Fractional bypass of raw gas to improve performance of ESP-FF hybrids after coal-fired boilers

Andreas Bäck[1] and Alain Bill[2]
[1]Alstom Environmental Control Systems, Alstom Power Sweden AB, Växjö, Sweden
[2]Alstom Thermal Services, Alstom Switzerland Ltd, Baden, Switzerland

Abstract — In this paper it is suggested that the performance of a hybrid ESP-FF system can be improved by utilizing a small controlled flue gas bypass stream to transport virgin fly ash from the ESP inlet to the fabric filter inlet. The purpose of this bypass stream, which may be in the order of 5-10% of the total flue gas flow, is to produce a particle size distribution at the fabric filter inlet that is quasi-similar to the original distribution leaving the furnace. This would avoid potential problems with e.g. bag blinding, resulting from the very fine particles escaping the ESP. Since the bypass flow is low compared to the total gas flow the resulting particle concentration is still much lower than the concentration at the boiler exit, allowing higher filtration velocity and lower pulse cleaning frequency in the fabric filter. The bypass stream flow can be adjusted until optimum performance is achieved, and may of course also be completely turned off in extreme cases, such as during bag failure in the FF.

Keywords — Electrostatic precipitator, Fabric filter, Hybrid ESP-FF, Fly ash, Bypass

I. INTRODUCTION

The removal of particles from the flue gas of coal-fired boilers is today effectively taken care of by an electrostatic precipitator (ESP) or a fabric filter (FF). The preferred choice depends on coal quality and process parameters, as well as other techno-economical considerations, local legislations and customer preference. Normally an ESP has a lower operational cost while the FF has a lower installed cost, especially for coals resulting in fly ash with high electrical resistivity. When the emission requirement becomes extremely low, e.g. below 10 mg/Nm^3, or if removal of volatile heavy metals such as mercury is needed, the bias tends to be towards a FF solution. The dominating FF design today is the high ratio fabric filter (HRFF), or pulse jet filter, where the dust is collected on the outside of the bags and periodically cleaned off by pulses of compressed air blown into the bags.

Another possibility for particulate removal is to combine an ESP with a FF. This combination, normally referred to as an ESP-FF hybrid, is in its simplest form nothing more than a conventional ESP in series with a conventional stand-alone FF [1-5]. A more advanced version exists, where the ESP and FF are placed in a common housing for a more compact design [1-2]. Often the design with ESP and FF in one common casing is referred to as a COHPAC II system, while the more conventional layout with a separate ESP and FF in series is called COHPAC I [1-2]. There are also fairly exotic systems where the electrostatic precipitator function has been fully integrated with the filter bags in various configurations, essentially having high voltage electrodes, collecting plates and bags in close vicinity of each other [6-7].

One of the goals of any hybrid solution is that the particle separation by the upstream ESP potentially allows a higher filtration velocity in the FF at the same time as the bag cleaning pulse frequency can be kept at a minimum. It is normally also considered that the electric charge present on the particles after passing through the ESP will allow a more porous dust cake to be formed on the FF bags [8-9]. A further attractive feature of a hybrid is the redundancy presented by the ESP in case of problems with the FF, such as bag failure. This advantage is especially interesting for customers that have traditionally used ESPs and that may not yet be experienced with FF operation. In the ideal situation, a very moderate ESP size will allow a downstream FF

Corresponding author: Andreas Bäck
e-mail address: andreas.back@power.alstom.com

that is significantly smaller than if it had been placed immediately after the boiler and at the same time lead to reduced pressure drop and reduced bag wear.

Some coal-fired boilers have been designed and commissioned with ESP-FF hybrid particle collectors from the start, but most installations are of retrofit character, retaining an existing ESP as pre-collector for a new FF. Reports on the actual performance and particle collection efficiency, pressure drop and bag life of existing hybrids have varied considerably [1-5]. Experimental results in pilot units have also been unable to reach firm conclusions regarding the benefit of having an ESP as pre-collector compared to a stand-alone FF. As a result of the mixed performance of ESP-FF hybrids, combined with the significantly increased cost and maintenance complexity of having two pieces of equipment, it is difficult to endorse a hybrid solution over a stand-alone FF (or ESP in some cases). This being said, there may be certain circumstances where hybrid solutions could be useful, such as upgrade projects with existing ESP or when the amount of coarse abrasive particles in the flue gas is very high.

