Control of Ultra-Fine Particulate Emissions

Compendium: State-of-the Art Technology Review

by
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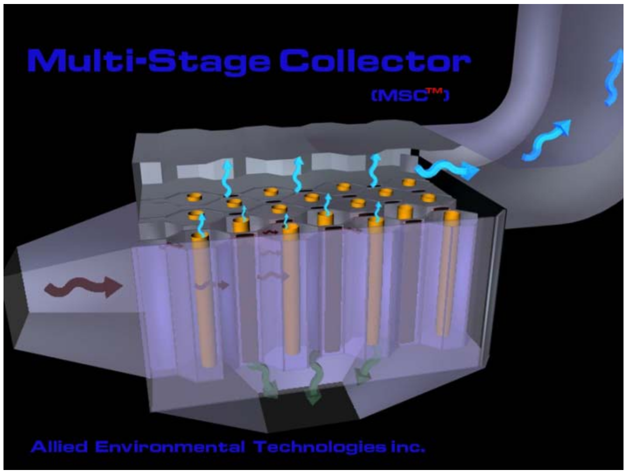
1.0 Foreword

Recent research findings have shown that fine, sub-micron particles suspended in the air cause a much greater negative health effect than had previously been suspected. These findings will very likely result in more stringent ambient air quality standards than the current PM-10 (particles less than 10 micrometers). Scientists expect the standard will likely be reduced to PM-2.5 or even PM-1.0. The state implementation plans that will develop in response to the more stringent Federal ambient air quality standards will require that many of the existing particulate control devices on coal-fired utility boilers and other industrial sources be upgraded to reduce their emission of the sub-micron fine particles.

The primary state-of-the-art technologies for particulate control are **F**abric **F**ilters (FF or baghouses) and **E**lectrostatic **P**recipitators (ESPs). However, each of these has limitations that prevent them from achieving ultra-high collection of fine particulate matter. ESPs have a major limitation in that the fractional penetration of 0.1- to 1.0-µm particles is typically at least an order of magnitude greater than for 10-µm particles, so a situation exists where the particles that are of greatest health concern are collected with the lowest efficiency. Fabric filters are currently considered the best available control technology for fine particulate, but they also have weaknesses that limit their application, especially in the submicron particulate collection range.

MSC™ is a new concept for particulate control. The intent of the MSC™ is to combine the best features of the two-stage ESP and a FF in a manner that has never been done before. The MSC™ concept can be broadly summarized as a system in which multiple stages are utilized, with each stage performing a primary function, and the multiple stages operating synergistically to provide significantly improved overall results. The principal objective of the MSC™ is to substantially improve fine particulate collection by combining both electrostatic charging/collection and filtration processes, not only by separating zones for particle charging and collecting, but, by providing a new unique collector design with improved efficiency to collect high resistance fine particles.



The MSC™ technology benefits and its major differences from other technologies will be apparent from the following discussion.

2.0 Ultra-High Particulate Collection

The purpose of a particulate collector is to provide as high a level of control as is practically possible while keeping the overall power consumption at the reasonable level.

2.1 FABRIC FILTERS OR BAGHOUSES

Current fabric filters can achieve 99.9% collection efficiency, and, when advanced fabrics are employed fabric filters can achieve 99.99% collection efficiency with no significant deterioration in performance for sizes from 0.1 to 1.0 μm. However, FFs cannot routinely achieve that level of control for all applications within economic constraints. Fabric filters sometimes also have problems with bag cleanability and high-pressure drop, resulting in a very conservatively designed, large, and costly baghouses.

One approach to make fabric filters more economical is to employ smaller baghouses called **P**ulse **J**et (PJ) filters that operate at much higher **F**ace **V**elocity (FV) ratios. The primary factors that determine collection efficiency in a FF are dust properties such as particle size and cohesive characteristics, pore size and porous media properties, pulse-cleaning frequency, and FV. However, studies have shown that collection efficiency is likely to significantly deteriorate for a given porous media when FV is increased.

2.2 ELECTROSTATIC PRECIPITATORS

State-of-the-art ESPs can provide 99.9% total mass particulate control, but collection efficiency for 0.1- to 1.0-μm particles is significantly lower. The most common form of electrostatic precipitator used for industrial gas cleaning is the so-called single-stage type in which the corona generating electrodes are used to charge the dust particles and act as the precipitating field electrodes. The flow in such a precipitator is in a fully turbulent range and the turbulence is further increased by the effect of electric wind resulting from the corona discharge. The turbulent flow velocity is high when compared with the velocity of particles in the gas under the influence of the electric field. For this reason, the fundamental electrostatic equations cannot be used to calculate precipitator performance.

There is a further important effect: due to the turbulence, a number of factors, one of which is the frequency with which it is brought into proximity of the receiving or **C**ollecting **E**lectrode (CE), determine the probability of a dust particle being captured by the CE. This is the main reason why a precipitator, although somewhat less effective on fine particles, does not fall off so badly as the theoretical migration velocities calculated from pure theory of the motion of a charged particle in an electrostatic field would suggest.

2.3 BASIC PRINCIPLES OF THE ELECTROSTATIC PRECIPITATION PROCESS

An electrostatic precipitator must provide three essential functions:

- the suspended particles must be given an electric charge;
- the particles must be subjected to an electric field to enable them to migrate from the gas stream to a suitable collecting electrode, and
- the collected material mush be removed from the collecting electrode in an efficient manner and deposited in a receptacle with the minimum amount of loss.

In an ESP the charging occurs by two mechanisms: diffusion charging and field charging.

Diffusion charging occurs when ions in the gas collide due to Brownian motion with particles and transfer their charge to them.

Field charging occurs when a particle is located within an electric field that contains ions. The ions will travel along the electric field lines. The presence of the particle will disrupt the electric field somewhat. If the particle holds relatively little charge, the electric field lines will tend to flow through the particle and in that case, ions that flow along the field lines will contact the particle and transfer their charge to it. As the particle becomes charged, the electric field lines will be repelled from the particle and field charging will no longer occur. At that point, the particle has attained its saturation field charge.

The generally accepted theory of electrostatic precipitation states that as particles enter the electric field they become polarized and, since the high-voltage, high-tension or discharge electrodes (DE) are generally negative, the particles are oriented with the positive zone opposite these electrodes. Electrons discharged from the DE quickly attach themselves to gas molecules that then become gas ions and begin to move under the influence of the electric field towards the collecting (grounded)/plates (CE). In so doing, some of the electrons collide with the positive zones of the polarized particles neutralizing these zones and leaving the particles with resultant negative charges. The particles now carry negative charges and in consequence move towards the CE under the influence of the electrostatic field. Laws developed from the above concept and other similar concepts are generally refer to single particle charged in a known field, not necessarily the same field. In this case, no account has been taken quantitatively for the following:

- The interference of particles with one another. They are present in very large numbers and are moving at different velocities.
- The electric field varies considerably in the inter-electrode space and it is difficult to accurately predict it even for cylindrical (pipe) type of the precipitator.
- Particles of equal size entering the field at different distances from the DE will carry different charges.
- The erosion or stripping/scouring of particles from the CE by the gas flow.

Next stage of the precipitation process is the deposition of the charged particle under the influence of the electric field. Dust is deposited predominantly on the collecting electrodes but there are significant deposits on DE as well.

The next step is the dislodgement of the dust deposited by rapping or vibrating the electrode system. Only dust that falls into the hopper contributes to the efficiency of dust collection of the precipitator. Hence, ensuring the maximum amount of dust reaching the hoppers is one of the most important steps in achieving the highest attainable efficiency. In practice, dislodged dust particles and agglomerates follow a trajectory determined by the horizontal gas velocity and the free-falling velocity in the vertical plane. The dust not falling into the hoppers is re-charged by the corona discharge, and re-deposited on the collecting electrodes. Subsequent rapping blows repeat the process until the dust either reaches the hopper or reaches the end of outer field and is carried by the gases out of the precipitator.

2.4 FINE PARTICULATE COLLECTION.

Migration velocity, **ω**, is the velocity that a charged particle achieves in a quiescent gas. It is a balance between the Coulombic (or electrical), viscous, and inertial forces that is described by the following equitation [1]:

$$\boldsymbol{\omega = \frac{3QE}{3\pi d\eta}[1 - e^{\frac{-3\pi\eta t}{m}}]} \quad \textbf{(1)}$$

Where: Q – Particle charge;

E – Electrical field;

d – Particle diameter;

η – Viscosity;

t – Time, and

m – Particle mass.

The equation numerator, **QE,** is the electrical force acting on the particle. The equitation denominator, **3 π d η**, is the resisting viscous force. The exponential, time dependent, inertial force is generally of short duration, which eventually go to zero leaving the migration velocity in its steady state form, which is the terminal velocity. However, until it goes to zero, it must be considered since it does affect collection. Once the inertial force goes to zero, it becomes the terminal velocity that the particle ultimately achieves.

