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A technical assessment of a particle hybrid collector in a pilot plant

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Abstract

We developed a hybrid collector (ESP + FF) to improve particulate matter removal from flue gases from coal power plants and then tested it in a pilot plant that processes up to 15,000 m^3/h of real flue gas.

The tests were designed to achieve economic and operating optimization of the hybrid collector. The removal efficiency in relation to the PM10 and PM2.5 and trace metals emissions, according to the legal limits in the European Union and the United States of America, was specifically considered. The efficiencies obtained were very high: PM10 removal efficiency of more than 99.95% and PM2.5 removal efficiency of between 96 and 98%, and a metal deposition greater than 99% depending on the metal, overcoming the limitations of ESPs with regard to achieving the particulate matter emission limits. However, a lower efficiency was obtained for the capture of mercury in the vapor phase (only 30%). We discovered a relationship between the rate of pressure loss and both the filtration velocity and the number of active fields in ESP. Likewise, we found a relation between these two parameters and the number of cleaning cycles.

Within the study a database was created and considered as a basis for designing hybrid collectors and retrofitting existing ESPs. Based on to these results, we determined the criteria for a full-scale design of hybrid collectors, and we have proposed a basic retrofitting of an existing ESP to convert it into a hybrid collector, for both a 550 MWe and a 220 MWe pulverized coal power station.

Keywords: Hybrid collector; Particulate matter; Filtration; Flue gas; Pilot plant; ESP; Metals

1. Introduction

The air quality directive of the European Community (1999/30/EC) [1] stipulates an average annual limit of 40 μg/m^3 from 2005 on and sets an indicative limit of 20 μg/m^3 for the year 2010. There is currently a Directive Proposal (2005/0183 CODE) [2], which is being revised, which sets the average annual limits for PM10 and PM2.5 at 14 and 10 μg/m^3, respectively. The United States, after the process of update and review carried out by the EPA at the end of 2004, set a limit on the annual mean for PM10 at 50 μg/m^3 and at 15 μg/m^3 for PM2.5 [3]. As we can see, the legislation concerning emissions is ever stricter.

Devices currently used in industry to remove particulate matter from various process gases include electrostatic precipitators (ESP) and fabric filters (FF). In addition, there are a number of hybrid devices under development that integrate ESP/FF concepts.

Among the major shortcomings of ESP performance are its dependence on resistivity and the particle size of the dust. Generally speaking, ESP have a collection efficiency of 99.5–99.9%, but, for fine particles, the collection efficiency is poorer. The electric power industry, not to mention other industrial companies that might use such technologies, is looking for ways to upgrade their particulate control equipment. The fabric filter is accepted as an alternative to precipitators for collecting fly ash from the flue gas. The fabric filter provides a rather large pressure drop, while exhibiting a greater collection efficiency regardless of either size or property.

Some options are available to improve and upgrade ESP performance, including flue gas conditioning, ESP replacement and enlargement, and the combination of ESPs with baghouse technology. Thus, in an effort to overcome the deficiencies mentioned above (i.e., to increase collection efficiencies with a moderate increase in pressure drop), a number of efforts have been, and are, underway to develop hybrid particle collectors.

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These hybrid devices attempt to integrate electrostatic and barrier filtration into a single device or system. The hybrid particulate collection concepts include:

- An electrostatically enhanced fabric filter.
- EPRI's COHPAC I and COHPAC II systems.
- The UNDEERC hybrid collector (Advanced Hybrid Collector).
- The multi-stage collector (MSC).

The compact hybrid particulate collector (COHPAC) concept is fairly simple. A high-ratio pulse-jet fabric filter collector is installed in series with an existing energized electrostatic precipitator serving as the final collection device. The COHPAC can be installed either in a separate casing (COHPAC I) located after the ESP, or within the last 1–2 fields of the ESP casing (COHPAC II), depending upon the actual size and condition of the existing ESP casing. The better the performance of the remaining fields, the higher the final filtration rate [4–6].

The University of North Dakota and the Energy and Environmental Research Center (UND/EERC) have developed another type of combined control device called the Advanced Hybrid Collector (AHC). A charging (and collection) section can also be placed before the bags in a fabric filter. This approach is used in the AHC along with the use of membrane fabrics (woven or felted fabrics with a membrane laminated to the filtration surface of the fabric). The membrane is typically polytetrafluoroethylene (PTFE). With about 90% of the mass of particles collected in the electrostatic charging and collection section of the AHC, the load on the fabric filter part of the system is greatly reduced. With a membrane fabric for the bags, it is likely that filtration velocity can be increased significantly [7].

The principal objective of the MSC design is to improve fine particle collection by combining electrostatic charging/collection and filtration processes not only by separating zones for particle charging and collecting, but also by providing a collector design to collect fine dust particles no matter what their electrical properties. The operation of the MSC seems to be independent of the electrical resistivity of the collected material, and hence its application would be especially beneficial when electrical resistivity of material either exceeds 10^{11} or is less than $10^4\ \Omega\,\mathrm{cm}$ [8].

Electrostatic deposition is effective for relatively large particles, but it is quite ineffective for the ultra-fine ones because their charging probability in the corona field is too low. However, the diffusional collection efficiency of particles on fibers is high for small particles but low for the larger ones. Therefore, the simultaneous diffusional–electrostatic collection can be a useful technique for efficient filtration of sub-micron particles. Fabric filters generally have collection efficiencies greater than 99.9% and are largely independent of fly ash properties. However, due to their low filtration velocities they are large, require significant space, are costly to build, and unattractive as replacements for existing precipitators. Reducing their size by increasing the filtration velocity across the filter bags usually results in an unacceptably high pressure drop and reduced collection efficiency. Therefore, the existing ESPs could be retrofitted into hybrid collectors by replacing their last fields with baghouses installed in the same casing.

2. Aims and scope

The main aim of this research is the development and testing of a hybrid collector consisting of an ESP section and a pulse-jet bag filter section, for the control of fine particles and heavy metals in flue gases from coal power plants. The hybrid device is a unit and it should not be confused with the use of two pieces of equipment (ESP and fabric filter) placed in series. Indeed, for retrofitting an existing ESP some electrical sections would be replaced by a fabric filter section, but that would be accommodated inside the ESP casing.

The tests were carried out in a 550 MWe pulverized coal power plant. The goal was to reach 99.99% efficiency for particles, using a greatly reduced collecting area in the ESP section and a small filtering area in the bag filter. Such high global efficiency has resulted in very effective control of PM10 and PM2.5 particles. We studied the effects of the cleaning system and mode, filtration velocity, and the number of active fields in the ESP on the performance of the hybrid collector system. We also achieved the better operating conditions with regard to those variables, in order to obtain very high removal efficiencies for particles. This research was focused mainly towards partial particle removal efficiency, but there were also some interesting results with regard to the removal of heavy metals present in the flue gas.