This paper looks at some problems that may be encountered in a combined ESP-FF hybrid due to the specific particle collection mechanisms of ESPs and FFs. It also addresses possible ways of alleviating some of these issues and at the same time achieving reduced pressure drop and reduced bag wear.

II. PRINCIPLES OF DUST COLLECTION IN ELECTROSTATIC PRECIPITATORS AND HIGH RATIO FABRIC FILTERS

The basic mechanisms of particle collection in ESPs and fabric filters are well-known and described in the literature [10-15]. A complete review is not the aim of this paper, but this section will briefly look at the collection mechanisms and the consequences that are relevant to an ESP-FF hybrid collector.

A. Dust collection in an ESP

In an ESP the electrostatic precipitation proceeds via a corona discharge generated at high voltage electrodes. The high electric field at the sharp high voltage electrodes ionize the gas via an electron avalanche process and the resulting ions then move along the electric field lines from the ionization region towards specially designed collecting plates. On their way through the inter-electrode region the ions attach to dust particles suspended in the gas, effectively charging them. The charged dust particles are driven towards the collecting plates by the electric field, albeit at a much lower velocity than the ions. The net drift velocity of the dust particles, referred to as migration velocity, is in the order of cm/s and depends on a number of parameters, such as particle size, ESP voltage, electrode layout, gas temperature and composition, etc. When reaching the collecting plates the particles form a dust cake, held in place by the current passing through the dust layer. The dust cake is then periodically removed from the collecting plates via rapping.

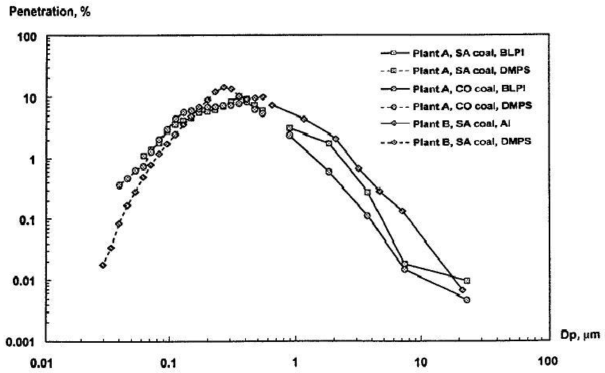

Fig. 1. Particle penetration vs. particle size for ESPs at two different coal-fired plants (from Ref. 16).

If rapping losses and numerous other non-ideal effects in the precipitator are neglected, the particle migration velocity towards the collecting plates in the inter-electrode gap is the main ESP performance parameter. The ESP dust collection efficiency, η, is then determined via the Deutsch equation: $\eta = 1 - \exp[-\omega A/Q]$, where ω is the migration velocity, A is the collecting area of the ESP and Q is the treated gas flow in m^3/s. Since the migration velocity depends (among other things) on the particle size, the Deutsch equation is only valid for each individual size fraction of the particle size distribution and integration over all sizes would have to be performed to arrive at the total collection efficiency. Via the field charging mechanism the number of electrical charges attainable for a particle increases as the square of the diameter. Since the balancing drag force for a migrating particle is proportional to its velocity and diameter, the net migration velocity becomes proportional to the particle diameter for sizes of a few microns and larger. For sub-micron particles the diffusion charging phenomena starts to become important, which increases with decreasing particle size. For the purpose of the coming discussions it is here enough to conclude that relatively large particles of several microns in diameter are very efficiently collected in an ESP, while there is a minimum collection efficiency in the sub-micron range. The minimum ESP collection efficiency typically occurs somewhere between 0.1 μm and 1 μm and has been verified in field measurements many times [16-18]. Fig. 1 shows the measured penetration as a function of particle size through two different ESPs after coal-fired boilers (graph from Ref. 16).

