Optimizing Electrical Precipitators with Multiclone Technology for Particulate Emission Control in Alumina Calcination

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Abstract

Net Zero Emission is on the agenda for many companies over the next generation. Legislation is supporting this goal by tightening emission norms. For particulate emissions, either electrostatic precipitators or bag filters are typically used. More than 13 000 electrostatic precipitators have been installed by Lurgi and its successors worldwide. Several units have also been installed in alumina calcination. However, this application requires special attention, as the particle load to the electrostatic precipitator is extremely high.

With a typical service life of about 20 years for the internal components of electrostatic precipitators, many units are now due for refurbishment - presenting an opportunity to implement improvements. One such improvement is the combination of electrostatic precipitators with multiclones to further reduce particulate emissions. Cyclones, which have no moving parts and feature a simple design, can operate under high temperatures and pressures. However, they involve complex, three-dimensional, highly turbulent two-phase gas flows.

Environmental regulations often allow exceptions during start-up or process disturbances in metallurgical operations. In such cases, applying multiclones enables effective particle separation from the gas stream, even when the electrostatic precipitator is safely de-energized. As a result, the combination of multiclones and electrostatic precipitators has achieved dust emission levels well below current regulatory limits.

All enhancements in particle separation come at the cost of increased pressure drop. Operational constraints, such as design temperature limits, must also be carefully considered.

While other emissions can also be addressed – and some industrial applications already exist – this article focuses solely on the reduction of particulate emissions.

Keywords: Net Zero Emission, Multiclone, Electrical precipitator, Bag filter, Metallurgical process.

1. Net Zero Emission and Development of Particle Emission Limits

The development of particulate matter (PM) limits worldwide is closely linked to the growing awareness of the harmful health effects of particulate matter. These limits vary depending on the region, legal framework, and objectives (e.g., health protection, environmental protection).

In general, the particulate emission limits follow the available technologies and best practices. Below just to illustrate the development we focus on the German standard of TA Luft:

1. TA Luft 1964 (first version):
    - Very general, with hardly any specific limit values for particles.

- Focus rather on "avoiding significant nuisance."

2. TA Luft 1986:
- First specific limit values for total dust.
- Frequent values of 50–100 mg/m^3 for industrial processes.
- Introduction of requirements for separation technologies (e.g., electrostatic precipitators, fabric filters).

3. TA Luft 2002:
- Significantly tightened.
- General limit value for dust reduced to 20 mg/m^3 (for many processes).
- Introduction of differentiated values depending on the type of substance and plant type.

4. TA Luft 2021 (current):
- Further reduction of many values to 10 mg/m^3 or less.
- Introduction of fine dust considerations, e.g. E.g., for PM10/PM2.5 in permit procedures.
- Greater consideration of best available technologies (EU standard) [4]

Particle emission limit standards are different with respect to the country but in general it can be observed that the particle emission limits are decreasing.

Net zero particle emission means that a system, activity, or company as a whole causes no net emissions of particles (i.e., small solid or liquid pollutants in the air). This does not necessarily mean emitting no particles at all, but rather that all emitted particles are offset or avoided through measures so that, on balance, there is no negative impact on the environment.
To achieve net-zero particle emissions, the following three strategies can be used:

a) Avoid emissions
- Use of electrically powered systems instead of diesel- or gas-powered machines
- Use of cleaner raw materials with lower particle emissions
- Process optimization, e.g., lower temperatures or closed systems

b) Reduce emissions
- High-performance filter systems (e.g., fabric filters, electrostatic precipitators)
- Exhaust gas cleaning systems (e.g., cyclones, wet scrubbers)
- Dust binding agents in storage areas and access roads

c) Offset emissions
- Installation of air purifiers around facilities (e.g., "City Trees" or photocatalysts)
- Reforestation near sites for natural air purification
- Investment in CO_2/particle offset projects.

This article will focus on the reduction of emissions via exhaust gas cleaning systems.

2. Exhaust gas Cleaning Systems

To remove particles from exhaust gas streams, cyclones, electrostatic precipitators, bag filters, ceramic filters or scrubbers can be used. The pressure drop for ceramic filters and scrubbers are usually too high for alumina calciner application while the separation efficiency from cyclones cannot reach the ambient emission limits.

Alumina calcination plants with their high exhaust volume stream typically operate electrostatic precipitators or bag filters.