Finally, as a result of the experience acquired and the results obtained in the plant tests mentioned above, we have proposed a basic retrofitting of an existing ESP to convert it into a hybrid collector, for both a 550 MWe and a 220 MWe pulverized coal power station.

3. Experimental set-up

Fabric filters generally operate at filtration velocities of 0.76–1.27 cm/s (1.5–2.5 ft/min), also defined as the air-to-cloth ratio, which is the volumetric flow rate of the flue gas per unit of effective filter area (cubic feet of flue gas flow/min/square foot of filtering area). The pulse-jet baghouses, on the other hand, generally operate at 1.52–3.05 cm/s (3–6 ft/min) [9].

The experimental hybrid collector was implemented by connecting an already existent pilot electrostatic precipitator to a new pilot fabric filter. The pilot ESP is capable of treating up to 20,000 $\mathrm{m^3/h}$ of flue gas taken from the outlet gas stream of the boiler. This gas flow rate is equivalent to 12 MWt in the boiler. The ESP configuration is very flexible: it is possible to change the plate spacing, type of discharge electrode, type and control of energization, flow rate and rapping variables. It consists of three independent electrical sections (or fields) in series. Each plate curtain is rapped independently with oscillating hammers, as is each frame holding the electrodes in each electrical section. The main characteristics of this pilot unit are shown in Table 1.

The new pilot FF was designed and mounted in the existing pilot plant to complete a hybrid. This experimental unit

Table 1
Characteristics of the pilot ESP

Precipitation chamber dimensions	
Length (m)	12.6
Width (m)	2.5
Height (m)	2.6
Number of electrical sections or fields	3
Configuration of electrical sections	
Effective length (m)	2
Effective height (m)	2.2
Number of gas passages	3–7
Plate spacing (mm)	200–500
Number of electrodes per passage	4–12
Operating conditions	
Gas flow rate (m^3/h)	9,000–20,000
Precipitation area (m^2)	79.2–184.8
Specific collection area, SCA (m^2/m^3 s)	14–74
Gas temperature (°C)	140–160
Fly ash load (mg/N m^3)	7,000–14,000
Gas velocity (m/s)	0.8–1.8
Transformers-rectifiers	
Peak voltage (kV)	120
Average maximum voltage (kV)	78
Maximum effective current (mA)	42

Table 2
Characteristics of the pilot FF

External dimensions	
Length (m)	2.4
Width (m)	2.4
Height (m)	6.5
Filtering media	
Bags dimensions:	
Internal diameter (mm)	150
Length (m)	6
Number of bags	32
Bags material	Ryton felt with PTFE membrane
Maximum cleaning pressure (bar gauge)	7
Cleaning system	HPLV (or LPHV or IPIV)
Operating conditions	
Gas flow rate (m^3/h)	9,000–20,000
Collection area (m^2)	90
Filtration velocity (ft/min)	5–25
Gas temperature (°C)	140–160

is a pulse-jet fabric filter (PJFF). Table 2 illustrates the main characteristics of this pilot fabric filter. To better modify the filtration velocity, bags were assembled in isolated groups. As a result, the FF is capable of operating with 16 or 32 active bags, with an active filtration area of 45 or 90 m^2, respectively. Several cleaning systems are available and were tested preliminarily: low pressure and high volume pulses (LPHV), intermediate pressure and intermediate volume pulses (IPIV) and high pressure and low volume pulses (HPLV).

Fig. 1 shows the layout of the pilot plant, and Fig. 2 shows a photo of the fabric filter joined to the last section of the pilot ESP.

The tests were controlled by a complete automatic control and monitoring system, shown in Fig. 3. The gas flow rate and the pressure inside the ESP were controlled by inlet vanes incorporated into two fans: the induced fan, located at the outflow of the hybrid collector, and the forced fan, located at the intake. The gas temperature was also controlled by a heating element located at the gas intake. A venturi meter measured the gas flow continuously and automatically. The emission of dust was monitorized through the extinction signal from a He–Ne laser opacimeter (MIP OY, model LM 3188), calibrated daily. Furthermore, manual measurements were taken during the tests at the inlet and the outlet of the hybrid collector in order to measure dust concentrations.

In addition, we continuously monitored all the electrical parameters of each section in the ESP: voltage, current, and sparking level. The precipitator was operated with continuous energization, which was controlled by maximizing the voltage and limiting the sparking level.

A differential pressure transmitter measures the draft loss produced in the fabric filter and the signal is sent to a controller,

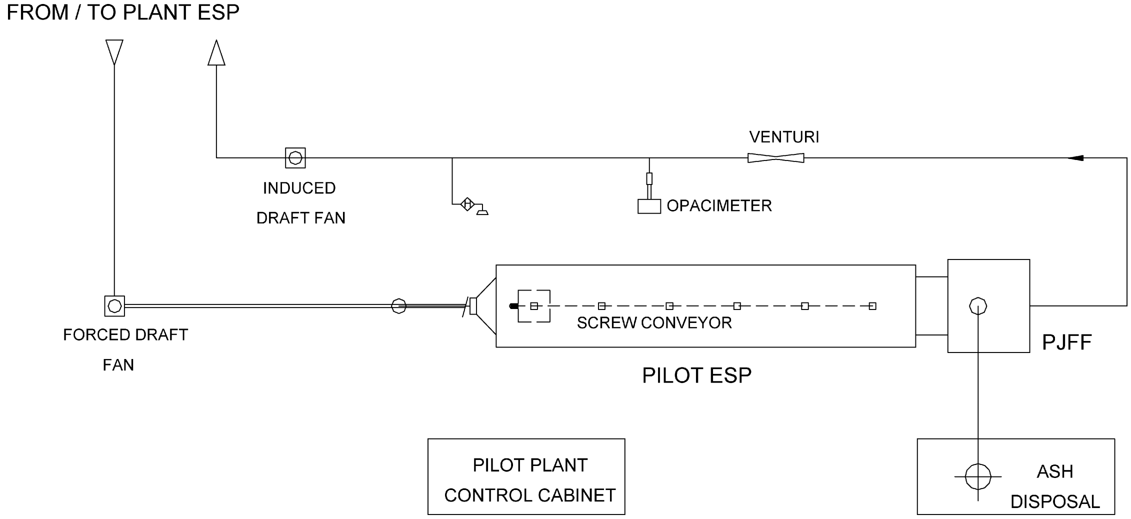

Fig. 1. Pilot plant flow sheet.