B. Dust collection in a HRFF

The fabric filter is based on filtration of dust as the flue gas passes through filter bags made of a synthetic polymer material or fibre glass. More precisely it is mainly the dust cake formed on the filter bags that provide the filtering effect and consequently the process is referred to as cake filtration, as opposed to fibrous filtration where the individual fibres of the filter media achieve the filtration. The filter bags in a HRFF, which can be up to 12 m long, are placed inside large compartments to which the flue gas is diverted from an inlet plenum. The frequency of the bag pulse cleaning, which is normally performed for one row of bags at the time in each compartment, is set to maintain a desired pressure drop over the entire system. Since a very large part of the total particle emission from a HRFF occur as dust peaks in connection with the pulse cleaning events, the properties of the filter cake and the pressure loss it generates is intimately connected with the dust emission from the unit. Thus, the dust properties affect the FF emission both via its tendency to penetrate the dust cake and the filter media, as well as via its ability to form a dust cake that is suitable for filtration and that is porous enough to avoid the need for very frequent pulse cleanings. In this way the relation between the performance of a FF and the dust properties becomes rather complex and attempts to derive relations from first principles have generally been unsuccessful. Instead, suppliers of FFs have built up experience and databases from operating units for a variety of operating conditions and dust properties, so that sizing and layout of new installations can be optimized.

One of the key FF sizing and design parameters is the filtration velocity, V_f, also referred to as the gas to cloth ratio. Typically given in m/h or ft/min, it determines the filter bag area and hence FF size needed to treat a given gas flow. According to Darcy's law the pressure drop over a porous medium is proportional to the filtration velocity, leading to an expression of the form $\Delta P = K_1 V_f + K_2 V_f W$, where $K_1 V_f$ and $K_2 V_f W$ represent the pressure drop over filter media and dust cake, respectively. The factor W is the amount of dust per square meter of bag material (g/m^2). The accumulated dust on the bag increases with time as $W = C_{in} V_f\, t$, where C_{in} is the incoming dust concentration in g/m^3. The dust properties enter the pressure drop equation via the constant K_2, which can vary in a wide range depending on, for example, the particle size distribution. Furthermore K_2 is not really a constant since it will often vary somewhat with the filtration velocity: $K_2 \propto V_f^r$. The exponent r may be in the order of 0.5 and depends on dust properties and process conditions, and represents the tendency of the dust cake to decrease its porosity as the filtration velocity increases. From the above it is clear that pressure drop (and rate of increase of pressure drop) is strongly dependent on the dust characteristics. One of the key parameters in this respect is the particle size distribution. Small particles tend to form a less porous filter cake that leads to a rapid increase in pressure drop, as demonstrated e.g. by Cheng and Tsai [19]. Furthermore, theoretical consideration of particle impaction on fibres shows that particles in the sub-micron range, especially between 0.1 μm and 1 μm, have the greatest ability to penetrate deep into the filter material. It has been demonstrated many times in full-scale installation that such deep penetration leads to a gradual increase of the residual pressure drop of the filter media, leading in the long run to ever increasing pulse frequency and shortening of bag life.

The frequency of pulse cleaning to maintain a desired pressure drop is basically proportional to the inlet dust concentration and the resistance parameter K_2. It is well known that a very large percentage of the total particulate emission from a HRFF comes from the emission peaks associated with the pulse cleaning. At a pulse cleaning event the filter bag is inflated as the compressed air pulse move downwards. After a meta stable rest at maximum inflation where the dust is thrown off by inertial forces and flushing of outgoing air, the bag then accelerates back and hits the supporting cage. The corresponding deceleration causes particles to become loosened and they can then penetrate the fabric material when normal filtration resumes. For the penetration of particles through the filter media itself, which is basically fibrous filtration, it is possible to derive relations between the penetration and the particle size. The result is that maximum penetration occurs for particles in the size range where neither inertial impaction on the fibre nor impact by diffusion is dominating. This size window is approximately for diameters between 0.1 - 1 μm, i.e. roughly the same range as where an ESP typically has the lowest collection efficiency.

C. Dust collection in an ESP-FF hybrid

The consequence of the above for an ESP and FF in series, i.e. a hybrid, is that the benefit compared to a stand-alone fabric filter may not be as significant as intended. The particle size distribution exiting the ESP, shifted towards the sub-micron range, is thus enriched in the size fraction most likely to penetrate deep into the filter media. Furthermore, the almost complete absence of coarse particles at the FF inlet, having already been collected in the upstream ESP, will tend to form a very non-porous dust cake. Because of this, the rate of increase in pressure drop is larger than what is indicated by the lower inlet dust load to the FF (i.e. the increase in K_2 offsets to a large extent the decrease of C_{in}). For example, pilot trials performed by Gutiérrez Ortiz *et al.* showed that K_2 increased by a factor of up to five with ESP pre-collection (compared to when the ESP was turned off) [3]. Even with cyclone pre-collectors removing the coarse fraction of particles at the FF inlet the value of K_2 was shown to increase several times in an experimental bench-scale study performed by Davis and Kurzyske [20].