For rigorous accuracy, the Cunningham slip correction to Stokes law for the smaller particles must be applied to the ratio of the Coulombic to the viscous force. The Cunningham slip correction factor, whose value is significant for very small particles, essentially goes to zero for particles in the micron range and larger.

Once it has achieved its steady state form, the migration velocity can be re-written as:

$$\boldsymbol{\omega = \frac{\varepsilon_0 d E^2}{\eta}} \quad \textbf{(2)}$$

The significance of this relationship is that, for the particles dominated by field charging (submicron and nano-particles specifically):

i. Theoretically, the limiting field charge on the particle is proportional to the radius squared because the migration velocity of the particle will increase with particle size.

ii. Since the electric field is proportional to the applied voltage, the migration velocity is proportional to the voltage squared.

In practical terms, this means that the larger particles are more easily collected than the smaller ones. The exception is those smaller particles whose charging is dominated by the diffusion process and are generally easily collected because of their inherent Brownian motion. Furthermore, it is desirable for the precipitator to operate with voltages as high as possible for maximum collection efficiency. For the particles, approximately 0.2 to 0.8 µm, neither diffusion or field charging dominate resulting in the lowest migration velocities, which are the most difficult to collect in an ESP.

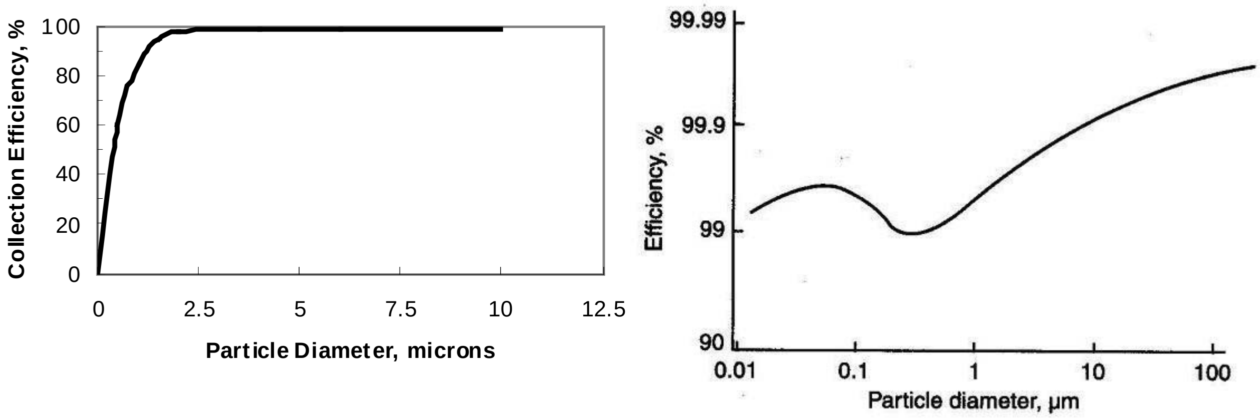


Figure 1. ESP Collection Efficiency as a Function of Particle Size

Figure 1 shows comparison between a typical theoretical (a) and "actual" (b) collection efficiency versus particle size relationship for an ESP. As can be seen, for sizes below 1 to 2 microns (µm), the collection efficiency rapidly degrades. A small increase in the efficiency could be observed in the sub-micron particle range (less than 0.1 µm) due to the improved collected because of their inherent Brownian motion. Figure 2 demonstrates the strong influence of electric field strength on performance in a 5 m precipitator zone. The typical minimum efficiency at around 0.3 – 0.4 µm is shifted from 5% up to 70% by increasing the field from 1.0 to 5.0x10^5 V/m [2].

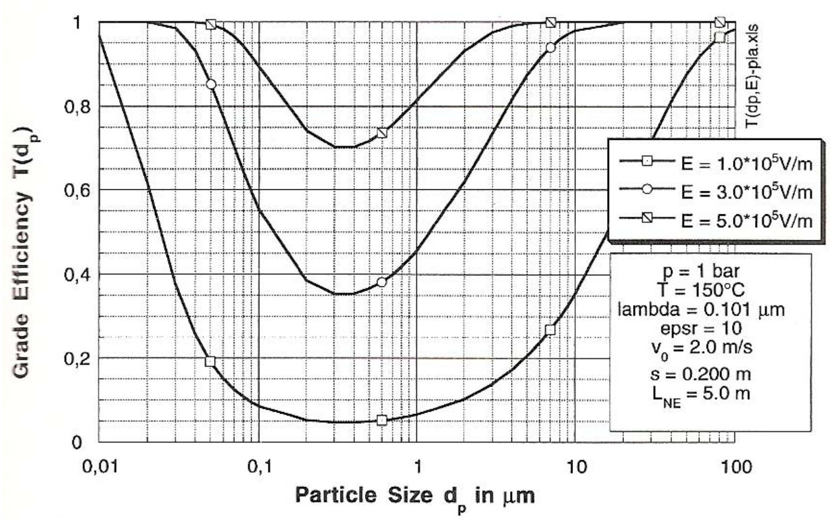


Figure 2. The Grade Efficiency for a Plate-Type Precipitator Zone

2.5 SPACE CHARGE AND CORONA QUENCHING

It is well-known fact that the electrical charge imparted on the aerosol particles is proportional to the electrical field and particle size. Furthermore, the effective migration velocity that determines the collection efficiency, is also proportional to the applied electrical field that moves the charged particulate from the gas stream towards (a) collecting plates and/or

(b) bags. Therefore, in order to effectively charge and collect the sub-micron particulate, the collecting device must provide first, effective and rapid particulate charging, and second, to be able to operate with an extremely high electrical field.

Additionally, while dealing with the sub-micron particulate/aerosol collection, there is a significant concern with the effects of space charge and/or corona quenching effects.

With the discharge electrode at the negative potential, which is the usual arrangement in most industrial applications, positive ions generated are attached to the discharge electrode and negative ions travel towards the grounded electrode. Although an equal number of positive and negative ions are generated in the corona region, almost 99% of the gas space between the corona and the grounded electrodes becomes filled with only negative ions. This forms a space charge of high opposing voltage, which limits corona current. Space charge is a phenomenon, which could be defined as a charge present in the inter-electrode space (between two or more oppositely charged electrodes) due to a flow of ions or a cloud of the charged particles.

Since the mobility of the charged dust is much lower than the mobility of the ions and electrons, the cloud of charged dust represents a significant increase in space charge that tends to quench the corona current. In electrostatic precipitation practice, it is known that in spite of very high potentials impressed upon the electrodes, essentially no discharge or corona current can be made to flow through the dust-gas mixture; the collection efficiency (under these conditions) is relatively low, although a considerable part of the suspended material is still separated from the gas.

The space charge imposed by the cloud of the charged particulate matter, however, would be greatly dependent on the particle size distribution, for a few big particles or a large number of the smaller ones could represent the same particulate mass. This would present more problems when dealing with the cloud of the charged fumes or smoke with MMD of less than 1 micron (sub-micron range). Assuming further that the mobility of the particulate is somewhat similar, the cloud of the finer charged matter could present a barrier (or obstacle) to the ions in their quest to carry charges from one electrode to the other. Hence, the other phenomenon called "corona quenching."

2.6 DUST RESISTIVITY AND BACK CORONA

In the operation of ESPs it was found that if the electrical resistivity of the particulate matter is excessively high, the result is a condition well known in the art of electrostatic precipitation called back ionization or back corona. When this occurs the gas in the interstitial spaces of the particulate matter and the filter media ionizes and injects ions of opposite polarity into the gas space that disrupts the charging process and non-uniform collection mechanism. Consequently, the inter-electrode space would become saturated with the bi-polar ions and bi-polar charged particulate.

3.0 Hybrid Technologies.

Fabric filters work well for many dust as long as the cohesive strength of the dust is not too high or too low. However, highly cohesive dust can lead to problems with bag cleanability and high pressure drop, and dust with low cohesive strength can promote dust bleed through resulting in higher emissions. ESPs work well (at least up to their theoretical potential) as long as the dust resistivity is in the range from about 10^8 to 10^{11} ohm-cm, but deteriorate significantly for high- or low-resistivity dust.