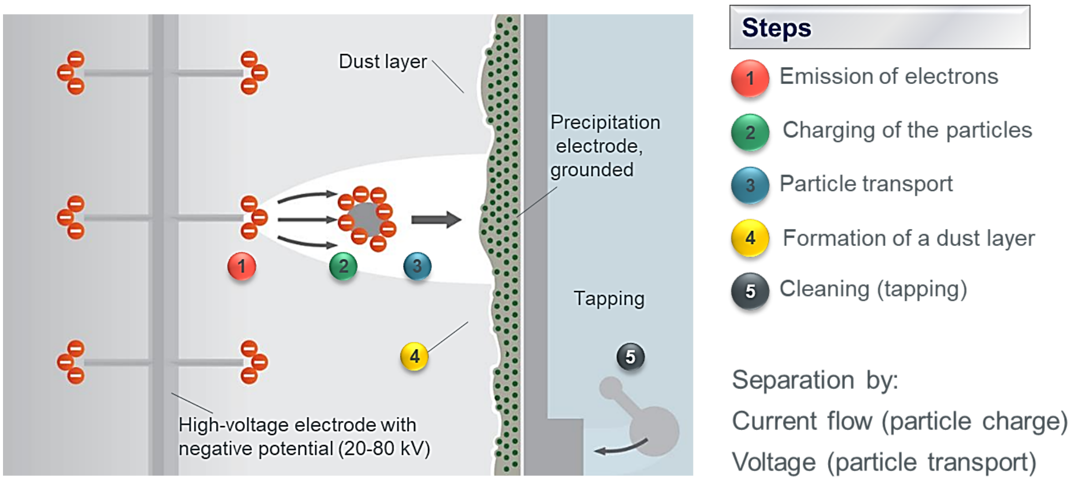

Figure 1. Process principle electrostatic precipitation – individual particle.

Figure 1 describes the separation principle in an electrostatic precipitator. The gas stream is passed through an electric field. In this field, ionization wires generate a high voltage. This voltage leads to the ionization of the gas molecules, the formation of ions and free electrons. The dust particles contained in the gas hit the ions and absorb their charge, leading to them being electrically negatively charged. The dust particles suspended in the gas are electrically charged and migrate under the influence of a strong electric field towards the collecting electrodes where they are deposited. The collecting electrodes are connected to earth via the precipitator casing. The discharge electrodes are suspended from insulators and have negative polarity. They carry a D.C. voltage ranging from 20 kV to more than 80 kV depending on the precipitator design and the application. In the immediate vicinity of the discharge electrodes corona discharges are produced due to the high field strength and electrons are set free. The negative gas ions produced charge the dust particles which migrate under the influence of the electric field towards the collecting electrodes, where they release part of their charge and are captured. The charged particles are attracted to the plates by the electric field and settle there. The collector plates are regularly freed of dust layers by tapping or shaking. The detached dust falls into collection containers and can be disposed of or further processed.

Figure 2 shows the process principle for bag filtration. Dust-laden gas flows through the filter mesh. The gas containing the dust particles is passed through filter bags or hoses made of a special fabric. The fabric acts like a sieve that retains the particles. The particles are retained in different ways:

- Sieve action (direct separation): Large particles are trapped directly in the mesh.
- Inertial force: Heavier particles collide with the fibres because they cannot follow the gas flow.
- Diffusion: Very fine particles (e.g., less than 0.1 µm) move by Brownian motion and randomly encounter the fibres.

Over time, a layer of dust forms on the fabric. This dust cake increases filtration performance because it acts like a filter itself; however, it also increases pressure drop. To prevent clogging, the filter is cleaned regularly, in this case here by a compressed air blast (jet pulse cleaning): Short bursts of air blow the dust from the inside out. The detached dust falls into a hopper and is collected there.