Fig. 2. View of the hybrid collector mounted at the power station.

which activates the cleaning cycles when the set point for starting is exceeded. The process continues until the signal value is lower than that set for stopping the cleaning cycles. Cleaning was performed by blowing air into each bag inlet according to a programmable predefined cleaning cycle.

The selected modes for each sampling point were EPA Method 5 (for total particulate matter) and EPA Method 29 (for trace metals). Likewise, to determine the particle size distribution of about PM10 and PM2.5, a set of cyclones was used at the hybrid collector inlet, where the dust concentration is high, and a cascade impactor (Sierra, model 220) was used at the hybrid collector outlet, where the dust concentration is very low.

4. Experimental program and test methodology

The feasible variables for the test definition were filtration velocity (air-to-cloth ratio), the number of active ESP fields (related to ESP efficiency), and the cleaning mode (off-line and on-line).

Two operational cleaning modes were tested:

- Off-line cleaning mode tests, with no gas supply during the cleaning periods, thus simulating the isolation of a compartment of the bag filter during the cleaning.
- On-line cleaning mode tests, maintaining the gas flow during cleaning periods.

Some bag cleaning parameters were fixed at the beginning of the experiment: blowing pressure (7 bar gauge) and blowing time for one pulse (40 ms). A value of 7 bar gauge was chosen because in some preliminary tests we were testing values from 2.8 (similar to IPIV system values) to 4, 5, 6 and 7 bar gauge, by increasing or decreasing from one to other. We observed that a pressure lower than 7 bar gauge led to an ineffective cleaning (the mean pressure drop was not kept constant at any moment).

The effect of the different operational conditions on the performance of the fabric filter unit can be described by means of the following parameters or factors:

- Pressure drop (mm water column).
- Rate of pressure loss (mm w.c./min).
- Time interval between two cleaning cycles (min).
- Number of cleaning cycles per day.

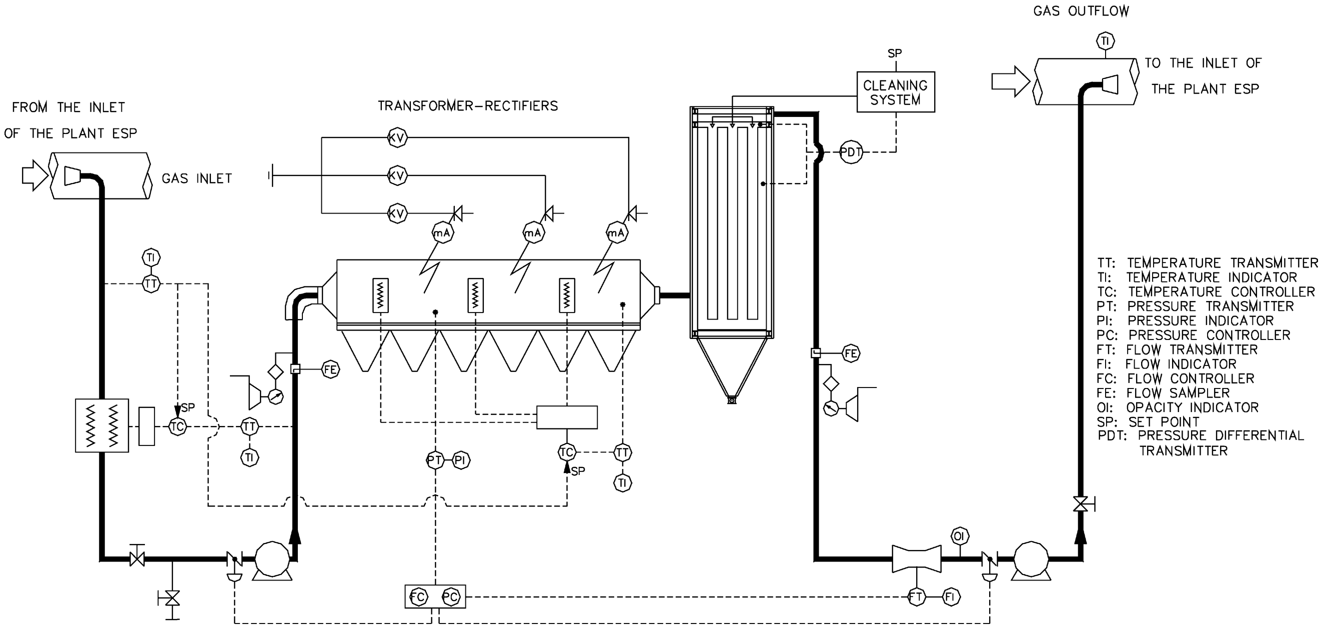

Fig. 3. Monitoring and control diagram of hybrid collector.

For optimum filtration rate and collection efficiency in the baghouse section of the hybrid collector, the operating pressure drop should approach a constant value. This involves a careful selection of cleaning mechanisms for the fabric filter because a poor cleaning will increase the filter drag; thus, the bags must be thoroughly cleaned to reduce the filter drag effect. If the cake repair time can be minimized, the pressure drop will be lower and, consequently, the effective filtration rate will be greater, for optimum filtering use. In addition, the unit should be operated with as long a bag cleaning interval as possible since more frequent bag pulsing can lead to premature bag failure and requires more energy consumption from compressed air usage. So, although the bag cleaning interval is a key performance indicator, the cleaning process used in this study was based on pulse activation when the pressure drop was equal to the pulse trigger point (mainly set at 200 mm w.c.) and the filtration time was a variable to be measured, not a factor to be fixed. Thus, the rate of pressure loss (ΔP rate), defined as the quotient of the difference in pressure drop (ΔP) between two cleaning cycles ($\Delta P_{\text{final}} - \Delta P_{\text{initial}}$) and the time interval between those cycles (filtration time), is useful as an indicator of bag cleanability. Besides, although the total pressure drop throughout the filter is another key indicator of the overall performance of the hybrid collector, note that the average pressure drop is not the same as the pressure drop at the pulse-cleaning trigger point, but rather is significantly lower. Consequently, in the assessment of the performance of the hybrid collector, the rate of the pressure drop ends up being a strategic parameter (as a measure of the dynamic hybrid collector performance) in order to assess its technical viability because it is directly related to the cake repair time and the bag cleanability.