In addition to the increased dust cake resistance, K_2, a point of concern with an ESP pre-collector removing most of the coarse dust is that the fine particles cannot form larger agglomerates in the filter cake. Thus the situation may be further aggravated by the very slow gravimetric settling of fine particles after a pulse cleaning event, leading to increased number of re-deposition of dust onto the bags before it reaches the hoppers. As a consequence this may lead to a larger number of cleaning cycles, which is highly unwanted since each pulse cleaning and re-deposition event gives a certain contribution to deep penetration and emission. All the factors above make the design and optimization of the pulse cleaning equipment even more crucial than for a conventional stand-alone HRFF.

III. POSSIBILITIES FOR IMPROVING ESP-FF HYBRID PERFORMANCE

In the previous sections some aspects of the dust collection in ESPs and FFs (HRFFs) were summarized, which are of importance when looking at the performance of an ESP-FF hybrid. It was concluded that an ESP has a relatively shallow collection efficiency minimum between 0.1 μm and 1 μm, while it is very efficient for particles larger than a few microns. Also, it was remarked that the penetration of particles through the filter media in a FF is largest for particles in roughly the same size range as where the ESP has its lowest collection efficiency. Clearly this coincidence is sub-optimal when placing a FF downstream of an ESP in a hybrid concept. Furthermore, it was pointed out that the properties of the dust cake formed on the filter bags, and the pressure drop that it builds up over time, is strongly dependent on the dust characteristics as well as the inlet dust load to the filter bags. Specifically, a relatively narrow size distribution of mainly small particles gives a low permeability of the dust cake and hence higher pressure drop for a given thickness of the cake. From this fact it is clear that the intended gain in terms of FF pressure drop and reduced pulse frequency due to the lower inlet dust loading in a hybrid may be offset to a large extent. To this comes the fact that bag blinding and hence a long-term increase of the residual pressure drop over the bag material itself is also accelerated by the presence of mainly very fine particles.

The above considerations imply that it is of utmost importance to have a very efficient pulse cleaning system to be able to minimize the

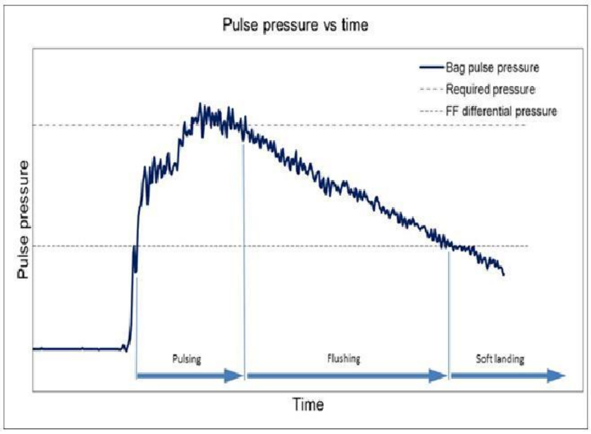

Fig. 2. Pressure profile as function of time for pulse cleaning with the MPC system.

disadvantages caused by the dust characteristics at the FF inlet in a hybrid arrangement. A highly optimized pulse cleaning system is crucial both for control of pressure drop and prevention of long-term bag blinding, as well as for keeping a low particulate emission level. The so-called modulated pulse cleaning (MPC) system has been used extensively in stand-alone FF installations all over the world and has shown to be very efficient to avoid emission peaks and deep penetration of particles during pulse cleaning [21]. The MPC system is based on rapid acceleration during the pulse, followed by flushing with a large quantity of air and finally a slow decrease of pulse pressure to reduce the impact when the bag returns to the support cage. The slow decrease of flushing air in the pulse that helps the bag to decelerate before hitting the cage is referred to as a “soft landing”. The three steps of the MPC pulse are illustrated in the diagram shown in Fig. 2. Both the flushing stage of the cleaning pulse and the soft landing are very effective in alleviating the problems with deep penetration of fine particles in the filter material. The soft landing also reduces the emission peaks associated with the impact of the bag onto the cage in connection with pulse cleaning. Thus, the use of a MPC system for dust removal from the bags is extremely suitable for the special conditions faced by a HRFF placed downstream of an ESP. The large relative amount of very fine particles that are prone to penetrate the filter media in a hybrid solution accentuate the importance of an optimized cleaning system.

