while Fläkt (Alstom) received the ESP portion. Unit #1 was placed into service in 1971, and the other units came on line in the following two years.

The ESP design and ductwork at Liddell was rather special, with the intention of using the low temperature from the secondary air preheaters (SAPH) to obtain enhanced ESP performance. The flue gas from the primary air preheaters (PAPH), on the other hand had a high temperature, and went into two separate ESP casings. The general ESP layout at Liddell is shown in Fig. 3.

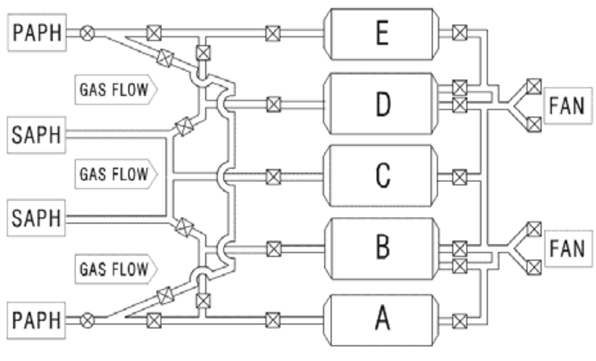

Fig. 3 Schematic picture of the ESP layout at Liddell (one boiler). The crossed squares represent damper locations

The flue gas passing the secondary air preheater constitutes about 80% by weight of the total gas flow, and enters the ESP (casings B-D) at a temperature of 95-100 ℃. The rest of the gas, which goes through the primary air preheaters, is treated in the two outer ESP casings (A and E), at a nominal temperature of 175 ℃. All five ESPs have three electrical fields, but the SCA of the low temperature casings B-D was designed significantly lower than that of casings A and E. This was based on the pilot test results at Pyrmont.

The results from the performance guarantee tests at Liddell confirmed the temperature trend seen at Pyrmont. Fig. 4 shows the relative migration velocity for the low temperature ESPs versus the high temperature ESPs at Liddell. This figure is based on the guarantee tests for unit #2 in May 1973.

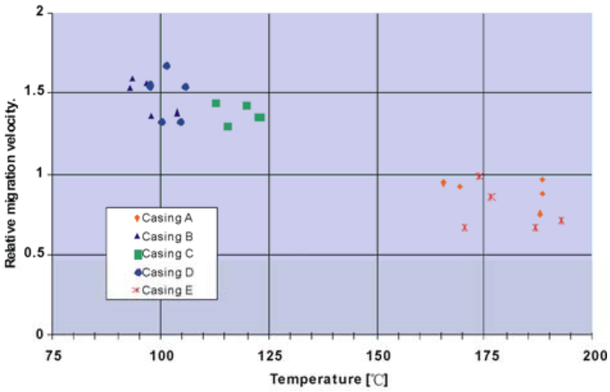

Fig. 4 Measured relative migration velocities during the performance testing at Liddell #2 for the cold and hot ESP casings

The Liddell measurements indicate an increase in migration velocity of about 70% if the flue gas temperature is decreased from 160 ℃ to 90 ℃. This is a somewhat smaller improvement factor than what was seen at Pyrmont. Part of the difference is of course that a pilot investigation is not the same as a full-scale test. Another reason could be that the gas velocity inside the low temperature ESP casings at Liddell was somewhat high, whereas the Pyrmont tests were designed to have equal gas velocity independent of temperature. In addition the much larger and more modern boiler at Liddell likely played a role. Anyhow the performance increase at low temperature is significant, and it is somewhat surprising that utilities and suppliers did not pursue this opportunity in many years to come.

4 IMPROVEMENT OF ESP EFFICIENCY AT REDUCED FLUE GAS TEMPERATURE IN DENMARK

Unit #3 at the Ensted power plant (owned by DONG Energy) was commissioned in 1979 and is the second largest boiler in Denmark, at a rating of 630 MWe. The unit utilizes two separate five-field ESP casings for particulate collection. The SCA had been determined for handling low to medium resistivity fly ash from West-Canadian and Polish coals, but due to market availability alternative coal supplies had to be considered shortly after commissioning. The plant then turned to the supplier of the ESP, Fläkt (Alstom), for advice on mitigations to increase fuel flexibility while still maintaining the legislated particulate emission level.

The primary solution became to decrease the flue gas temperature to about 105 ℃, which was possible due to a conservatively sized Ljungstrom air preheater. This approach allowed firing of a wide range of difficult low sulphur coals with high resistivity ash, which had not been possible at the original design temperature.

In 1984 a major test campaign took place, where different approaches were tested in order to minimize the particulate emission. Among other things this led to an early successful demonstrations of Semipulse (intermittent energization), using the first generation of microprocessor ESP controllers (EPIC) [3]. Special interest was also paid to the effect of flue gas temperature on the ESP performance.

The ESP performance was monitored by a data acquisition system with continuous storage of over 300 variables. The dust emission in particular was measured by opacity meters, which had been thoroughly calibrated by gravimetric sampling. During the test campaign low sulphur Ulan coal from Australia was fired. The fly ash from this coal is well known for being extremely difficult to collect in a precipitator due to its high resistivity.