The testing program was divided into three stages. First, once the opacimeter was calibrated to measure very low dust concentrations, we carried out the evaluation of the bag filter performance without any active ESP field, establishing a test to be used as a reference test for hybrid collector. Second, to study the influence of each variable in the global operation of the hybrid collector, the testing procedure followed consisted of the modification of only one variable, one level from reference conditions in each test, repeating the reference test weekly, in order to take into account any deviation through time. Next, maximum improvement tests were carried out to maximize the efficiency of the hybrid collector through the right combination of manipulated variable levels. This was achieved through the modification of more than one variable from the reference conditions, each time along the expected path for reaching the maximum performance improvement. The reference test was then repeated weekly, as we mention above.

The final test matrix is shown in Table 3.

Table 3
Tests matrix

Variable	Levels			
Filtration velocity (ft/min)	5.5	**6.5**	7.5	8.5
Number of active ESP fields	**0**	1	2	3
Bags pressure drop (mm w.c.)	100	150	175	**200**
Cleaning system	**HPLV**	IPIV	LPHV	
Cleaning mode	**On-line**	Off-line		

The reference test is remarked in bold.

The contribution to the pressure drop throughout the filter due to the dust accumulated on the bags since the last bag cleaning is comprised of the product of the specific dust cake resistance coefficient (K_2), inlet dust concentration, the square of the filtration velocity and the filtration time (filtration time between bag cleaning) [10]. K_2 is a parameter related to the dust cake build-up on the filter surface in a baghouse and, hence, to the overall pressure drop throughout the filter media; its importance was made clear by Cheng and Tsai [11], through an investigation of the factors influencing dust cake build-up and pressure drop for several fine dusts. However, for the hybrid collector, the concentration of the dust that reaches the bags is usually not known (unless it was continuously measured, which it is very complicated). Thus, it is very difficult to measure K_2 values (determined by the fly ash particle size distribution, porosity of the dust cake and gas viscosity) experimentally. Besides, the amount of the dust precollected (in the ESP section of the hybrid collector) is likely to fluctuate significantly with changes in the operating conditions tested. Since the dust concentration at the fabric filter inlet is not known, for evaluating the hybrid collector performance, the K_2 and the inlet dust concentration can be considered together (the product of C and K_2, i.e., CK_2). This parameter can prove helpful in assessing the fabric filter section in the hybrid collector, like K_2 is in evaluating the baghouse performance.

5. Results and discussion

A total of 70 tests were carried out. The hybrid collector always achieved particulate matter collection efficiency greater than 99.9% for all the operating conditions tested. After the first tests, both the set points for ΔP minimum and ΔP maximum were fixed (160 and 200 mm of water column, respectively) except for the tests carried out in the off-line cleaning mode, where ΔP minimum did not settle. In any case, once the value of 200 mm w.c. in the filter was reached, the cleaning cycles were activated, for all the tests. This was due to the specification of the filtering media (the limit cited is very common in all the suppliers) and because of there was no reason to operate at a higher ΔP as doing so would increase the energy consumption. Due to the low efficiency of the other two cleaning systems as verified in some initial tests, all the tests were performed by using the HPLV system.

Fig. 4 represents the relationship between filtration velocity and the rate of pressure loss for both the different numbers of active ESP fields and the two modes of cleaning tested. We can see the dependence of the ΔP rate on the dust load entering the FF, which was determined by the filtration velocity and the number of active ESP fields.

5.1. Effect of the cleaning mode

In the on-line cleaning mode, a progressive increase in the baseline of the pressure drop or residual pressure drop between consecutive cleaning periods is observed (Fig. 5). This is due to the formation of stable ash around the bags that become blinded.

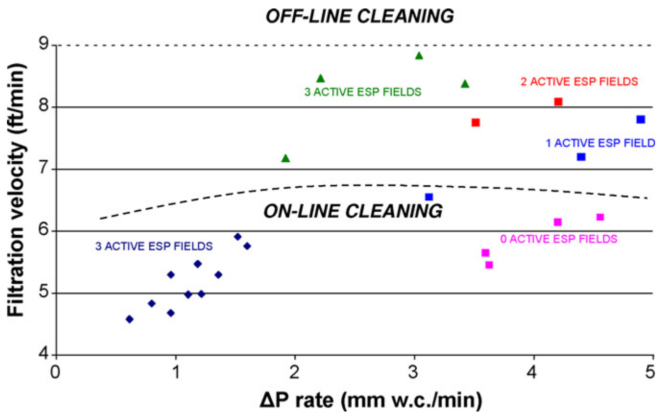

Fig. 4. Relationship between filtration velocity and ΔP rate at different cleaning modes and number of active ESP fields.

After a certain period of time, cleaning cycles cannot reduce the pressure drop; it never decreases to the lower limit (set point of ΔP minimum). Consequently, the cleaning cycles overlap quite a bit. This situation is very critical for the filter because of dust accumulation in bags and the reduction in the filtration capability.

In the off-line cleaning mode, the filtration operation is performed by dividing the clean gas zone in the filtration chamber into two different isolated compartments, which allows us to stop the gas flow during the cleaning periods in the compartment in which the cleaning is taking place. As Fig. 6 shows, the off-line mode is much more effective for bag cleaning; in effect, ΔP values after cleaning are lower than those for the on-line cleaning mode with the same filtration velocity. Therefore, higher filtration velocities can be reached (at least 50–60% higher). However, the rates of pressure loss are also higher for the off-line cleaning mode, as a consequence of the higher filtration velocity. As a result, more frequent cleaning cycles are necessary to maintain the pressure drop (from 72 cycles per day, with three active ESP fields, up to 120 cycles per day, with no active ESP fields).

In the off-line mode, the rise in the pressure drop over time in the tests was approximately linear (slightly curved), which gives rise to the assumption that the filter cake does not undergo significant compaction in the relevant region of the pressure drop. However, for the on-line cleaning mode the rise in pressure drop over time is more obvious. The recapture of dust on the bags during cleaning cycles is increased due to the gas circulation. If a compartment is cleaned while on-line, a smaller fraction of the dust removed from the bag (as compared to the off-line cleaning mode) falls into the hopper. The remainder of the dislodged dust is redeposited (i.e., "recycled") on the bag by the forward gas flow. The redeposited dust layer has different pressure drop characteristics than the freshly deposited dust. The effect is equivalent to an increase in the global dust resistance, thus raising the rate of the pressure loss and the residual pressure drop. This leads to a shorter and a more poorly-controlled operation.