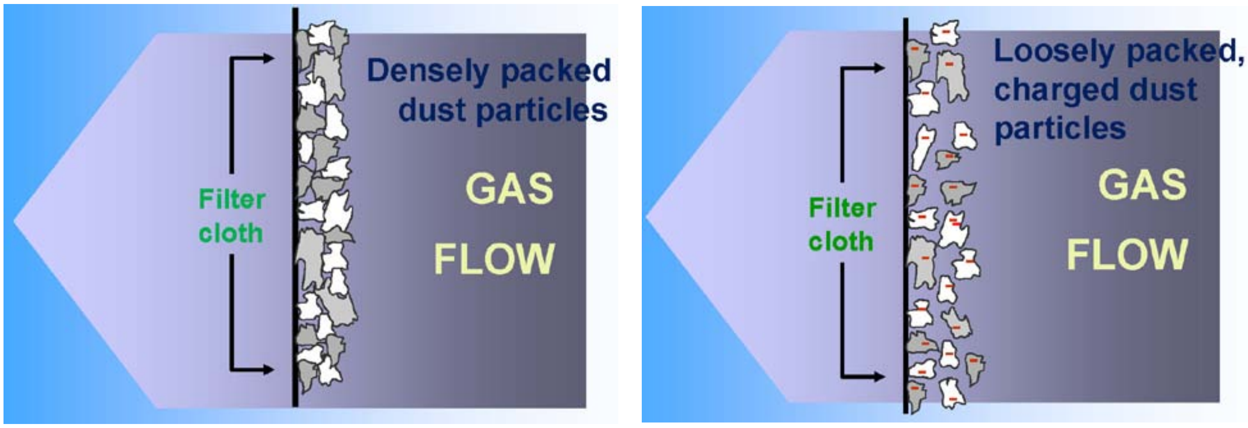


Figure 3. Charged Particles Dust Cake

Additionally, neither technology will work effectively with the submicron particulate matter as fine particulate shall pass directly though the filter material or would require a substantial time to become charged in the electric field to be precipitated.

It had been found that the electrical enhancement of the fabric filtration provides for a system with a far less pressure drop than that of a bag filtration unit alone (Figure 3) [8, 9]. Charged fine particles tend to follow electric field lines, which terminate upon the filter medium, rather than the gas streamlines that flow through open paths through the material. This discovery led a completely new group of the particulate control devices called HYBRID Collectors.

3.1 COMPACT HYBRID PARTICULATE COLLECTOR

Figure 4 and Figure 5 present a combination Fabric Filter/ESP hybrid device developed by EPRI and named Compact Hybrid Particulate Collector (COHPAC) [3, 4]. In accordance with the COHPAC concept, a high ratio pulse jet fabric filter collector is installed in series with an existing, energized electrostatic precipitator, serving as the polishing or final collection device.

Figure 4. COHPAC I

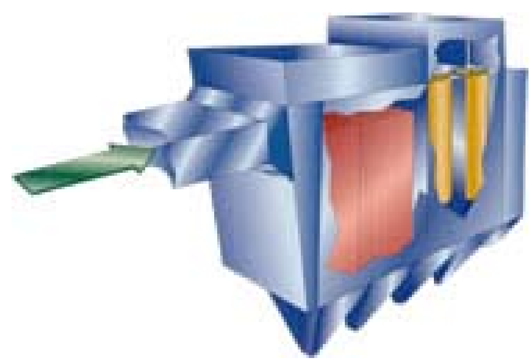


Figure 5. COHPAC II

Conceptually, because the ESP removes the majority of the dust prior to entering the fabric filter, the filtration rate (air-to-cloth-ratio) can be increased substantially while still maintaining the same pressure drops as conventional filtration rates. It is also believed that the ESP serves as a pre-charger and helps agglomerate the dust particles into a larger and more porous structure, which should aid in the filtration process.

However, in the ESP/FF installation in series, the particulate matter that reaches the fabric filtration bags will predominantly contain fine fractions. The collection of fine particulate matter fractions will generally result in a higher resistance to flow across the filter medium than will the larger particulate size distributions. Additionally, as the ESP serves as a pre-collector in this hybrid filter, all high resistivity dust problems like back corona, etc. will result in serious performance deterioration.

3.2 ADVANCED HYBRID PARTICULATE COLLECTOR

The Advanced Hybrid Particulate Collector (AHPC) concept consists of a combination of fabric filtration and electrostatic precipitation in the same shell [5].

In a typical pulse-jet baghouse, the dust is collected on the outside of the bags while the flue gas passes through the fabric, then exits through the top of the bags into the clean air plenum. In the original **A**dvanced **H**ybrid **P**articulate **C**ollector (AHPC) concept, approximately three out of four rows of bags are removed and a grounded plate is placed between each two rows of bags. In the original concept, the high-voltage corona discharge electrodes (wires or rigid electrodes) are installed between each plate and row of bags. A top view of the initial configuration is shown in Figure 6. Gas flow is introduced into opposite sides of a compartment and directed by baffles into the ESP zone. The particles in the ESP zone become charged and migrate toward the grounded plate at a velocity (migration velocity) dependent upon the particle charge and electric field strength. Since all of the gas flow must pass through the bags, there would be a velocity component perpendicular to the plates that pass the wires.

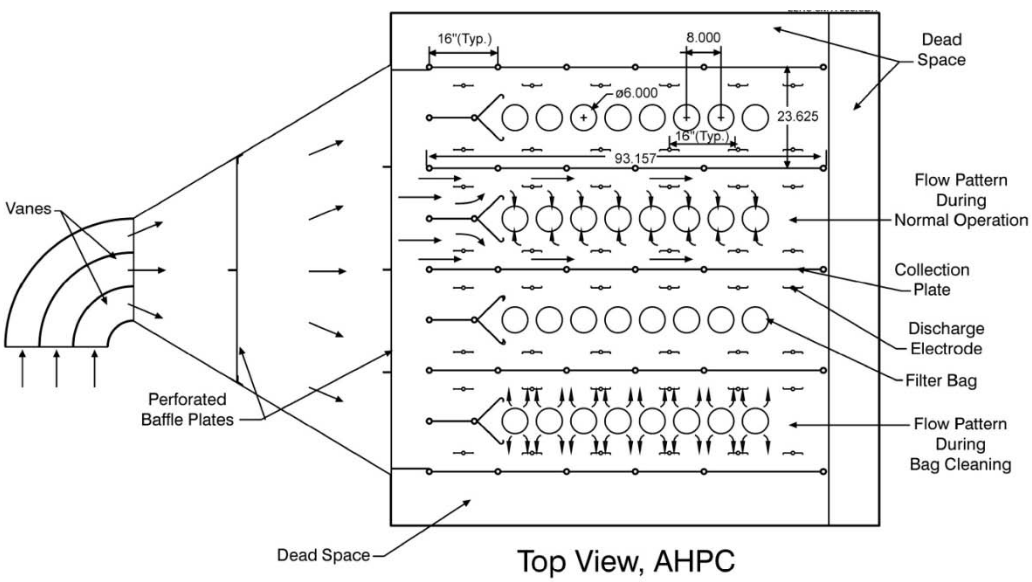


Figure 6. Advanced Hybrid - Original Concept

Subsequently, in order to protect bags from intense sparking between the discharge electrodes and the grounded bags, the original geometry was replaced with a tri-electrode system, where the perforated grounded collecting electrodes surrounded bags in a box-like manner (Figure 7).

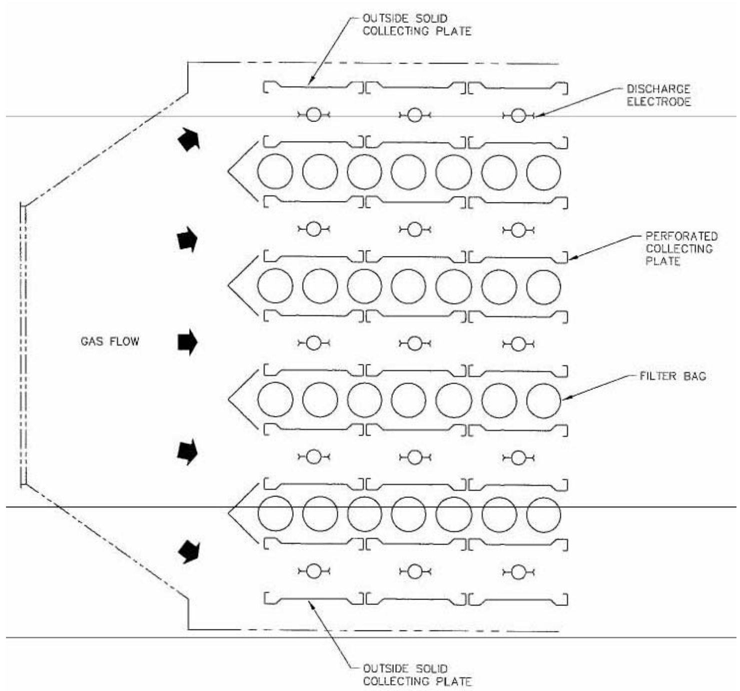


Figure 7. Advanced Hybrid - Modified Concept

The perforated collecting plate, besides capturing the charged particles, also serves as protection for filter bags from potential electrical damage from the electric field. The collecting plates and discharge electrodes are periodically cleaned using typical rapping methods. Figure 8 depicts the gas flow direction in the Advanced Hybrid during both operation and the cleaning phases. Figure 9 presents an artist's rendition of the final Advanced Hybrid internal arrangement.