During the temperature tests the plant personnel increased the flue gas temperature from the nominal 105 ℃ up to about 130 ℃, while keeping the boiler load constant at 620 MW. At about 130 ℃ the emission levels were typically so high that the temperature had to be brought back to 105 ℃ after some time due to environmental concerns. One temperature test is shown in Fig. 5. As can be seen, the east ESP casing performed better than the west, which is probably due to the lower pulsing frequency in the Semipulse settings (charging ratio 1:9 in the east casing compared to 1:5 in the west). For optimum performance higher charging ratios should likely have been used, especially for the high temperature. This was however not done.

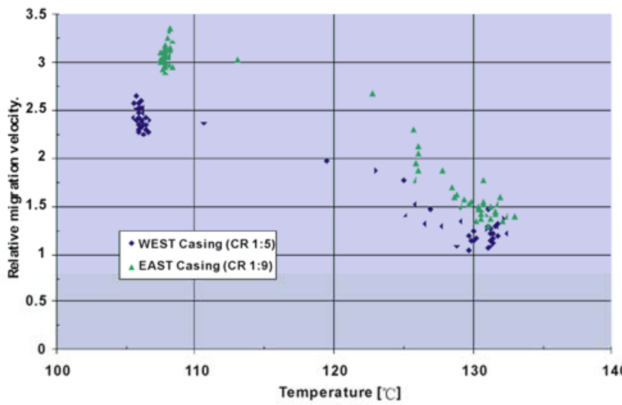

Fig. 5 ESP performance (relative migration velocity) during a temperature excursion. The points shown in the graph represent about 4 hours and 45 minutes of data logging

Each point in Fig. 5 represents one sampled value, with a four minute averaging time. The figure shows two hours of stable operation at 105 ℃, after which comes an increase to 130 ℃ during about 45 minutes where the temperature then was kept for two hours. The emission peaks due to rapping in the last field resulted in an increase of outlet particulate with about a factor of three during the corresponding four-minute average. Thus the rapping peaks also decreased in proportion to the base line emission when operating at a lower temperature. The corresponding data points during rapping are however not shown in Fig. 5 (five points in both east and west casings).

The data in Fig. 5 show an even more pronounced temperature trend than what was seen at the Liddell plant. This makes sense, since the Ulan coal at Ensted generates even higher resistivity fly ash than the Bayswater coal fired at Liddell. The performance enhancement for the Ulan coal is as high as a factor of two for the moderate temperature difference of 105 ℃ versus 130 ℃.

In the mid-1980's Alstom erected and commissioned an ESP pilot at the Ensted plant. The pilot, which treated a slipstream from boiler #3, was further developed in the 1990's, comprising a total of three two-field ESPs. In view of the re-emerging interest for low temperature ESP operation some testing of the temperature dependence was performed at this pilot in 1994. In the following years additional pilot tests at other sites, e.g. at the Saijo power plant in Japan, were also carried out, paying special interest to operating temperatures around 100 ℃.

During the pilot testing at Ensted in 1994 the three ESPs were connected in series, for a total of six electrical fields. The temperature could be varied between approximately 120 ℃ and 150 ℃. For the low sulphur South African coal fired in the boiler during the testing a clear temperature trend for the ESP collection efficiency could be seen even for this interval. As for the previous cases a prediction model used by Alstom for ESP sizing was found to correlate very favourably with the experimental data. The theoretical model could then be employed to estimate the efficiency at temperatures also below 100 ℃. This is demonstrated in Fig. 6.

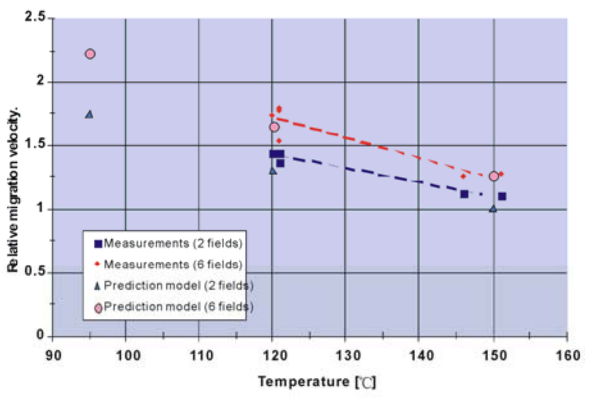

Fig. 6 Pilot results at Ensted 1994 for South African coal. The prediction model is the standard Alstom ESP sizing program

The pilot tests at Ensted also support the temperature trend seen in the other examples above. The increase in migration velocity for the South African coal is predicted to be similar to that measured for Bayswater coal.

5 LOW-LOW TEMPERATURE ESP AT THE TOSOH NANYO COMPLEX IN JAPAN

The ESP after unit #6 boiler at the Tosoh Corporation Nanyo complex in Shunan city is the most recent of the new generation of low temperature ESPs in Japan. These are often referred to as "colder side ESP" or "low-low temperature ESP" (LLT-ESP), operating at typical flue gas temperatures of 85 ℃-95 ℃.