For the on-line cleaning mode with three active ESP fields, there were from 24 to 48 cleaning cycles per day, with an increase in the cleaning time per cycle during the test performance of from 1 to 40 min, or even longer. Thus, both the time interval between cleaning cycles and the number of cleaning cycles per day were quite small, since the total cleaning time was very high. Moreover, the cleaning time per cycle increased greatly. However, when no ESP field was active, even though the dust concentration leaving the ESP and entering the fabric filter is higher, these cleaning parameters were clearly more favourable, even close to the results achieved for the off-line cleaning mode, where the cleaning time per cycle was 1 min and the time interval between two cleaning cycles was about 10–12 min. The number of cleaning cycles per day was from 100 to 144. Thus, although the cleaning pulse is very brief (40 ms), and the flow of dusty gas would not have to be stopped during cleaning (on-line cleaning mode), the use of separate compartments, which can be isolated for cleaning, keeps the dust from the cleaned bags from being drawn immediately to the other bags when very high gas velocities are used. This aspect has been verified in the tests carried out in this study. Besides, in the on-line cleaning mode it is difficult to modulate the pulse cleaning and, thus, both the emission during cleaning of bags (especially of sub-micron particles) and the re-entrainment of fine particles into the media in connection with bag cleaning cannot be significantly reduced. For all these reasons, we can conclude that the off-line mode is more effective when applied in hybrid collectors.

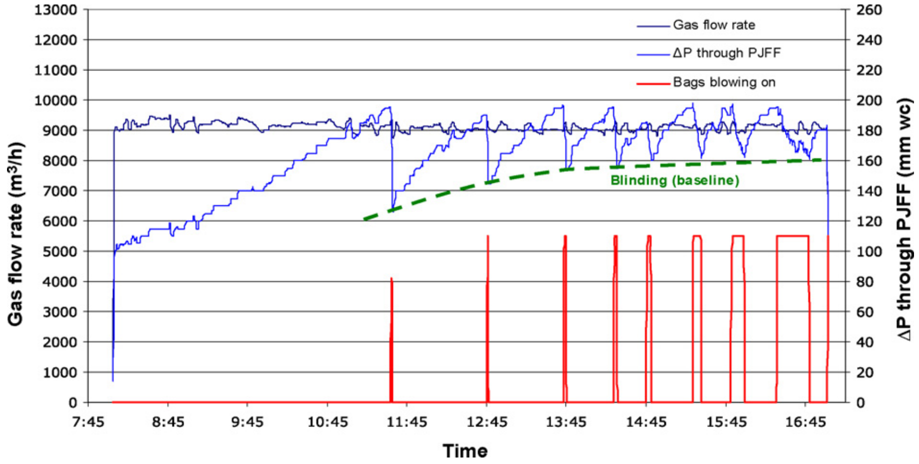

Fig. 5. On-line cleaning in hybrid collector (three active ESP fields).

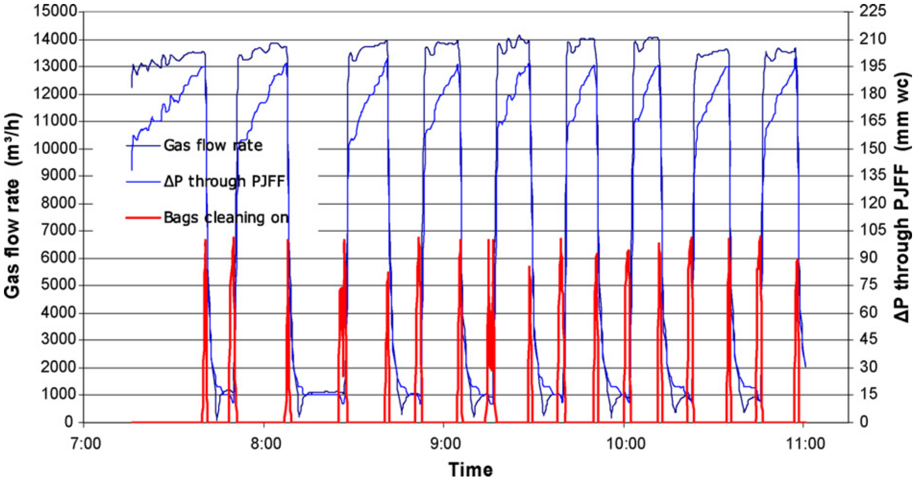

Fig. 6. Off-line cleaning in hybrid collector (three active ESP fields).

For the off-line cleaning mode (Fig. 6), where an average pressure drop can be kept nearly constant, it is possible to obtain the parameter proposed above, CK_2. The net filter drag (total filter drag minus the residual drag) can be divided by the average filtration time and filtration velocity to obtain CK_2. For the test shown in Fig. 6, CK_2 has a value of 2×10^{-3} in. w.c. min/ft^2. By using the method described, other values of CK_2 can be obtained. In the next sections, more values of CK_2 and a further discussion about the CK_2 parameter and the K_2 coefficient will be given.

5.2. *Effect of the filtration velocity*

The rates of pressure loss and the number of cleaning cycles per day are greater when the filtration velocity is increased following an approximately lineal relationship for both types of cleaning modes tested, and for a given number of active ESP fields (Fig. 4). From the data acquired in the tests, correlations between the rate of pressure loss and filtration velocity have been performed for both cleaning modes; they are the following:

- On-line cleaning mode, and three active ESP fields.

$$\Delta P_{\text{rate}}(\text{mm w.c./ min}) = -1.597 + 0.503 v_{\text{filt}}, \quad \text{for}$$
$$v_{\text{filt}} \subset [4.5; 6.2](\text{ft/ min});\ r^2 = 0.65$$

- On-line cleaning mode, and no active ESP fields.

$$\Delta P_{\text{rate}}(\text{mm w.c./ min}) = -5.310 + 1.540 v_{\text{filt}}, \quad \text{for}$$
$$v_{\text{filt}} \subset [5.6; 6.8](\text{ft/ min});\ r^2 = 0.64$$

- Off-line cleaning mode, and three active ESP fields.

$$\Delta P_{\text{rate}}(\text{mm w.c./ min}) = -3.000 + 0.667 v_{\text{filt}}, \quad \text{for}$$
$$v_{\text{filt}} \subset [7.2; 9.0](\text{ft/ min});\ r^2 = 0.84$$

where ΔP_{rate} is the rate of pressure loss (mm water column per minute) and v_{filt} is the filtration velocity (ft/min). The coefficients of determination, r^2, for the empirical models show that a high fraction of the variation in the rate of pressure loss can be attributed to the filtration velocity.