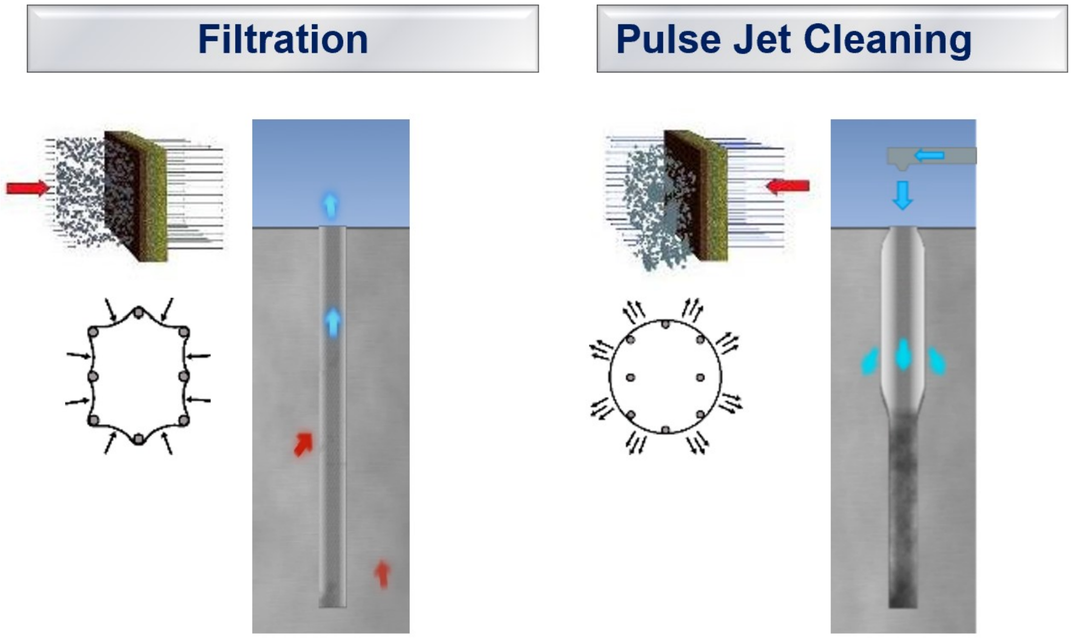

Figure 2. Process principle. Left: bag filtration, right: pulse jet cleaning.

Table 1. Comparison of electrostatic precipitation vs bag filtration.

	Electrostatic precipitation	**Bag Filtration**
Maturity of the technology	Very high	Very high
General aspect	Electrical gas cleaning is based on electrical forces. The system is open in the gas path and reacts with increased dust emissions if physical parameters deviate from the design.	Dust separation on filter media. Clean gas is largely safe, provided hoses are intact. Dust layer can clog under unfavourable conditions, increasing pressure loss, and cleaning is irreversible.
Pressure Drop	2–4 mbar	8–16 mbar; Irreversible increase in pressure loss in case of dense dust.
Stability	All components extremely stable	Bag materials sensitive to wear, damage possible through frequent cleaning (pressure surges)
Temperature	With appropriate design, gas temperature up to approx. 450 °C in continuous operation	The temperature resistance of the filter media is limited to approximately 220 °C. Filter media then becomes very expensive.
CAPEX	Similar	Similar
OPEX	Components in the electrostatic precipitator are more stable and durable	Higher for the bag filter due to pressure loss. If the bags are damaged, they must be replaced.

Above table shows the difference between bag filter and electrostatic precipitation. It should be noted that the bag filter can be operated also in conditions when the gas mixture leaving the calcination plants might be potentially flammable, while at an electrostatic precipitator the current needs to be switched off. As a result, the peak emission of a bag filter is lower than of an electrostatic precipitator. Due to its lower OPEX Electrostatic Precipitators have been the widely chosen particle gas cleaning method for alumina plants.

3. Electrostatic Precipitators Upgrades

Walther Deutsch developed in 1922 his equation describing the separation efficiency of electrostatic precipitator [1]:

$$\eta = \frac{c_0 - c}{c_0} = 1 - e^{-w\frac{A}{V}} \tag{1}$$

where:

c_0	inlet concentration
c	outlet concentration
w	migration velocity
A	precipitation area
V	gas volume stream.

Above Deutsch Equation (1) can be further refined by applying correction factors for deviating gas and solids properties. With such correction factors, the positive effect on the separation efficiency of increasing sulphur and ferrous oxide content can be depicted. Such elements can come from burning of heavy fuel oil depending on its sulphur content and from hydrate entering the calcination process with ferrous contaminations. The migration velocity can be increased by raising the voltage.