One further aspect of the bag cleaning for a HRFF, which was mentioned in the previous section, is the settling of dust into the hoppers below the bags. The dust that is dislodged from

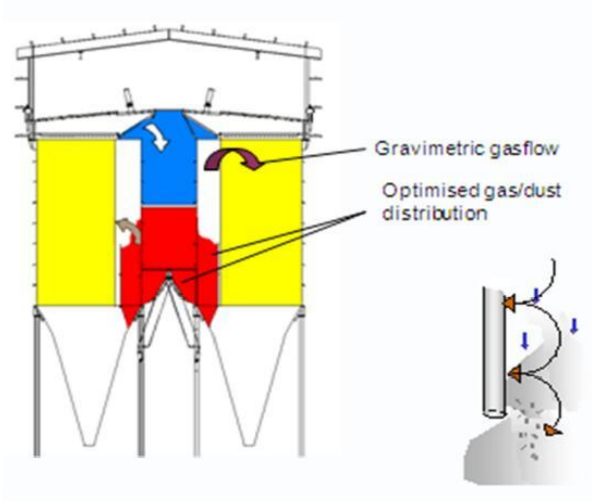

Fig. 3. Principle of gravimetric flow inside the filter compartments to improve settling of the dust.

the bag during a cleaning pulse is subject to gravity as well as drag forces from the gas moving in the vicinity of the bag. Typically the dust settles relatively slowly through gravity, which in combination with the short duration of the cleaning pulse leads to multiple re-depositions of the dust particles onto the bag before reaching the hopper. The average number of such re-depositions depends strongly on the dust characteristics. Very small particles settle extremely slowly by gravity and experience many re-depositions, while large and relatively heavy particles quickly find their way down to the hoppers. Via the pre-separation provided by the ESP in a hybrid the particle size distribution is shifted towards smaller diameters, and there are extremely few particles in the size range above 10 - 20 μm. With no coarse particles available to form agglomerates the fine particles will stay suspended and will be collected again and again on the filter bags. This leads to more frequent pulsing to keep the pressure drop at the required level and this will also increase deep penetration and emission of particles. However, it is possible to assist the settling of particles to the hoppers via an optimized gas distribution inside the filter compartments. By directing the gas flow downwards, so called gravimetric flow, the gas flow will work together with gravity to move the particles to the hopper region. Compared to a stand-alone FF, the benefit of gravimetric flow then becomes even more pronounced for a FF downstream of an ESP. An illustration of gravimetric flow in an Alstom HRFF design is shown in Fig. 3 together with an inset showing re-deposition on the bags and the gas flow driving the dust downwards.

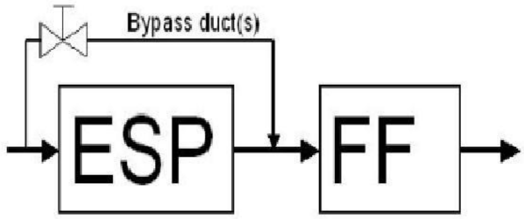

Fig. 4. Sketch of the basic concept with fractional bypass of raw gas to condition the ESP cleaned gas with coarse particles before entering the FF.