The unit, which was commissioned in March 2008, consists of a 220 MWe pulverized coal boiler supplied by IHI Corporation, followed by the LLT-ESP and a limestone scrubber. The ESP, shown in Fig. 7, was supplied by Alstom and has two parallel gas passes (A and B) and four electrical fields in the direction of gas flow.

Fig. 7 View of the #6 low-low temperature ESP at Tosoh Nanyo

The reduction of flue gas temperature to below 100 ℃ is accomplished by a tubular non-leakage gas-gas heater upstream the ESP, which re-heats the saturated flue gas exiting the scrubber. In this way there will be no visible plume at the exit of the stack, and a wet stack is avoided.

Shortly after the commissioning dust measurements of the ESP was carried out. The main purpose was to calibrate the optical dust meters and to prepare for the upcoming performance tests. The testing took place during three days while the boiler was operating at about 210 MW load, firing a 50-50% mix of Indonesian and Chinese coal. This was not the most difficult fuel out of the contract specification from an ESP perspective, but some Chinese coal types are known to give very fine fly ash [7], which could present a complication.

During the test campaign the flue gas temperature in the ESP was kept at 87 ℃-88 ℃.

The gravimetrical testing and on-line dust monitoring showed emissions well below the designed emission of 30 mg/Nm^3. In fact, during the measurements the power input to the ESP had to be reduced to give higher emission that did not fall under the measurement precision of the gravimetrical sampling. The emissions at maximum power input could then be estimated by extrapolating the calibrated dust monitoring curve downwards. This method led to an estimated outlet of around 4 mg/Nm^3. At the lowest point of the calibration curve the gravimetrical sampling gave an emission of 6.7 mg/Nm^3 (at about half the power consumption compared to maximum input). Alternatively the power consumption of the ESP could be further reduced to less than 1/10 of the maximum, while still staying below the design emission. This was done during the gravimetrical sampling to obtain the highest point of the calibration curve. Fig. 8 shows the outlet signal from the A-pass of the ESP at two different power input levels.

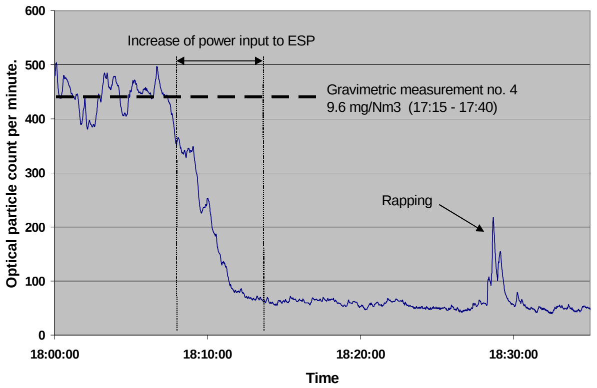

Fig. 8 On-line signal after gas pass A. The emission is seen to decrease when the power input to the ESP is increased

In Fig. 8 one can also see the impact of collecting electrode rapping. During four minutes fields 1 through 4 are being rapped sequentially, and a peak in emission can be observed. The emission peak is however very moderate, corresponding to less than 7 mg/Nm^3.

In summary the low-low temperature ESP at Tosoh Nanyo performed very satisfactory. Since the unit is operating continuously at temperatures below 100 ℃ the emission at higher temperatures can only be estimated using prediction rules. Given the fly ash characteristics and flue gas composition for the present operating conditions the temperature dependence will be less pronounced than e.g. for the difficult Australian coals described above. The present fly ash at Tosoh Nanyo could be classified as being of medium resistivity (at ordinary ESP temperatures) and will become low resistive in the low-low temperature regime. It is interesting to see that outlet emissions in the 5 mg/Nm^3 range can be readily achieved by an ESP, and that the emission peaks associated with rapping are relatively small. This could indicate that low temperature operation enhance the agglomeration properties of the dust so that rapping losses are reduced.

6 DISCUSSION AND CONCLUSIONS

As shown by the examples in this paper a very significant performance improvement can be achieved for an ESP by reducing the flue gas temperature. This is valid for a wide range of low sulphur coals, and with proper design and operation the potential risks like corrosion and clogging can be avoided. For specifications containing coals that generate fly ash of very high resistivity the ESP size can be reduced to less than half, if the design temperature is lowered from e.g. 150 ℃ down to below 100 ℃.

The decrease of flue gas temperature can be achieved either by an increased size Ljungstrom air preheater, or by addition of an extra gas-gas heater upstream the ESP. The second approach uses the recovered energy in the GGH to re-heat the flue gas exiting the limestone scrubber. This concept has been used for several large plants in Japan during more than a decade. For future development the path using merely an upsized Ljungstrom air heater could have more potential in terms of plant efficiency and savings in capital cost. Different approaches to effectively utilize the recovered energy to increase the plant net efficiency are possible. In future scenarios it may also be possible to use the low-grade heat in various CO_2 capture technologies.

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