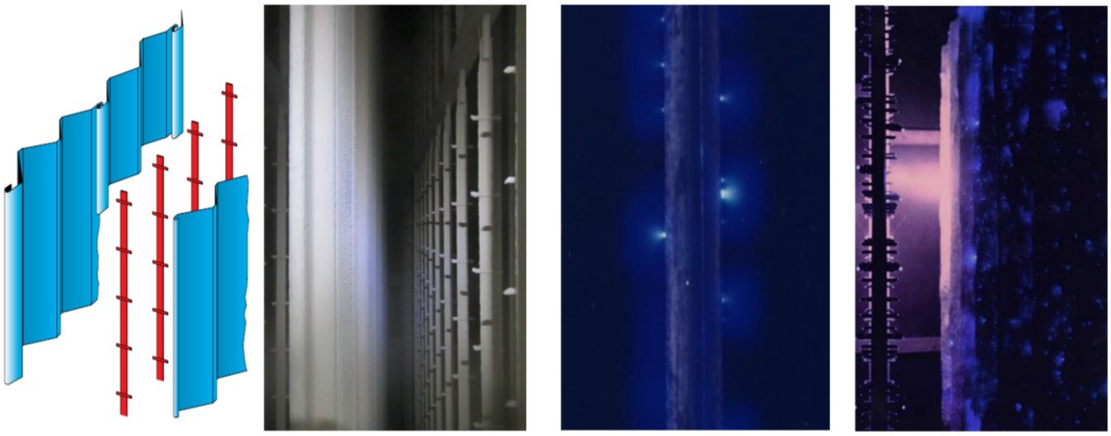

Figure 3. Plate and Electrodes schematic, installed picture, Corona spray discharge, Corona discharges and electrical short cut.

In Figure 3, the schematic installation of the separation plates and charging electrodes is shown the first panel while the next panel shows the real-life picture of such an installation. The normal operation with its spray discharge is shown in the third panel while the corona discharges with the electrical short cut is pictured in the last panel. To improve the separation efficiency and put it to its optimum, the voltage should be kept just below it electrical short cut. This is usually done with a control system.

The corona power is the product of the arithmetic mean values of the filter voltage (Uf) and the filter current (If). A first possible upgrade addresses the regulation system. Due to the circuit design, W1C single-phase or W3C three-phase thyristor systems result in current gaps and ripple in the filter voltage. Thanks to the very short IGBT (Insulated Gate Bipolar Transistor) switching times (10 µs) and the inverter frequency of 60 Hz, the 50 Hz/60 Hz HV rectifier unit generates a virtually smooth output voltage, regardless of the operating point.

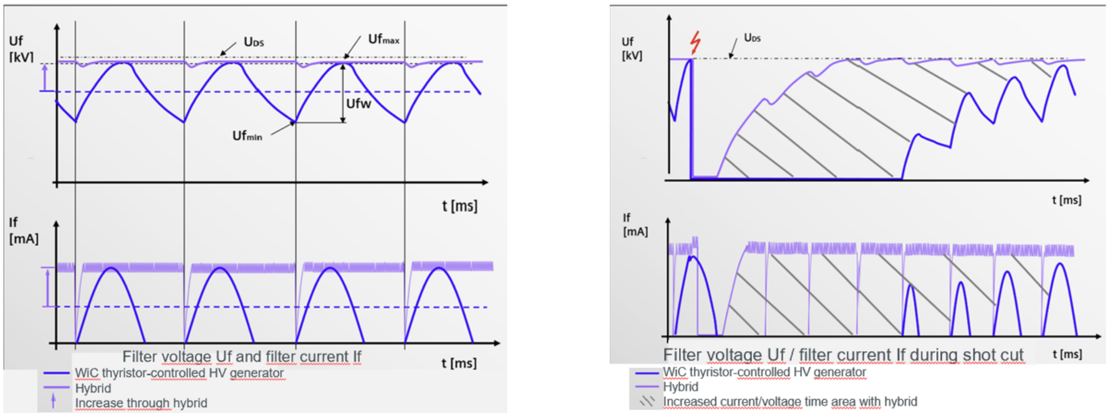

Figure 4. Filter voltage (Uf) and filter current. Left: normal operation, Right: short cut condition.

As a result, Hybrid, which is the combination of the IGBT and the existing transformer, can increase the average filter voltage and filter current up to its peak value. Compared to thyristor technology, experience has shown that the corona power is more than doubled. The filter voltage and thus the filter current are limited when the breakdown voltage U_{DS} is reached, and discharges occur between the discharge and precipitating electrodes.