Another possibility for improving the performance of an ESP-FF hybrid may be the solution indicated by the title of this paper: A small stream of raw gas bypassing the ESP in order to increase the average particle size at the FF inlet [22]. The principle of the ESP bypass concept can be appreciated by the simple sketch in Fig. 4 where a small stream of raw gas, in the order of 5-10% of the total flow, bypasses the ESP directly to the FF inlet region. Though this concept may seem somewhat counter-intuitive, a closer analysis reveals that the method can result in increased performance of a hybrid both in terms of bag life and particle emission level. The main idea is to provide a certain amount of coarse particles to the FF inlet, where they will help to form a more porous dust cake on the bags and reduce deep penetration of the fine particles. Also, the mix of fine particles from the ESP outlet and coarse particles from the bypass duct provide agglomeration possibilities, which may help to reduce the number of fines and assist gravimetric settling. The agglomeration normally occurring between particles may be further enhanced by the charge present on the particles at the ESP outlet and the gas mixing provided when the bypass stream enters the common duct. Efficient agglomeration via charging of particles and gas mixing has been demonstrated by, for example, the Indigo agglomerator that has been installed upstream of the ESP in a couple of plants to increase collection efficiency [23]. Even if the possibly significant agglomeration effect between fine and coarse particles is disregarded, it is clear that the introduction of a bypass stream will dramatically change the particle size distribution at the FF inlet. In fact, with a reasonably modest fraction of raw gas it is possible to obtain a combined particle size distribution that is relatively similar to the original distribution of the fly ash produced in the boiler. At the same time the dust concentration in the mix of ESP-cleaned gas and bypassed raw gas is of course significantly lower than in the boiler exhaust, on account of the limited amount of bypassed gas.

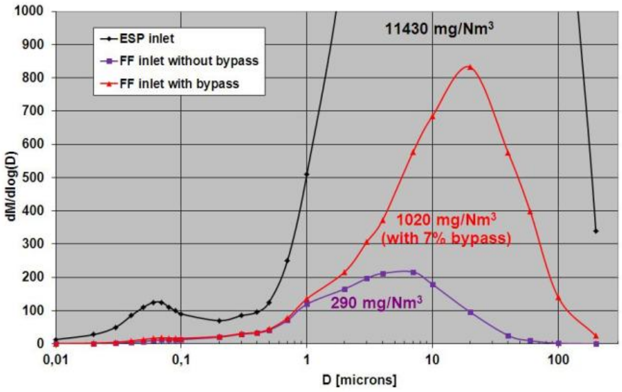

Fig. 5. Estimated particle size distribution at the FF inlet with a raw gas bypass fraction of 7%.

A numerical exercise for the resulting particle size distributions and total dust concentrations is shown in Fig. 5. The calculations are based on the measured size resolved ESP collection efficiencies of Ref. 16. The raw gas bypass is assumed to be 7% of the total flow, ideally mixed with the ESP outlet gas at the FF inlet region. Via the Deutsch equation the particle emission as a function of diameter has been calculated from the measured size spectra at the inlet and outlet of the ESP. The collecting area of the precipitator, *A* in the Deutsch equation, has been scaled down to be more appropriate for a pre-collector ESP, resulting in a total emission (by integration of the size distribution) of 290 mg/Nm^3. The fly ash loading from the boiler corresponds to 11.4 g/Nm^3. Combining the streams of bypassed raw gas (7%) and gas cleaned in the ESP (93%) results in a gas mix having a total particulate concentration of 1020 mg/Nm^3, with a much more favourable particle size distribution than pure ESP-cleaned gas. No assumption regarding agglomeration of fine and coarse particles, which would further improve the particle size distribution, has been made. It can be seen in Fig. 5 that the ESP/bypass mixed flue gas has a particle size distribution that is quasi-similar to the ESP inlet distribution, while the total amount of particulates is less than one tenth. The consequence for the performance of the FF will be lower pulsing frequency and particle emissions, while avoiding some of the difficulties with the very fine particle size distribution in ESP-cleaned gas discussed above.

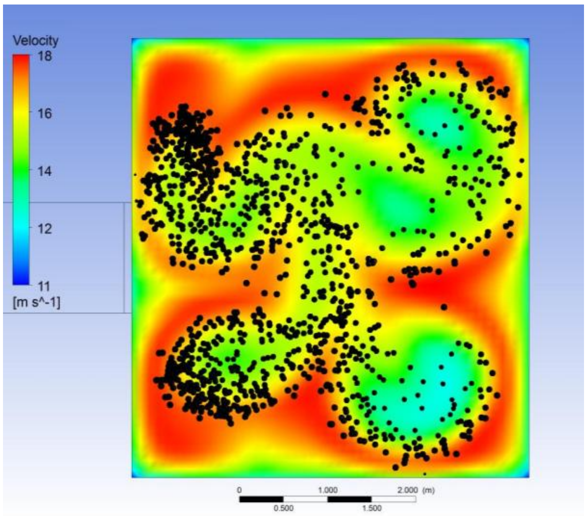

Fig. 6. CFD computation, showing the velocity and particle distribution at a cross section in the main duct between ESP and FF, for one possible layout of the raw gas bypass duct.