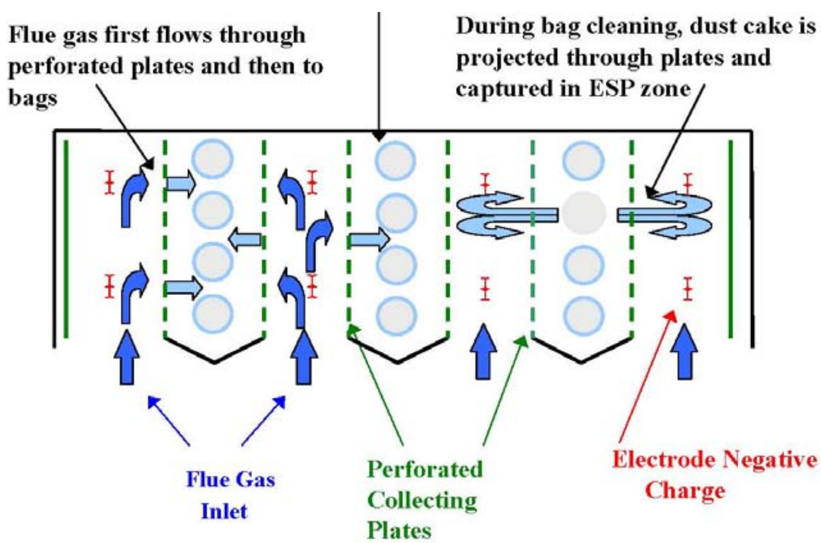


Figure 8. Gas Flow Direction in the Advanced Hybrid Collector

It should be noted that the tri-electrode system, with the bags completely enclosed in the box-like grounded structure, most likely would act as a grounded screen preventing penetration of the charged particles towards the bags. Hence, the particles, which did eventually reach the bags, will be collected by a "conventional" mechanism and will not produce the desired porous dust cake with lower porosity and the pressure drop.

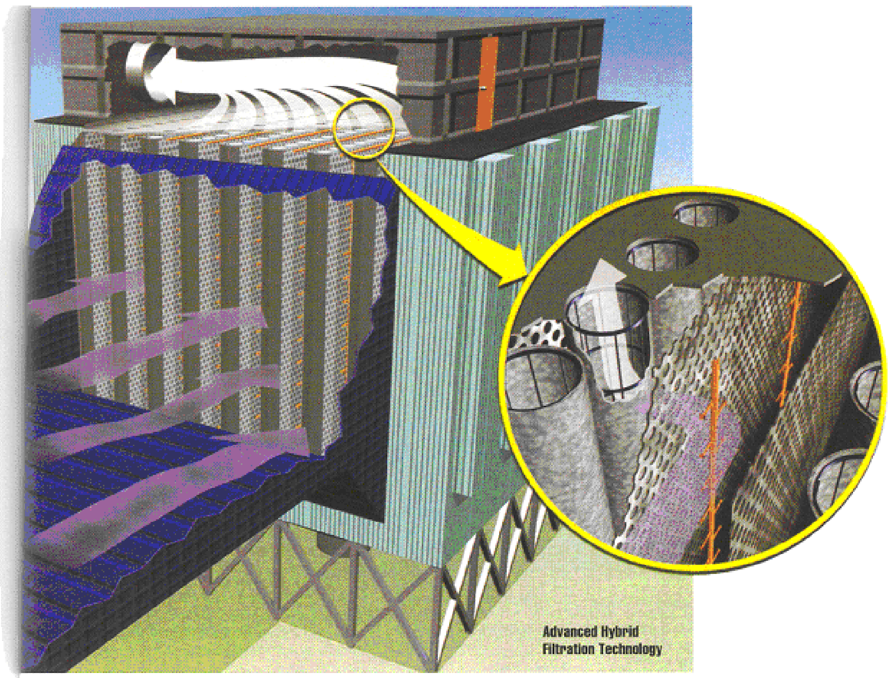


Figure 9. Advanced Hybrid – Artist's Rendition

Moreover, as the ESP portion serves as a pre-collector in this hybrid filter, the high resistivity dust problems will also result in serious performance deterioration.

The full-scale Advanced Hybrid installation at the Big Sandy power plant of the Otter Tail utility that began operation with very good results, virtually collapsed shortly after startup of the retrofit, due to the performance problems that began to occur and continued for the next two years [6]. These problems included a high tubesheet differential pressure exceeding 10" w.g., causing continuous cleaning with pulse pressures raised to between 100 to 110 psi and bag failures occurring within 6 months. The results of these problems were boiler derates of 30 to 50 MW due to ID fan limitations with the high bag pressure drops and the stack opacity exceeding the 20% limit due to bag failures. Ultimately, the Advanced Hybrid system was converted to a conventional pulsejet baghouse.

The high pressure drop operation, in our opinion, was caused by the "revised" design where the grounded collecting electrode system enclosed each raw of bag in a box-like grounded screen. These grounded screens prevented charged particles reaching the bags surface. Therefore, the dust, while penetrating the grounded collecting plates, for the most part lost its initial charge, thus greatly diminishing the charged porous dust cake effect that was suppose to improve the dust cake properties and reduce the pressure drop.

3.3 ELECTROSTATICALLY ENHANCED FABRIC FILTRATION – ESFF/MAX-9

The concept of the Electrostatically Enhanced Fabric Filtration (ESFF) is based on the fact that the electrical enhancement of the fabric filtration provides for a system with a far less pressure drop than that of a bag filtration unit alone [7, 8, 9].

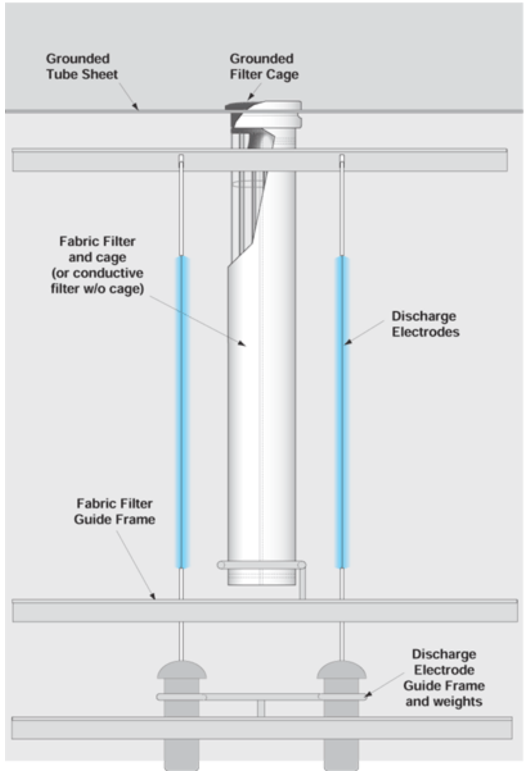


Figure 10. ESFF/MAX9 Conceptual Design

GE Energy licensed this concept from EPA and designated it as MAX-9.

It is claimed that the negative corona discharge provides two distinct mechanisms for increasing performance of the fabric filter. Once the incoming dust is charged:

- The negative charge causes individual particles to repel each other in the dust layer, reducing pressure drop.
- Negatively charged fine particulates are repelled from the "like" charged dust layer.

As a result, collection efficiency increases, and system pressure drop decreases.

Figure 10 presents the ESFF/MAX9 conceptual design. The potential pitfalls of this hybrid design will be addressed later.

3.4 MULTI STAGE COLLECTOR – MSC™

MSC™ is a new concept for particulate control [10, 11]. The intent of the MSC™ is to combine the best features of the two-stage ESP and a FF in a manner that has not been done before. The MSC™ concept can be broadly summarized as a system in which multiple stages are utilized, where each stage performs its primary function, and the multiple stages operate synergistically to provide significantly improved overall performance.

The principal objective of the MSC™ is to substantially improve fine particulate collection by combining both electrostatic charging/collection and filtration processes. It separates zones for particle charging and collecting, thus providing a new unique collector design with improved efficiency to collect high resistance fine dust particles.