Due to the very short switching times and fast current regulation, the short-circuit current is significantly lower than with thyristor technology and is switched off within a few microseconds.

As a result, a significantly shorter deionization time is required for non-self-extinguishing discharges (breakdown), and the previous operating values are reached again within a few milliseconds. Detected self-extinguishing arc flashovers are processed without deionization time. As a result, Hybrid leads to a significantly higher filter separation efficiency, especially in breakdown operation, which is not only for all gas inlet fields of the electrostatic precipitator.

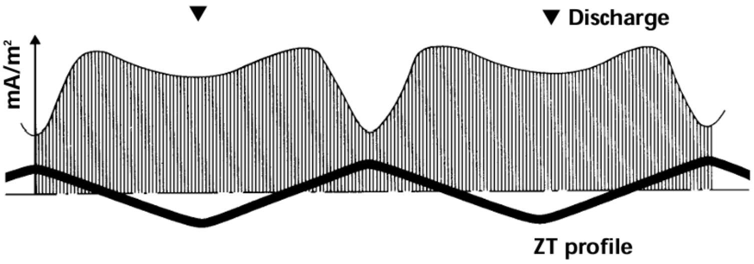

Figure 5. ZT collecting plate profile from Lurgi as seen from above and current density distribution.

Figure 5 shows the current distribution in the standard Lurgi ZT profile. The current distribution follows the profile shape. This illustrates the importance of detailing the shape and distances of the electrodes in an electrostatic precipitator. This profile avoids local voltage peaks and thus maximum flashover voltages are attainable, especially in retrofit applications, such details should not be overlooked. It can be seen as another type of potential upgrade where the collecting electrodes can be optimized to achieve uniform current distribution.

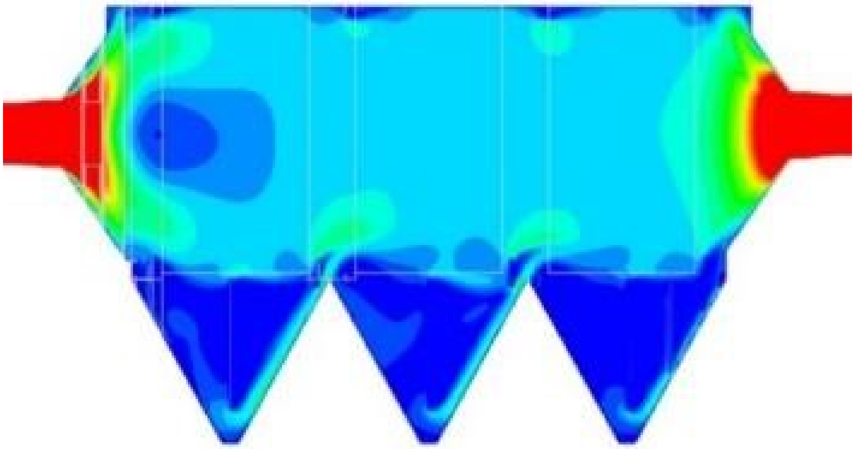

Figure 6. Velocity Distribution in an electrostatic precipitator.

Dividing in Equation (1) the gas volume stream with cross sectional area results in the gas velocity in the electrostatic filter, which should be about 1 m/s. As a general rule, the gas velocity should be uniform in the whole electrostatic filter, avoiding turbulence, back flows or localized high velocities. Figure 6 illustrates an accelerated gas stream at the hopper, which will lead to re-entrainment of particles and also to a reduction of separation efficiency. Therefore, great care must be taken with respect to the gas flow in the electrostatic filter. The identification of the correct particle dust load entering the electrostatic filter is of upmost importance since the particle load dominates the gas stream field. Particle load in cyclones [2] also dominates the separation and flow pattern due to high impulse the particles have in relation to the gas stream.

Equation (1) also shows that the outlet concentration of an existing electrostatic precipitator can be decreased by reducing the inlet concentration. The inlet concentration to an existing electrostatic precipitator can be effectively reduced by a multiclone. Furthermore, multiclone design can be done quite efficiently for smaller particle sizes.