It can be seen that the empirical models obtained by regression analyses agree with the analysis of the experimental data. What is more, these relationships are in accordance with the models found in the literature. Thus, based on the equation developed by Billings and Wilder [10], Dennis and Klemm [12] proposed a simple model of drag across a pulse-jet filter, where the drag across the filter consists of three terms: the drag of a newly-cleaned filter, the drag due to the specific dust resistance of the recycling dust (if the on-line cleaning mode is used) and the drag due to the specific dust resistance of the freshly deposited dust. Dennis et al. [12,13] showed that both particle size and velocity have an effect on the dust-fabric filter resistance coefficient, and other researchers have verified this [14–18]. Other authors [19] have found that the resistance coefficient, K_2, is somewhat a function of filtration velocity as well as pressure drop throughout the bags. For given operating conditions, the values of the above-cited resistances may be assumed to be constant so that they can be grouped together. Thus, the drag is dependent mainly on the filtration velocity [17] through an overall resistance that takes into account the effective drag of residual dust and the specific dust resistance of the freshly deposited dust. This effect was verified experimentally by measuring the rate of pressure loss between cleaning cycles (a dynamic measurement of the drag across the filter) for a given ESP inlet dust concentration, number of active ESP fields and a particular cleaning mode.

However, higher filtration velocities produced difficulties in bag cleaning when three ESP fields were active (Fig. 4), increasing the pressure drop and the rate of pressure loss in spite of the fact that the dust concentration entering the fabric filter was lower. This phenomenon could be related to the differences in the build-up of the ash layer on the bags, which depends on the particle sizes. Although the particle load leaving the ESP was greatly reduced, the finest particles arrived at the FF when there were three active ESP fields. These finest particles build a more compact layer than coarse particles, a layer that is more difficult to remove because of the higher value of K_2. As a consequence,

Table 4
Collection efficiency vs. filtration velocity (with no active ESP field)

Filtration velocity (ft/min)	Location	Particles content (mg/N m^3)			Fractional efficiency (%)		
		>10 μm[a]	(2.5 μm; 10 μm)[a]	<2.5 μm[a]	>10 μm[a]	(2.5 μm; 10 μm)[a]	<2.5 μm[a]
6.8	Inlet	11,450	1,822	270	99.98	99.78	95.93
	Outlet	2	4	11			
6.5	Inlet	9,733	1,721	274	99.99	99.98	95.26
	Outlet	1	2	13			
6.0	Inlet	8,053	1,957	203	99.95	100.00	92.61
	Outlet	4	0	15			

[a] Particle diameter (dp) range.

Table 5
Size distribution for inlet/outlet samples (with no active ESP field)

Filtration velocity (ft/min)	Location	Content by size (wt%)		
		dp > 10 μm	10 μm > dp > 2.5 μm	dp < 2.5 μm
5.4	Inlet	85.4	12.5	2.1
	Outlet	20.0	53.3	26.7
6.7	Inlet	83.0	14.7	2.3
	Outlet	6.3	12.5	81.3

the total cleaning time increases greatly, as mentioned above. This effect was also observed in the off-line cleaning mode.

Tables 4 and 5 show that the global removal efficiency of PM10 and PM2.5 particulate matter, with no active fields, is very high compared to removal only with an ESP, where the removal efficiency of PM2.5 was always lower than 75%. What is more, we can see that fractional efficiency for the coarsest (PM10 fraction) and finest particles (PM2.5 fraction) increases when filtration velocity increases. However, the combination of these two fractional efficiencies results in a higher fraction of the finest particles when the filtration velocity is high as opposed to when it is lower, obviously, because the finer particles weigh less. When ESP was energized the removal efficiencies were even higher: PM10 particulate matter remained as high as before and for PM2.5 particulate matter increased nearly 98%.

5.3. *Effect of the number of active fields in ESP*

When the number of active fields in ESP is increased, the particle load entering the fabric filter is lower and the particle size distribution is finer. This leads to a reduction in the cleaning time, but only a small one because of the more compact dust layer that forms around the bags due to the finer size of particles. In other words, when the number of active fields in the ESP is increased, the dust concentration entering the fabric filter is lower but the particles are smaller. Thus, with regard to the pressure drop contribution from the dust accumulated on the bags since the last bag cleaning, two terms partially counteract each other: the inlet dust concentration, which is lower, and the K_2 coefficient, which is higher. For very small dust particles, the dust cake resistance (K_2) will tend to be high, causing a higher pressure drop across the dust layer. Cora and Hung [20] pointed out, as a rule of thumb, that baghouses used for filtering dirty airstreams containing a relatively high number of very small particles (2 μm or less) will tend to have a high dust cake resistance (K_2), requiring a more frequent bag cleaning cycle, i.e., an increase of the cleaning time. In fact, this occurs in the fabric filter section of the hybrid collector when the previous ESP section is energized.

Table 6 shows the sensitivity to the number of active fields in ESP tests. Particle contents in the ESP inlet, ESP outlet (FF inlet) and FF outlet were measured for 0, 1, 2 and 3 active fields in the ESP. These tests were carried out for approximately the same filtration velocity (about 6.2 ft/min). The overall capture efficiency was calculated for the ESP and the hybrid collector (ESP + FF). It can be observed that the ESP capture efficiency

Table 6
Overall efficiency of ESP and hybrid collector for different number of active fields in ESP

Active fields in ESP	Particles content (mg/N m^3)			Efficiency (%)	
	ESP inlet	ESP outlet	FF outlet	ESP	ESP + FF
3	10,500	411	14	96.1	99.9
2	14,200	830	8	94.1	99.9
1	10,500	3,279	15	68.8	99.9
0	7,700	3,771	19	51.0	99.8

Table 7
Tests carried out using the off-line cleaning mode

Filtration velocity (ft/min)	$\Delta P_{\text{initial}}$ (mm w.c.)	$\Delta P_{\max}$ (mm w.c.)	Cleaning time (min)	Number of cleaning cycles per day	ΔP rate (mm w.c/min)	Opacity (%)	Active ESP fields	CK_2 (in. w.c. min/ft^2)	K_2 estimated (in. w.c. min ft/lb)
8.41	165	200	1	60	2.3	15.4	3	1.28E−03	52.6
9.01	165	200	1	67	3.2	13.6	3	1.55E−03	63.7
7.21	140	197	1	64	1.9	NA	3	1.44E−03	59.1
8.23	160	200	1	60	4.0	16.0	2	2.33E−03	63.1
7.81	155	212	1	48	3.3	12.6	2	2.13E−03	57.8
7.81	150	200	1	120	4.4	15.6	1	2.84E−03	14.6
7.21	145	197	1	96	4.3	12.0	1	3.26E−03	16.7
7.21	145	197	1	144	5.1	13.5	0	3.86E−03	12.6

is significantly high (51%) when no electric fields are active. Efficiency increases from 51 up to 69% when one field is active. Efficiency increases remarkably when two and three fields are active (94 and 96%, respectively). However, it is worth noting the very high efficiency of the fabric filter in all cases.