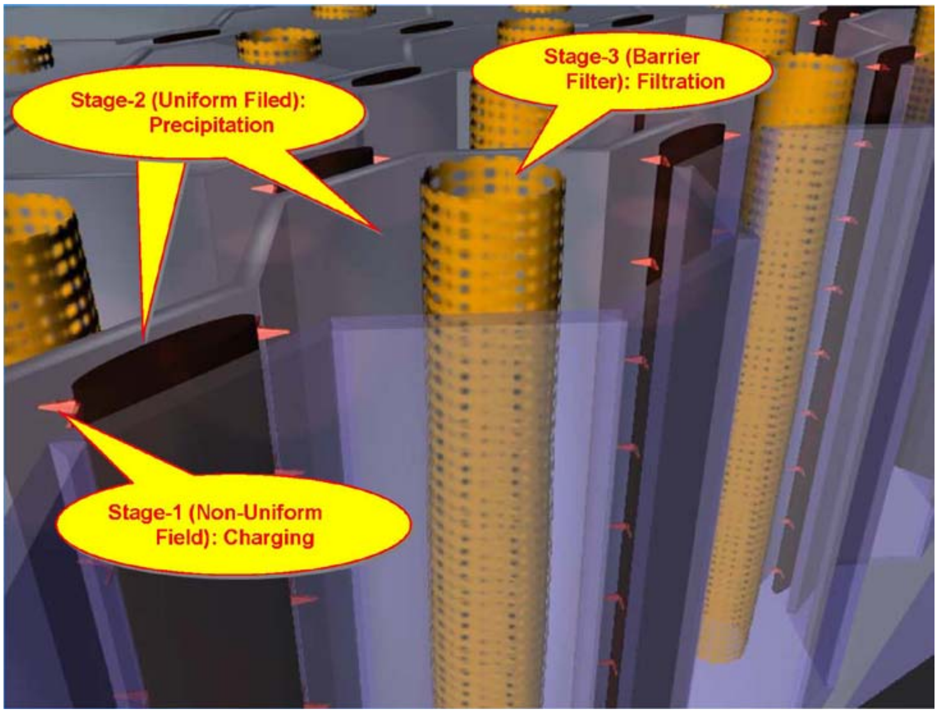


Figure 11. Conceptual MSC™ Design

MSC™ offers a uniquely compact concept (Figure 11) utilizing an upstream stage comprised of a generally conventional electrostatic precipitator followed by a downstream zone comprised of the parallel surfaces that create uniform electric field, followed by yet another stage which incorporates **B**arrier **F**ilter (BF) the external surfaces of which provide a uniform electric field.

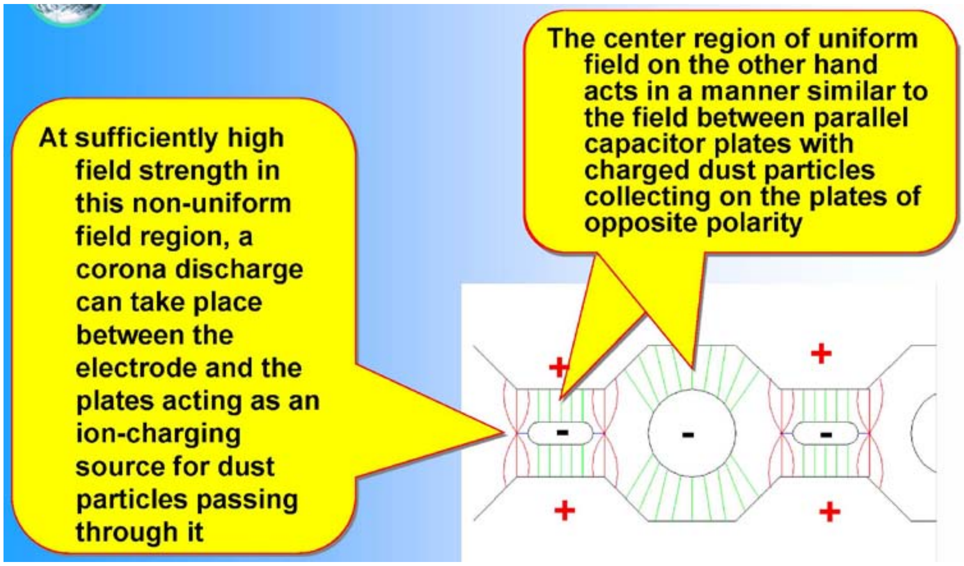


Figure 12. MSC™ Operation

The spacing between the discharge points (corona sources) and collecting surfaces are different, wider in the charging or corona generating zones and narrower in the collecting ones where a high-tension uniform electric field is required. This feature allows for the use of a single high voltage power source for all electrostatic fields (in all zones).

At sufficiently high field strength in the non - uniform field region, a corona discharge can take place between the electrodes and the plates acting as an ion-charging source for dust particles (Figure 12). The center region of uniform field acts in a manner similar to the field between parallel capacitor plates with charged dust particles collecting on the plates. The MSC™ is engineered in such a way that both barrier filters (bags) and the discharge electrodes are grounded, therefore, the high voltage in the MSC™ device is not limited by a concern of the sparking towards the bags. Hence, it could operate with the maximum possible applied high electric field to ensure the most effective sub-micron particulate charging and collection.

In MSC™, particles are deposited onto the BF by two mechanisms: electrostatic and diffusional deposition that act simultaneously. Collection by diffusion occurs due to both fluid motion and the Brownian (random) motion of particles. Diffusional collection effects are most significant for particles less than 1 micrometer (µm) in diameter.

Another collection mechanism, direct interception, occurs when a particle comes within one particle radius of an obstacle. The path that the particle takes can be a result of inertia, diffusion, or fluid motion. On one hand, 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. On the other hand, the diffusional collection efficiency of particles on fibers is high for small particles but low for larger ones (Figure 13) [14].

Therefore, the simultaneous diffusional- electrostatic collection is a useful technique for efficient filtration of particles below 0.1µm. Alonso, et al. [15] reported superior performance of an electrostatic precipitator in which the collector electrode has been substituted by a series of wire screens transposed to gas flow. The particles deposition by diffusion was highly efficient for particle diameters in the range of only few nanometers. The larger particles are collected by conventional electrostatic deposition.

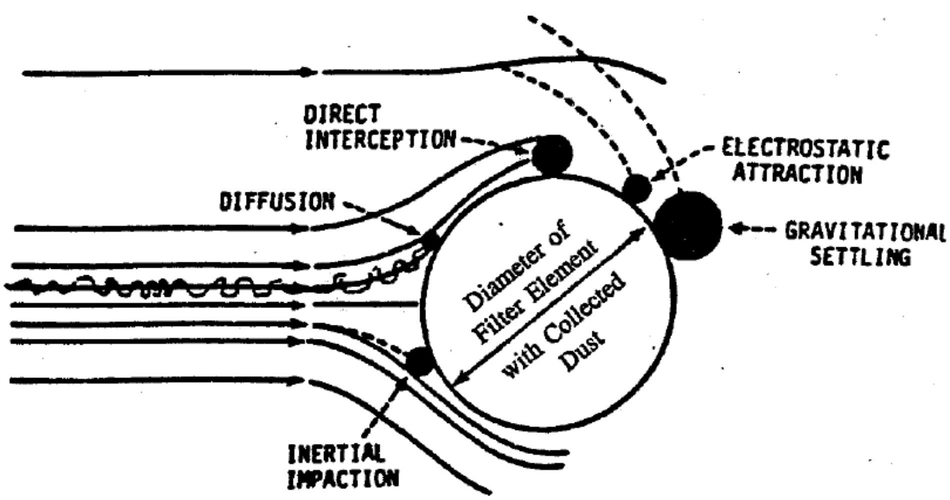


Figure 13. Particle Interception Schematic

The combination of both mechanisms, led to high particle collection for the entire particle size range below 0.1µm. Mermelstein, et al. [16] conducted a study to investigate the effect of using stainless steel fibrous and porous filters as the ground electrode of a point-to-plate electrostatic precipitator on particle penetration. The effect of filter medium structure and pore size on particle removal has been investigated as a function of particle size for particles in the range of 0.03-1µm and filter FV's in the range of 15-75 cm/s (29-147 ft/m). The application of the electrical field decreased particle penetration by a factor of 6 to 54. The experiments confirmed that sub-micron particles were captured in the first few layers of the filters by the action of electrostatic forces. *Therefore, ultrahigh submicron fine-particle collection should be achievable by employing a combination of removing about 95-99% of the dust in the ESP section, precharging the particles, and using a porous media barrier filter*.

3.5 TEST RESULTS

The Proof-of-Concept phase has been completed using real combustion gases on a working prototype of the MSC™ that was designed to operate with FV in the range of 3.59 to 28.73 ft/min range. Figure 14 depicts an improved performance, which can also be seen in the pressure drop characteristics and cleaning intervals.