4. Multiclones in Alumina Calcination

Alumina calcination presents a particularly challenging scenario for particulate emission control. Calciners – whether of the Circulating Fluid Bed (CFB) or gas suspension type – emit large volumes of fine alumina particles in hot off-gases. Traditionally, electrostatic precipitators (ESPs) or fabric filters have been employed as the primary dust collectors on calciner stacks. Many legacy systems, such as those at Alcoa's refineries in Western Australia, were originally fitted with ESPs when emission limits were relatively lenient.

As environmental regulations tightened, the alumina industry increasingly adopted multiclone pre-separators upstream of ESPs to improve performance. A notable example is the retrofit at Alcoa's Kwinana refinery, where each calciner was equipped with a multiclone in series with an ESP [3, 5]. The multiclone captures the majority of coarser alumina dust before the gas reaches the ESP, effectively reducing the inlet dust concentration. According to the classical Deutsch equation, this reduction significantly lowers the ESP's outlet emissions for a given size and configuration.

In practical terms, this hybrid configuration – multiclone plus ESP – has enabled alumina plants to consistently achieve stack dust levels well below regulatory thresholds, even as standards have become more stringent. As shown in Figure 7, multiclones are also capable of separating some of the finer particles, further enhancing system performance.

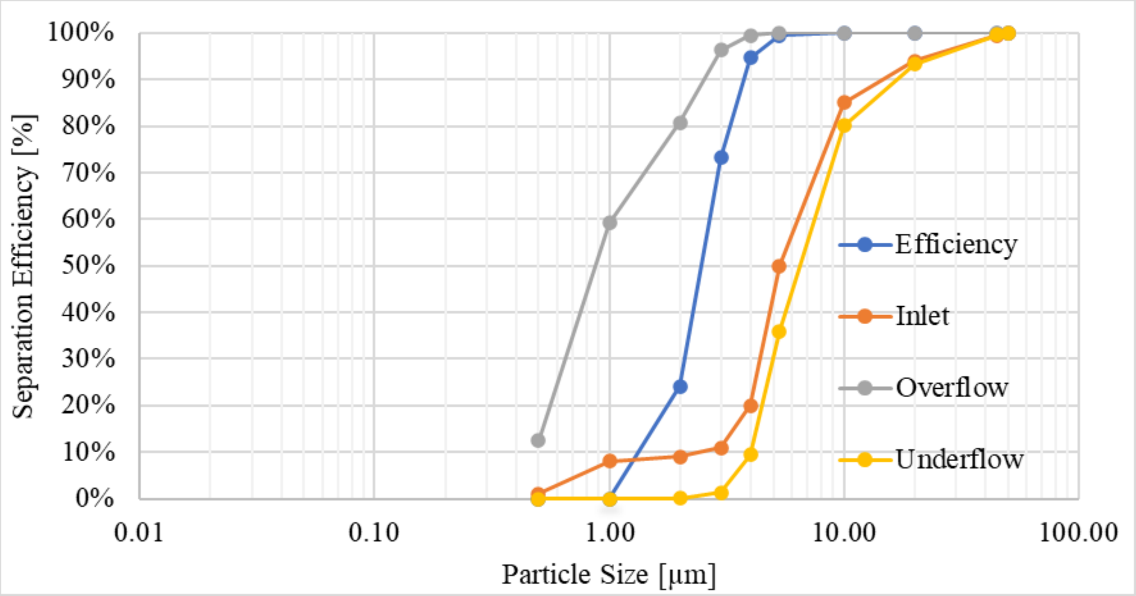

Figure 7. Efficiency for a multiclone.

4.1 Dust Removal Efficiency and Operational Gains

Multiclones are highly effective at removing coarse particulate matter. U.S. EPA studies show single cyclones can achieve capture efficiencies between 58 and 97 %, depending on particle size and gas conditions. In multiclone assemblies, overall efficiency reaches approximately 85–94 % for particles in the 15–20 µm range. While sub-10 µm particle removal is more challenging, well-designed systems still collect a significant portion of these fines [2].

By pre-cleaning the gas stream, multiclones reduce both mass loading and alumina losses to the ESP. The result is improved ESP reliability and total system effectiveness. Coupled systems routinely achieve overall particulate removal efficiencies exceeding 99 %, corresponding to single-digit mg/Nm^3 stack dust concentrations – an improvement over older ESP-only configurations, particularly during peak load or upset conditions.