In the Deutsch model, widely used in the design and evaluation of precipitators, the concentration of dust is assumed to be a function of the distance from the inlet only. This is equivalent to assuming a complete turbulent mixing of the dust. Deutsch considered the thin boundary layer near the walls from which the dust particles are removed and where the particle migration velocity is assumed to be invariant along the precipitator length. The Deutsch model for the removal efficiency is the following:

$$\eta = 1 - \exp\left(-\frac{v_{\text{E}}L}{v_{\text{G}}D}\right)$$

where L is the length of the collecting plate and D is the distance between the collecting plate and the discharge electrode. v_{E} and v_{G} are the particle migration velocity and the gas velocity, respectively. Therefore, for a given gas flow rate, it is possible to correlate the removal efficiency of the ESP with the number of active fields, i.e.:

$$\eta = 1 - a\ \exp(-b\text{NESP})$$

where NESP is the number of active fields in the ESP. Using the data presented in Table 6, we obtain the following equation:

$$\eta = 1 - 0.549\ \exp(-0.926\text{NESP}); \quad r^2 = 0.934$$

There were also lower rates of pressure loss and fewer cleaning cycles per day when the number of active ESP fields was increased (Fig. 4 and Table 7), as was expected because of the reduced particle load entering the fabric filter.

Table 7 also shows some values for the CK_2 parameter, introduced above. Taking a reference of 10 g/m^3 for the ESP inlet dust concentration and assuming ESP efficiencies for different numbers of active fields, given in Table 6, or the last correlation for removal efficiency of the ESP, values for K_2 could be estimated. Thus, if the number of active ESP fields is 2 or 3, K_2 is about 60 in. w.c. min ft/lb; if only one ESP field is active, K_2 is about 15 in. w.c. min ft/lb and if there are no active ESP fields, K_2 is around 10 in. w.c. min ft/lb. As can be seen, the K_2 values when two or three ESP fields are active are much higher than when the ESP is not energized because of the finer particles and, therefore, the considerably lower porosity of the dust cake. Finally, as another benefit of the use of CK_2, an evaluation of this parameter could help in assessing how well the ESP portion of the hybrid collector is functioning, especially by comparing the CK_2 values for the hybrid collector when the ESP is energized with the CK_2 during short test periods in which the ESP power is shut off. Thus, Table 4, mentioned previously, is illustrative.

By a multivariable regression analysis, a correlation between (1) the combined effects of both filtration velocity and number of active ESP fields and (2) the rate of pressure loss as well as another correlation between those same combined effects and the number of cleaning cycles per day (assuming cleaning cycles of 1 min of duration) were obtained from the data recorded during the tests carried out for the off-line cleaning mode. The empirical models obtained are the following:

$$\Delta P_{\text{rate}}(\text{mm w.c./min}) = 0.316 + 0.682v_{\text{filt}} - 1.129\text{NESP}; \quad R^2 = 0.960$$

$$\text{NCC} = 116.83 + 1.980v_{\text{filt}} - 26.667\text{NESP}; \quad R^2 = 0.740$$

$$\text{for} \quad v_{\text{filt}} \subset [7.2; 9.0](\text{ft/min}) \quad \text{and} \quad \text{NESP} = 0, 1, 2, 3$$

where NCC is the number of cleaning cycles per day. The variation in the rate of pressure loss and in the number of cleaning cycles can be explained mainly by means of the combined effects of the filtration velocity and the number of active fields in the ESP. Hence, we can link the ESP efficiency to the rate of pressure loss and the number of cleaning cycles.

5.4. Metals deposition

In relation to the metal determination tests, mean values of capture efficiency for metals in particulate matter are shown in Table 8. Removal efficiency for all metals was highly satisfactory due to the high removal efficiency of fine particulate matter. Only mercury appeared in vapor phase in a detectable concentration. A capture efficiency of 30% was achieved for mercury in vapor phase.

Metal deposition rates varied depending on the metal studied, but the rates were always higher than 99%. For arsenic,

Table 8
Capture efficiency for metals in particulate matter

Test number	Location	Concentration (mg/N m^3 particulate)							Concentration (mg/N m^3 vapor)						
		As	Cd	Cr	Hg	Ni	Pb	Se	As	Cd	Cr	Hg	Ni	Pb	Se
15.1	Inlet	93.8	6.25	863	4.17	331	375	7.92	ND	ND	ND	0.55	ND	ND	ND
	Outlet	0.6	NA	4.14	NA	3.01	3.76	NA	ND	NA	ND	0.39	ND	ND	NA
13.3	Inlet	38.1	5.52	198	2.49	163	126	NA	ND	ND	ND	ND	ND	ND	NA
	Outlet	NA	NA	3.98	NA	1.5	NA	NA	NA	NA	ND	1.13	ND	NA	NA
17.1	Inlet	31.5	NA	249	3.35	184	122	11.7	ND	NA	ND	0.21	ND	ND	ND
	Outlet	NA	NA	NA	NA	0.4	NA	NA	NA	NA	NA	NA	ND	NA	NA

Arsenic	Cadmium	Chromium	Mercury	Nickel	Lead	Selenium
99.36%	100%	99.52%	100%	99.09%	99.00%	100.00%

cadmium, mercury and selenium deposition rates of practically 100% were reached, since at the outlet of the hybrid collector the concentrations of these metals were under the detection limit (indicated as ND in Table 8). Furthermore, while a lower filtration velocity favours chromium removal, nickel and lead removal improve at higher filtration velocities.

5.5. Scale-up

As a consequence of the results obtained in the tests carried out at the pilot installation, the keys for retrofitting electrostatic precipitators into hybrid collectors were discovered. Also, a large operational database and significant practical knowledge were obtained in this study. Thus, in order to transform an ESP into a hybrid collector, the following design criteria were determined:

(a) Cleaning mode: off-line, using high pressure and low volume pulse system, working at a pressure of 7 bar gauge.
(b) Air-to-cloth ratio (filtration velocity): 6 ft/min.
(c) Specific collection area of about 60% of the existing ESP, which is equivalent to three active fields (the fabric filter will be housed where fields 4 and 5 were).
(d) Blowing pulses: 40 ms (the expected cleaning time per cycle is 1.5 min, as maximum).
(e) Cleaning activation by pressure drop inside the fabric filter.

The bag material is the same as that used in the pilot plant.