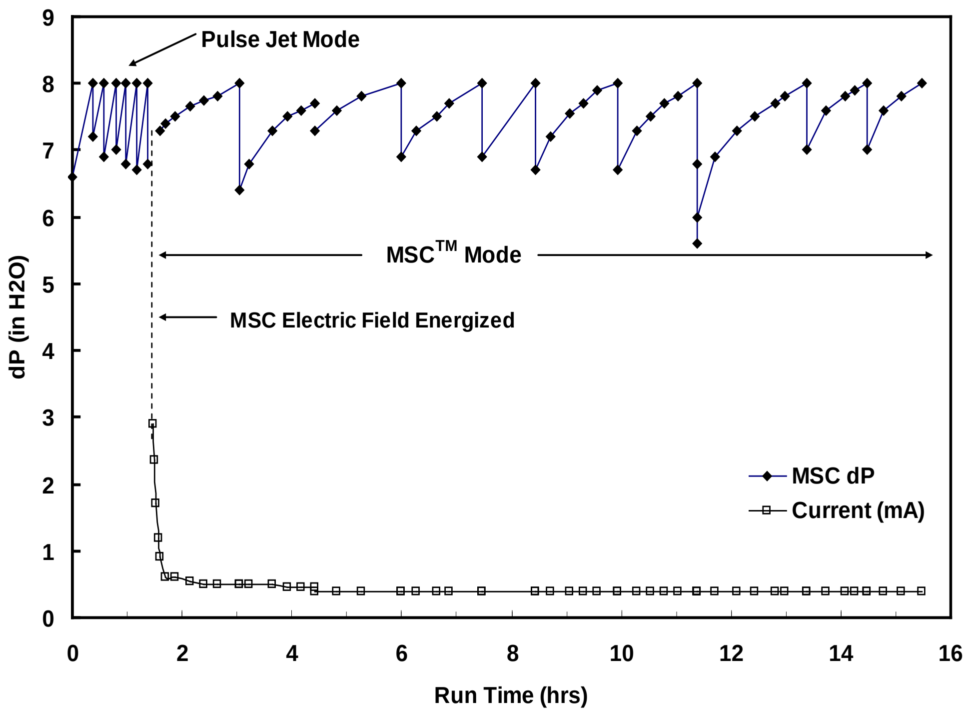


Figure 14. Operating Pressure Drop Comparison: Pulse Jet vs. MSC™ Modes

Figure 15 shows the unit operation characteristics: with the electrical field off, the particle collection efficiency improved from 99.71 to 99.81% as the pressure drop increased, but then the efficiency began to decline as the differential pressure approached 8 inches H_2O. With the electrical field energized (MSC™ mode), the particle collection efficiency was markedly higher than for pulsejet operation: up to 99.99%. Further, the collection efficiency was essentially constant over the entire range of pressure drop up to 8.0 inches H_2O.

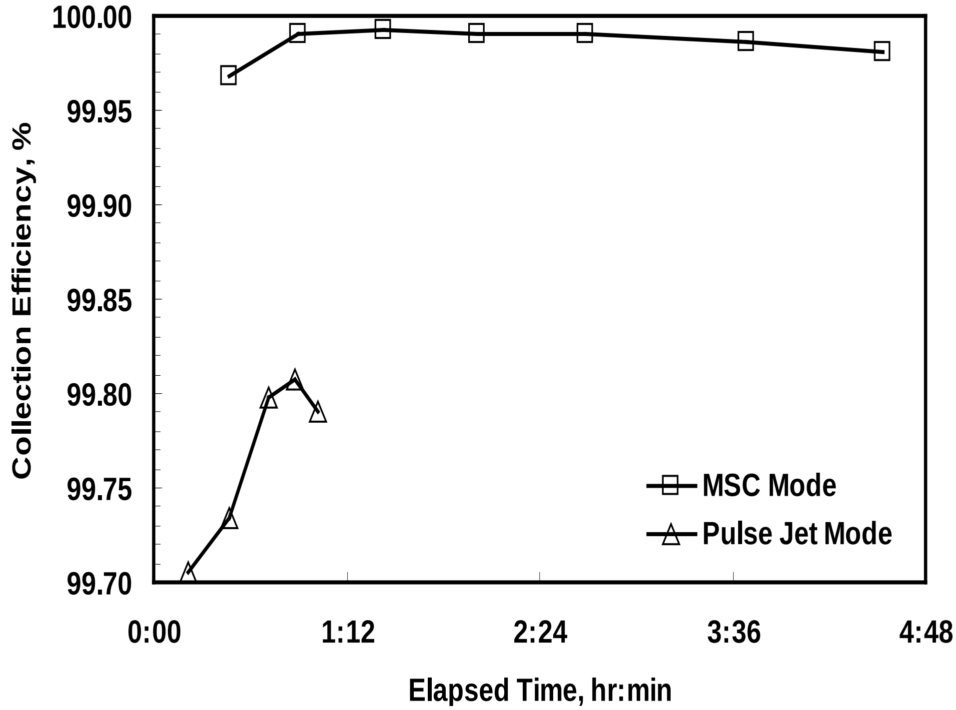


Figure 15. Collection Efficioency Comparison; Pulse Jet vs MSC™ Modes

Figure 16 shows the particle size distributions measured. The inlet showed a mass mean diameter of about 38 microns. In the pulse jet mode, the largest outlet particle size that was measured was 17 microns. In the MSC™ mode, the largest outlet particle size was only 7 microns. The higher collection efficiency in the MSC™ mode is also apparent in Figure 16.

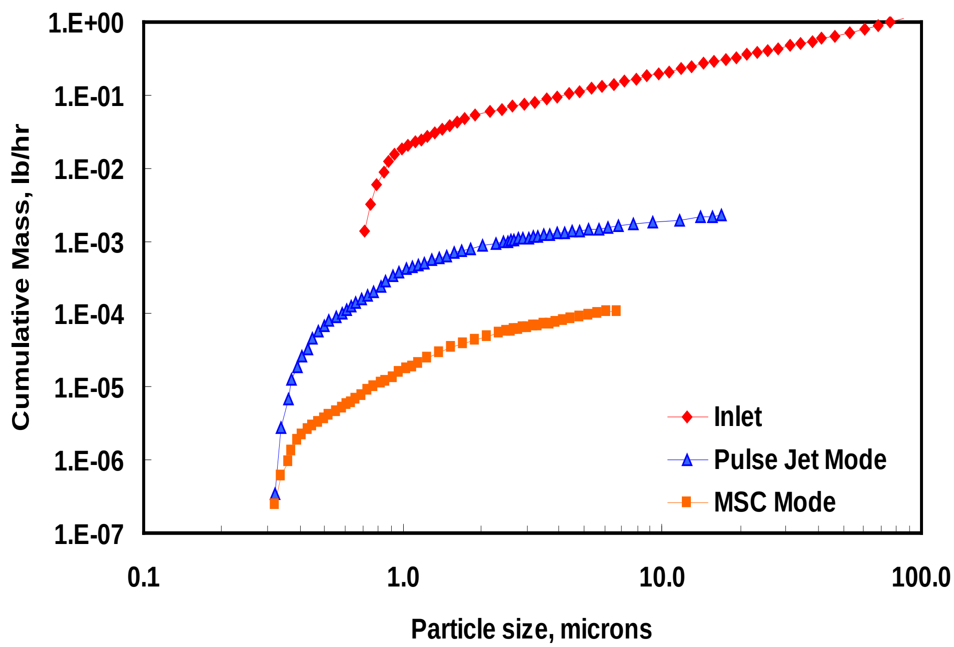


Figure 16. Particle Size Distribution Measured

3.6 INDEPENDENT RESEARCH

Researchers in Korea [17] have tested various hybrid configurations, as shown in Figure 17.

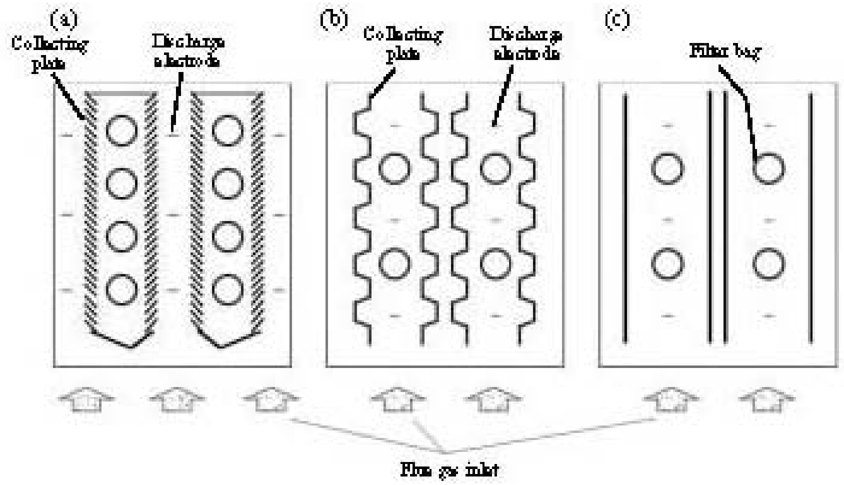


Figure 17. Korean Research Configurations

Note, the center configuration in Figure 17 is somewhat similar to the MSC™ configuration (although they used commercially available un-optimized corrugated plates and the bags were located in every other wide space created by the plates) while the configuration on the left is more like the Advanced Hybrid™ with ESP and fabric filtration in series.