4.2 Reliability During Start-ups and Transient Events

One of the most valuable features of multiclone systems in alumina calcination is their passive functionality during start-ups or process malfunctions. ESPs often need to be de-energized under such conditions to prevent sparkovers or protect internal components, resulting in unfiltered emissions. In contrast, multiclones continue to operate mechanically without interruption. This ensures partial dust capture and significantly reduces peak emissions during transient events, as confirmed by operator reports.

Given that many modern environmental regulations, particularly in the EU, mandate continuous emission control, multiclone pre-separators serve as a critical safety net. Their inclusion ensures that even during upset conditions, emissions remain within permissible limits or are at least substantially reduced.

4.3 Process Integration and Ancillary Benefits

From an operational standpoint, multiclones also offer additional process advantages. Since they function as dry collection systems, the captured alumina fines can often be recovered and reused. In certain calciner designs, the multiclone underflow is directly recycled into the process, improving material yield and minimizing waste. In fact, the installation of multiclones has rendered some pneumatic lifting systems obsolete, simplifying solids handling infrastructure and reducing maintenance.

However, these benefits come with a pressure drop penalty, which must be considered in the overall system design. Multiclones introduce flow resistance, requiring sufficient fan capacity and careful integration to avoid upsetting gas flow distribution into the ESP. When properly designed, these constraints are manageable and outweighed by the gains in emission performance and reliability.

4.4 Retrofit Applications and Standards Compliance

The multiclone has proven particularly valuable in retrofit scenarios, where upgrades to existing calciner trains are needed to comply with more stringent dust limits. As illustrated in Figure 8, multiclones can be effectively retrofitted upstream of fluidized bed calciners, in combination with existing ESPs, to meet modern emission standards.

This strategy not only improves environmental compliance but can also yield operational cost savings and simplify process flow. Overall, multiclone technology represents a robust and scalable solution for alumina calcination plants striving to achieve net-zero particulate emissions.

Figure 7 shows the efficiency of a multiclone, demonstrating that smaller particles are effectively separated.

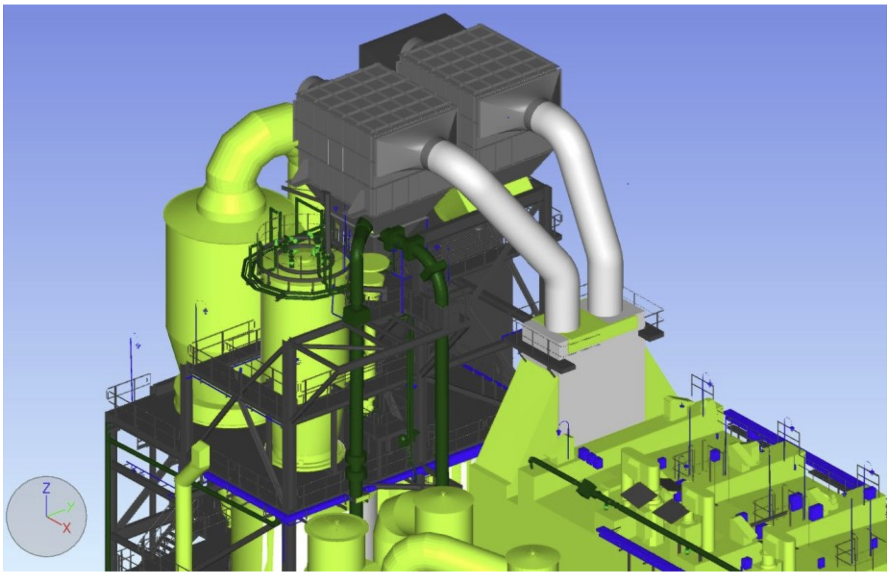

Figure 8. Multiclone retrofit to an existing fluidbed calcination plant.

5. Conclusion

Environmental standards are getting more and more stringent, driven in part by technological advances in gas cleaning. Different gas cleaning systems have been compared, with a special focus given to bag filtration and electrostatic precipitation since such systems are primarily used in alumina calcination and refineries.

The performance of electrostatic precipitation was discussed with respect to upgrade possibilities to comply with new standards. The increase in corona power and / or the installation of multiclones can help to reduce the particulate emission. Equally important is maintaining the original design functionality of the electrostatic precipitator, especially regarding the gas flow dynamics. While the working principle for electrostatic precipitators has been known for more than 100 years, its execution and details hold plenty possibilities for deviation from optimal performance, which can lead to increased particulate emissions.

6. References

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