Therefore, the modifications determined to carry out this retrofitting are the following:

I. *Removal of last ESP fields*. In order to achieve the proper configuration of the hybrid collector, it is necessary to eliminate the last two or three electric fields, depending on the initial ESP size. At least three activate fields must be used. Discharge electrodes, collecting surfaces as well as electric energization and rapping systems are replaced by bags and cleaning bag systems. In this case, the first fields require no modification and they would operate as in the initial ESP.
II. *Installation of a new structural arrangement*. A base structure abetted over the primitive filter structure is required in order to sustain the bags and blowing system as well as to isolate the compartments for cleaning of the dirty gas.
III. *Partition of the chamber into dirty and clean gas zones*. Dirty and clean gas zones are to be separated completely by means of plaques which support the bags and which tightly adjust the closing of each bag.
IV. *Isolation of different cleaning chambers*. Separations are required to isolate a set of bags, which will close and stop the gas flow when the cleaning system is activated. Due to a reduction on the filtration surface in the equipment, filtration velocities are increased when one of these separations is closed for cleaning. A number of separations are required so as not to exceed the filtration velocity designed for the equipment when one of them becomes inoperative because of cleaning procedures.
V. *Installation of bags and cleaning system*. The bags are arranged over a support plaque with holes in it. The air transport system, blowing valves and venturis for air distribution are placed over the bags.

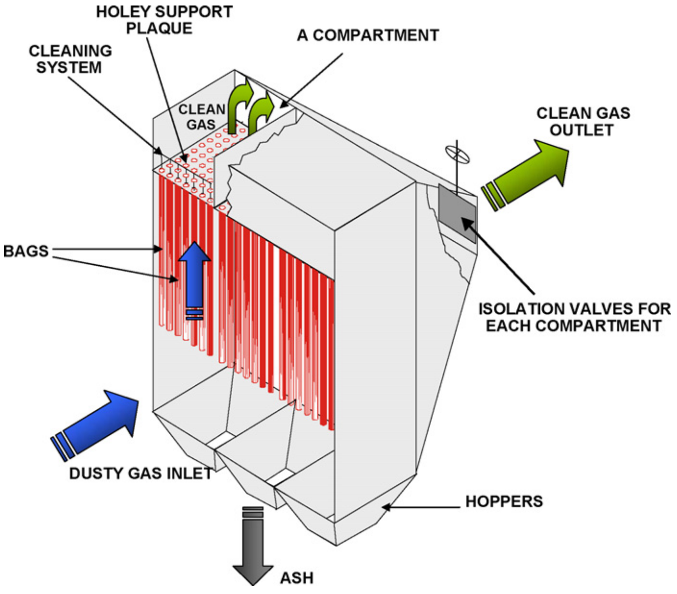

Fig. 7. Arrangements of the fabric filter section of a retrofitted ESP.

Table 9
Characteristics of retrofitted ESPs

Power plant	550 MWe	220 MWe
Operation parameters		
Gas flow rate (m^3/h)	2,436,900	1,645,200
Ash coal content (%, w/w)	12	12
Gas temperature (°C)	140	120
Bag characteristics		
Diameter (cm)	15	15
Length (m)	3	3
Number of bags per compartment	2,226	1,515
Total number of bags	17,808	12,120
Filtration area (m^2)	25,175	17,134
Design air-to-cloth ratio (ft/min)	6	6
Cleaning system characteristics		
Number of compartments	8	8
Blowing valves per compartment	742	484
Number of bags per blowing valve	3	3
Number of compressors	8	8
Blowing time of each compartment (s)	90	90
Cleaning air pressure (bar gauge)	7	7
Air flow on compressor (m^3/h)	1.30	0.95

Fig. 7 shows a scheme of the ESP retrofitted to a hybrid collector.

On the basis of this study, we have proposed a basic retrofitting for the ESPs in two pulverized coal power plants, one of them a 550 MWe (large) plant and the other one a 220 MWe (medium-sized) plant. The main specifications and operative characteristics of these plants and retrofitted installations, as proposed, are shown in Table 9.

6. Conclusions

A hybrid collector (ESP + FF) for improving particulate matter removal from flue gases from coal power plants was developed and then testing in a pilot plant that processes up to 15,000 m^3/h of flue gas. The pilot hybrid collector was tested using real combustion gases at a pulverized coal power station.

The tests were designed to achieve economic and operational optimization of hybrid collectors for removing particulate matter and metal from flue gases. We studied the effects of the cleaning system and mode, filtration velocity, and the number of active fields in the ESP on the performance of the hybrid collector system. We also achieved the better operating conditions with regard to those variables, in order to obtain very high removal efficiencies for particles. Thus, the removal efficiency in relation to the PM10 and PM2.5 and trace metals emissions, according to the legal limits in the European Union and the United States of America, was specifically considered. The efficiencies obtained were very high – PM10 removal efficiency of more than 99.95% and PM2.5 removal efficiency of up to between 96 and 98%, and a metal deposition of more than 99%, depending on the metal – overcoming limitations of ESPs with regard to achieving the particulate matter emission limits. However, a lower efficiency was obtained for the capture of mercury in vapor phase (only 30%).

We have concluded that the off-line mode is more effective when applied in hybrid collectors. We found a relationship between the rate of pressure loss and both the filtration velocity and the number of active fields in ESP. A relationship between these two parameters and the number of cleaning cycles was also found. Furthermore, we have deduced the removal efficiency for the ESP as a function of the number of active ESP fields, for a given filtration velocity. Thus, the fly ash load and particle size distribution are linked to dust inlet conditions for the fabric filter and cleaning cycles, which in turn are related to the pressure drop and the rate of pressure loss in the FF, considered as a dynamic variable. Finally, with respect to the experimental section of this study, a new parameter (CK_2) was introduced and calculated to help in assessing the fabric filter section in the hybrid collector and even in evaluating how well the ESP section is functioning.

A significant operational database and a good deal of practical knowledge were built up during the study. This database was considered a starting point for the design of the hybrid collectors and the retrofitting of existing ESPs. According to these results, the criteria extrapolated for a full-scale design of hybrid collectors are proposed. Thus, we have concluded that this technology requires a total collection area of about 60% of a conventional ESP plus about 50% of a conventional FF (because of the use of a higher velocity and the greatly reduced particle load at the inlet of this device) to achieve the collection efficiencies required. As an application of this study, we have proposed a basic retrofitting for the ESPs in two pulverized coal power plants, one of them 550 MWe and the other one 220 MWe.

New developments and improvements could be carried out in future research in order to analyze the capability of this technology for the simultaneous collection of particulate matter and metals with SO_x an NO_x and not only the removal efficiency of PM10, PM2.5 and metals in flue gases from coal combustion. The capture of mercury in the vapor phase is also of the utmost importance.

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