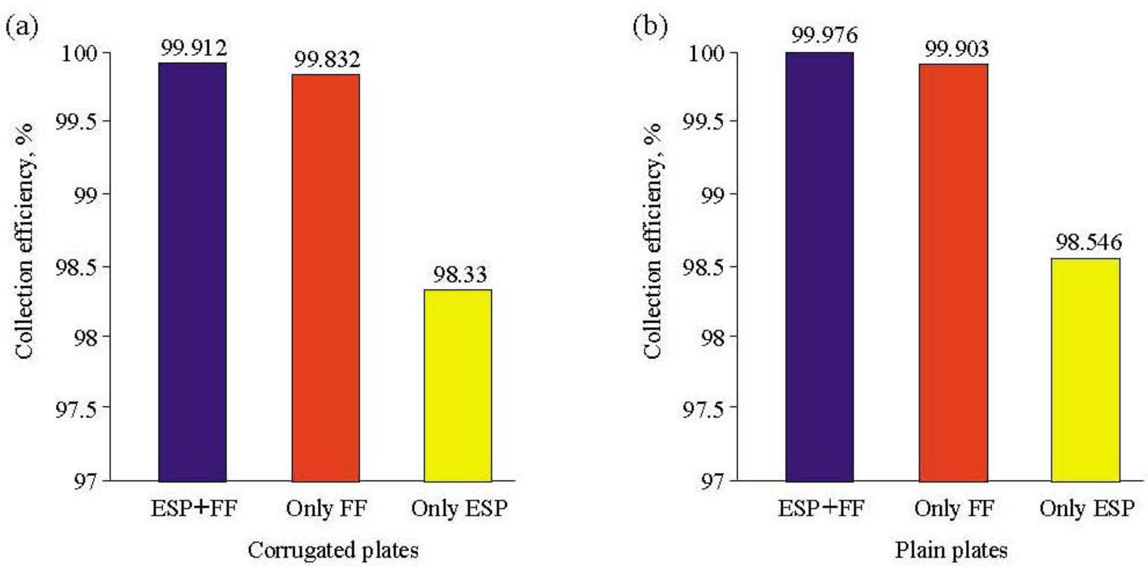


Figure 18. Efficiency Comparisons

The configuration with the plain plates on the right also closer approaches the MSC™ with ESP and fabric filtration occurring in parallel. The pilot scale test results were similar to the MSC™ results. Both the corrugated and plain plate configurations were very effective in collecting $PM_{2.5}$ particles (Figure 18 and Figure 19).

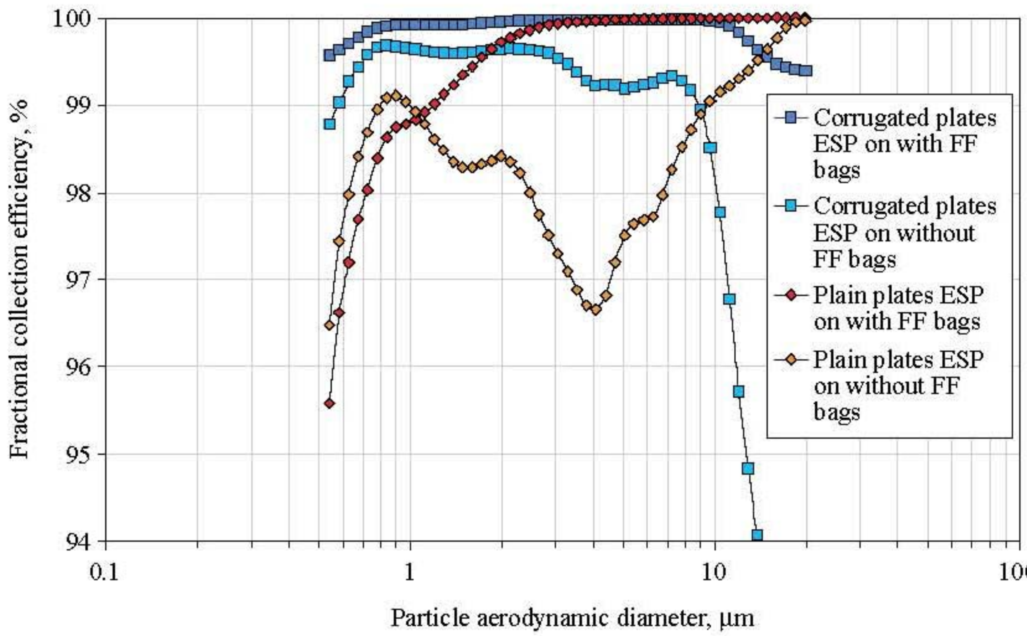


Figure 19. Fractional Collection Efficiency

4.0 Discussion

4.1 EARLIER DEVELOPMENTS – GENERAL ISSUES

Earlier attempts at combining fabric filters and electrostatics have involved several different concepts:

1) precharging the particles upstream of a baghouse,
2) weaving the alternative polarity electrodes into the bags,
3) weaving the grounded electrodes into the bags and then installing a high-voltage electrode at the center of the bags,
4) installing high-voltage wires between pulse-jet bags (ESFF/MAX9), and
5) installing a high-ratio baghouse behind an ESP (the EPRI COHPAC concept).

Precharging provided some pressure drop advantages, but all of the dust was still collected on the bags, so the advantage did not warrant the cost. In the case of installing electrodes in the bags, reliability has been the major problem, and the electric field strength is very limited. In addition, any sparking tended to cause rapid deterioration of the fabric, and the bags still had to handle all of the dust. The concept of installing a high-voltage electrode in the center of bottom-entry bags provided improved electric field strength, but there was still concern over the effect of sparking on bag life

For electrostatically enhanced baghouse to be economical, it must operate at fairly high FV ratios, from 12–20 ft/min. Some benefit is seen because of the particle charging, but bag cleanability is still a major problem at the high FV ratio. To help solve this problem, off-line cleaning had been recommended. This would add complexity and require additional filtration area to prevent excessive pressure drop during the off-line period. Moreover, the benefit of off-line cleaning is questionable in cases where the dust is significantly redispersed. For example, the settling velocity of 10-µm particles is only 0.5 cm/s. The time required for these particles to effectively reach the hopper is over 10 minutes. For smaller particles, the time would be significantly longer.

The high-resistivity dusts will cause problems with the ESP portion of the hybrid filters, just as they do with state-of-the-art ESPs due to the bi-polar charged particulate. High-resistivity dust will increase the portion of the total dust that the filter must handle, which will make pressure drop control more difficult.

4.1.1 ADVANCED HYBRID.

The Advanced Hybrid operates as a precipitator and the PJ in series, thus making it not very suitable for the sub-micron particulate efficient collection since the precipitator's performance is significantly diminished in the sub-micron particulate range. Moreover, as soon as the corona or the quenching phenomena initiates, the precipitator section efficiency significantly diminishes and therefore the overall unit performance.

In addition, as discussed previously, the box-like grounded screens encompassing the bags, prevent the charged particulate reaching the bags, hence, in fact, nullifying all benefits of the charged dust cake on the bags surface.

Furthermore, the high-resistivity dust will cause the back corona in the ESP section, which, in turn, would result in a significantly higher dust loading in the FF section, hence violating the design balance resulting in a higher emissions.

4.1.2 ESFF-MAX-9.

In this hybrid design, the corona discharge electrodes serve two functions, i.e. to impart a charge to the particulates carried by the incoming gas stream and to establish an electrical field running through the filter fabric to the grounded support frame. It is necessary to operate the corona discharge electrodes of the filter precharger at an electrical operating voltage above that which is known as the corona onset voltage. The corona onset voltage is that voltage at which the gas immediately adjacent to the corona discharge electrode starts to ionize. The corona onset voltage mainly is a function of the gas temperature and density, corona discharge electrode diameter, and its distance from the opposite electrode or a bag as in this case. The corona onset voltage for an electrode increases with its diameter and distance from the bags.

The high-resistivity dust deposited on the filter bags will result in a condition well known in the art of electrostatic precipitation called back ionization or back corona. When this occurs the gas in the interstitial spaces of the particulate matter and the bags surface ionizes and injects ions of opposite polarity into the gas space. This will result in bi-polar charges that disrupt the charging process and disrupt the collection.

Furthermore, in an ESFF/MAX9 device, the charging electrodes are located in the close proximity to the bags, hence to overcome sparking towards the bag, which would cause the bag puncture and subsequent failure, it is necessary to maintain operation below the sparking level. This contradicts the requirements of the effective sub-micron particles charging and collection: i.e. in order to effectively charge the submicron and nano-particulate material, the highest attainable applied voltage would be required.

Additionally, if space charge occurs, instead of dealing with it by increasing the applied voltage to overcome the charged particulate cloud, the system would have to retain the reduced voltage in order not to overcome the sparking threshold.