With an adjustable bypass stream, as indicated in Fig. 4, it is possible to tune the particle size distribution at the FF inlet for optimum performance. If bag failure or boiler problems occur, or if the boiler e.g. is starting up on oil-firing, the bypass may be completely turned off to protect the bags or avoid emission violations.

Several variants of the system with raw gas bypass may be envisioned. For example, the bypass stream could be carried inside the ESP rather than in an external duct. One special version of internal bypass inside the ESP is to render some of the existing gas passages of the precipitator inactive. This could in the simplest embodiment be made simply by removing all discharge electrodes in a few of the gas passages. However, the ESP works as a settling chamber removing some of the coarsest dust which may be a slight disadvantage. One very important aspect is to have good mixing of the gas from the bypass into the main flow from the ESP. The space between the ESP and the FF may be limited, in which case a proper design is crucial. For example, the bypass duct may enter the duct between the ESP and FF from the side or top and then split into a manifold of injection points to evenly distribute the raw gas over the cross section. If the available mixing distance in the main duct between ESP and FF is short, it may also be necessary to include a static mixer downstream of the raw gas injection point.

A CFD study was performed to demonstrate the mixing of dust in the ductwork between ESP and FF. One variant of bypass duct design enters the main duct between ESP and FF at an angle from the side and then splits into four members to cover each quadrant. A cross section of the main duct 10 m downstream of the injection point(s) with this type of design is shown in Fig. 6. The black dots represent 40 µm particles emanating from the bypass duct, which has entered from the left in the figure. The flue gas velocity profile is given as a colour map, with the flow direction being out from the paper. With this particular design, there is a certain left-right asymmetry, reflecting that the duct enters from one side. If needed, this could be rectified by a somewhat modified design or addition of a mixer, which is not included in the study shown. Regarding the mixing on a smaller scale, this could also be accomplished by static mixers, but is in principle not necessary since this will automatically occur as the gas flow changes direction when entering the FF filter compartments from the plenum (c.f. Fig. 3). Proper distribution of particles on a quadrant level, or somewhat better, would typically be enough to guarantee that all filter compartments and bags in the FF benefit from the coarser particles supplied via the bypass duct. In this way the hybrid concept with bypassed raw gas results in a situation where the filter bags experience conditions that are similar to those where a FF is placed directly downstream of the boiler (but with much lower ash concentration).

IV. CONCLUSION

It has been concluded that the shifted particle size distribution after an ESP at a coal-fired boiler, comprised of a very large portion of sub-micron particles and very few coarse particles, presents difficulties for a downstream FF. Due to the very non-porous dust cake formed by such fine particles, and problems with deep penetration into the fabric material, the impact of an ESP upstream of the FF in a hybrid solution is much less beneficial than the reduced inlet load to the FF would indicate. To minimize some of these difficulties, especially bag blinding and emission peaks during the cleaning pulses, it is necessary to have a highly optimized pulse cleaning system. Modulated pulse cleaning with soft landing of the bags on the cage can thus help to alleviate the particle emission peaks and deep penetration into the bag material. Another aspect of the fine particles at the ESP exit in a hybrid solution is that they settle extremely slowly by gravity after the pulse cleaning. This may lead to an unacceptable number of re-depositions of the dust onto the bags before it reaches the hoppers. The increase of pulse cleaning frequency that must be implemented to compensate the slow settling leads to further increased bag blinding and emission. With a FF design that utilizes gravimetric flow inside the bag compartment, i.e. a downward inclination of the gas stream profile, these problems can be minimized. Finally it has been suggested that the particle size distribution at the FF inlet can be improved by a small bypass of raw gas carrying coarse dust from the ESP inlet to the FF inlet. By having the bypass stream adjustable the resulting particle size distribution after mixing with the outlet gas from the ESP can be tuned for optimum FF performance. Since the bypass stream may be in the order of 5-10% of the total flow, the dust concentration will still be low, while having a particle size distribution that is similar to the original fly ash at the boiler outlet. This will allow the FF to operate almost as a stand-alone unit, but with a much lower pulse cleaning frequency due to the low inlet dust concentration. Should special circumstances occur, such as bag failure or boiler problems, the bypass may be closed so that the unit operates as a conventional hybrid.

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