4.1.3 MULTI STAGE COLLECTOR (MSC™)

The MSC™ is engineered in such a way that both barrier filters (bags) and the discharge electrodes are grounded, therefore, the applied high voltage in the MSC™ device is not limited by a concern of the sparking towards the bags (Figure 20). Therefore, it can operate with the maximum possible applied high electric field to ensure the most effective sub-micron particulate charging and collection. Furthermore, by utilizing combination of single- and two-stage electrostatic precipitation (Figure 12), the MSC™ technology offers the best possible combination of the non-uniform and uniform high-tension electric fields for the most effective sub-micron aerosol charging and collection. As the applied voltage is not limited by a concern of the sparking towards the bags, the MSC™ can continue its operation with the maximum applied high electric field to ensure the most effective sub-micron particulate charging and collection.

Evald Andersen [13] offered the following four (4) possible ways in dealing with the corona-quenching problem:

a. The first is some sort of an agglomerator preceding the precipitator.
b. The second is dilution of the gas stream before it reaches the precipitator, using clean air for the dilution, for example.
c. The third is to find a way to increase the supply of ions considerably above that attained by a normal corona discharge between the usual corona wire and collecting plate.
d. The fourth is to use a two-stage precipitator with separate high voltage power source for the first and the second stages.

Clearly, the MSC™ technology offers the way to manage the detrimental influence of the space charge and corona quenching

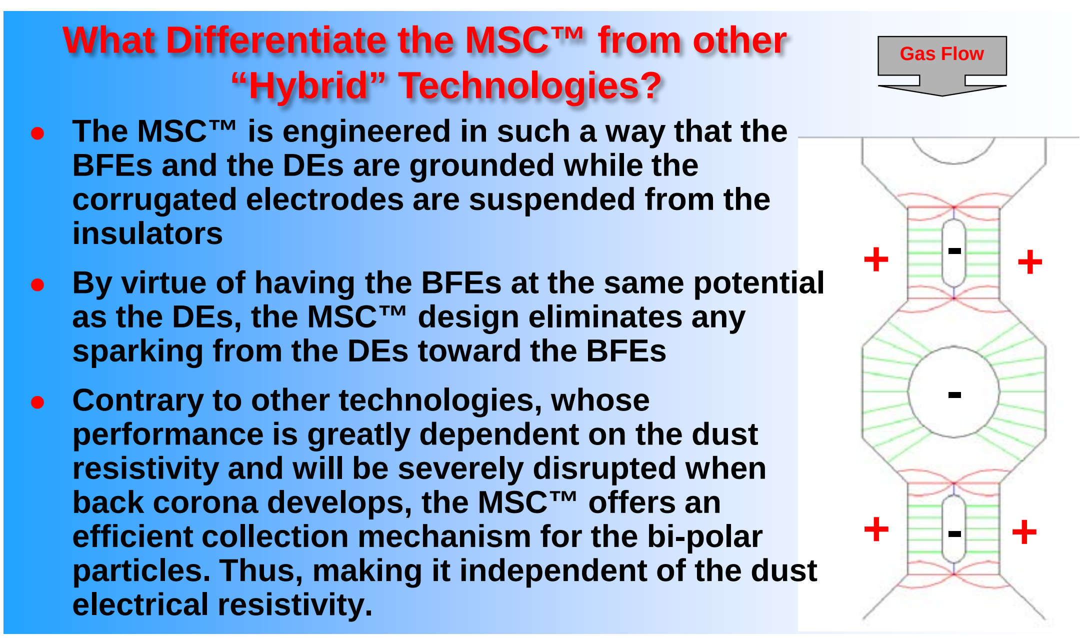


Figure 20. MSC™ Operation - Major Differences

Furthermore, in the event of the back corona, the MSC™ will continue to effectively collect particles of both polarities irrespective of the discharge electrode system polarity (Figure 21).

There, the dust particles, which were charged to negative polarity, will be caught by either the uniform field-forming parts of the DE, or the bags when the collecting electrode charged negatively. Meanwhile, the dust particles near the collecting electrode, which have been charged to a positive polarity by the positive ions resulting from reverse ionization, are conveniently collected by the collection electrode charged negatively (left-hand portion of the Figure 21). In the event when the collecting electrodes are charges positively, the process is reversed (right-hand portion of the Figure 21).

5.0 Summary & Conclusions

The MSC™ by virtue of synergistically incorporating ESP and FF technologies offers significant improvement over the existing technologies.

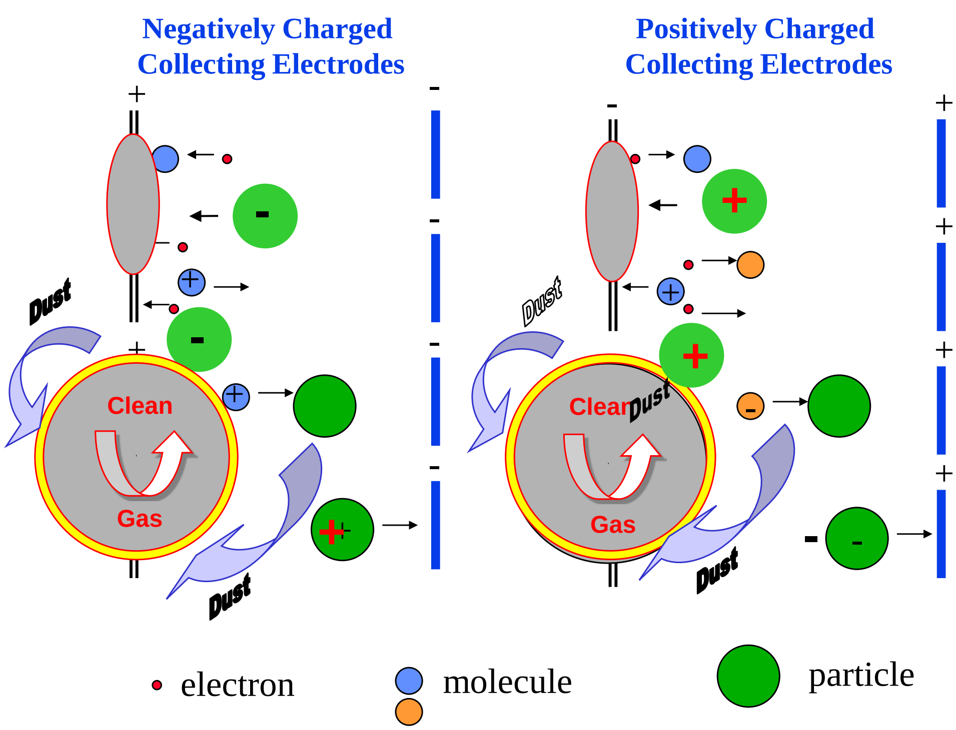


Figure 21. MSC™ Operation - Bi-Polar Particulate Collection

While very large ESPs are required to achieve >99% collection of the fine particles, a small ESP can remove 90% to 95% of the dust. In the MSC™ concept, the ESP plate area (including the surfaces of the BF) would be used to remove approximately 99% of the dust and to sufficiently trap the reentrained dust after bag cleaning. Therefore, the filter area could be held to a minimum to keep the cost reasonable. Very likely, the MSC™ will be able to operate at 20-25 ft/min. At a FV ratio of 16 ft/min, the total plate and fabric collection area would be about 77% less than either the conventional baghouse or ESP. Thus, the MSC™ has significant potential to be much more cost effective than existing technologies. Furthermore, the MSC™

design completely eliminates any potential for sneakage seen in conventional ESPs, since all the flow must pass through the bags.

Additionally, no other hybrid technology is capable to effectively collect the bi-polar charges and charged particulate material. In the MSC™ design where the bags and the discharge electrodes are grounded, there is no danger of the electrical sparking towards the bags, hence, the MSC™ unit should be able to operate at the maximum applied voltage for the best possible fine particulate material charging and collection.

To summarize:

- MSC™ technology offers significant energy-savings.
- MSC™ is suitable for the new installations or as a retrofit replacement technology for existing particulate collectors as well as an add-on retrofit technology.
- MSC™ solves the problem of excessive fine-particle emissions with conventional technologies.
- MSC™ greatly reduces the problem of higher fine particulate emissions from conventional baghouses.
- MSC™ solves the problem of reentrainment and recollection of dust in conventional pulsejet baghouses caused by the close bag spacing and the effect of cleaning one row of bags at a time.
- MSC™ requires significantly less total collection/filter area than conventional ESPs and baghouses.
- MSC™ requires significantly less footprint area than conventional ESPs or baghouses.
- MSC™ overcomes hurdles that prevent operation at high FV ratios.
- MSC™ reduces the applicability problem for ESPs with high-resistivity dusts.
- MSC™ requires significantly less filter surface area than conventional fabric filter.

Finally, the fiber material will offer additional collection mechanisms similar to that described in the research by Alonso, et al [15] as well as Sioutas, et al [16]. The charged aerosol/sub-micron particulate suspended in the high-tension uniform electric field will be forced towards barrier filter surface. Moreover, while on the barrier filter surface, its interaction with the charged fibers of the barrier filter would prevent the barrier filter “blinding” under influence of the uniform high-tension electric field.

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