# DESIGN, INSTALLATION AND TRIALS OF AN INDUSTRIAL-SCALE PROTOTYPE OF A HIGH-EFFICIENCY ELECTROSTATIC PRECIPITATOR FOR CAPTURING PARTICULATES IN FRIT MELTING KILNS

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## 1. ABSTRACT

*This paper sets out to present the results and conclusions of the building, installation and running of an industrial-scale prototype of a high-efficiency electrostatic prototype for capturing particulate solids at the tail of a continuous frit-melting kiln.*

*The paper consists of the following points:*

- *General description of the problem.*
- *Setting the design parameters (specifications, etc.).*
- *Solutions adopted and explanations for the solutions.*
- *Test strategy.*
- *Analysis of the results obtained.*
- *Conclusions.*

## 2. GENERAL DESCRIPTION OF THE PROBLEM

In the frit-melting process in continuous fritting kilns, owing to process conditions and kiln construction characteristics, exhaust stack emissions are produced characterised by a large quantity of suspended particulates and the presence of gaseous compounds. On tackling the study of an emission abatement system, two main lines of actions can be considered: suppressing the production of emissions by changing kiln design or designing filtration systems that can be fitted in the emission exhaust path, or a combination of both.

The first course of action requires a long-term approach, involving a considerable research effort, and given the current structure of the sector, it would not be applicable to the existing facilities.

The second approach is of doubtful effectiveness, if the design constraints require developing a system that will yield wholly adequate emissions, as from a technical point of view, it would be impossible to ensure required functioning with fixed specifications independently of working conditions.

The only way to tackle the problem, with some assurance of effectiveness, stability and acceptable cost, is based on setting step-wise targets. The ultimate objective is to achieve adequate emissions, in accordance with all the parameters that need to be improved, by acting progressively in terms of the priorities and availability of proven technologies.

In accordance with this approach, the first objective is to reduce the solid particulates in the gases to values that enable complying with current regulations, as well as with the more restrictive regulations that will ineluctably become enforceable in the medium term. After achieving and validating this objective, actions can be undertaken on the compounds in the gaseous phase.

## 3. SETTING THE DESIGN PARAMETERS

The system is to be designed in accordance with certain constraints and specifications, given by process conditions, end user criteria, technologies, etc.

### 3.1 STARTING CONSTRAINTS:

By design starting constraints are meant all those features that can be demanded of the facility, which do not depend directly on process conditions, and which the system builder must establish a priori and hold throughout the design, building and service. The following constraints need to be taken into account:

- Functioning: the system to be installed shall run without interfering with the kiln's own regulating systems.
- Costs: implementation, operation and maintenance costs shall be as low as possible, individually and overall.

- Reliability: the system's operating reliability shall approach 100%. This constraint requires starting and stoppage processes to be as short as possible.
- Use: operating complexity shall be minimum.
- Size: system size shall be maximally optimised.
- Location: the positioning of the system shall not impede normal kiln maintenance operations or that of directly related systems.

## 3.2 SPECIFICATIONS:

By specifications are meant all the parameters that define operating conditions and desired system performance. Most of these are set by the kiln owner, and after being accepted by the system builder, need to be met in the installation, thus verifying the proper functioning of the system.

Setting fixed specifications is practically unfeasible, owing to the wide operating range and diversity of products that are processed in fritting kilns.

The best way to establish specifications in these cases is by agreement between the owner and the system builder, setting maximum emission levels that reflect that actual state of the regulations and foreseeably applicable values. Subsequently, extreme kiln operating conditions need to be evaluated, and the most unfavourable foreseeable conditions chosen, to determine required minimum output.

Using this approach, increasing the extreme values for greater security, the following exhaust gas conditions were set:

- Temperature: between 250°C and 550°C.
- Flow rate: 7000 $Nm^3/h$.
- Solid particulate content: 3000 mg/ $Nm^3$.
- Solid particulate content after cleaning: < 30 mg/ $Nm^3$.

These data yield the following filter design specifications:

- Output:

$$\eta = \left(1 - \frac{30}{3000}\right) \bullet 100 = 99\%$$

- Flow rate:

$$C = 7000 \bullet \left(\frac{550 + 273}{273 + 20}\right) = 19662 \text{ m}^3/\text{h a } 550^\circ\text{C}.$$

## 4. SOLUTIONS ADOPTED AND EXPLANATIONS FOR THE SOLUTIONS

The design of the facility consisted of an electrostatic precipitator and its connecting fittings to the kiln exhaust stack, together with the whole system's controlling software.

After establishing the specifications and constraints, precipitator configurations were sought that would yield optimum output. By configuration is meant the adjustment of the parameters (inter-electrode spacing in a field, electrode design, field lengths, inter-field spacing, number of fields, type of corona, etc.) affecting precipitator operation.

Before entering into detail in studying the configurations, the precipitator cross section was established on the basis of the specifications, and the number of electrical fields and required efficiency were estimated:

The gas volume to be treated enabled establishing the cross-sectional area of the precipitator, as for the precipitator to be effective, a gas throughput rate was needed in practice of between 0.8 and 1.8 m/s.

The specified precipitator output provided the necessary information to set the output per field, determine the required number of serialised electrical fields or establish the number of fields, determining the output required per field. As a first approximation, it was assumed that each field would have a certain collection efficiency ε and would allow a particle fraction δ through, where:

$$\delta = 1 - \varepsilon$$

For a number n of serialised fields, the output is:

$$\eta = 1 - \delta^n$$

Rearranging and combining the foregoing equations gives:

$$\varepsilon = 1 - \sqrt[n]{1-\eta}$$

The precipitator to be designed would consist of three serial fields, with a necessary effectiveness per field of:

$$\varepsilon = 1 - \sqrt[3]{1 - 0.99} = 0.7845 \rightarrow 78.5\%$$

The following equation, known as the extended Deutch equation, allows estimating the output of an electrostatic precipitator with a given configuration:

$$\log(1 - \varepsilon) = \log(1 - \varepsilon_g) + C\alpha dV^2$$

where:

- $\varepsilon$ : efficiency
- $\varepsilon_g$: efficiency at the corona-effect point
- $\alpha$ : collector specific surface area
- d : particle mean mass diameter
- V : electrostatic field potential
- C : constant mainly depending on temperature, type of particulate solids, and filter configuration.

From the foregoing equation it can be inferred that electrostatic precipitator output is affected by the following features, which need to be taken into account in the design:

- Particle size: The particulates contained in the gases obviously have varying sizes, ranging between the maximum and minimum limits of a size distribution. For this reason, mass mean diameter is used in the above equation, which corresponds to the diameter in the particle-size curve above or below which 50% of the particles are found. On keeping all the parameters constant that affect precipitator output except for particle size, precipitator output rises with increasing particle size.

- Temperature: Temperature has a very important effect on electrostatic precipitator output. It also affects other parameters by its multiple relations, and each needs to be assessed:

  - Effects relating to gas temperature: As gas viscosity rises with temperature, the forces drawing along the particulates increase, making it more difficult to separate these from the gaseous stream, so that precipitator output decreases with temperature if the other parameters are held.

  - Effects related to particle temperature: Raising temperature entails a rise in the particle dielectric constant. This in turn raises precipitator output. Temperature changes can also have an appreciable positive or negative effect on the tendency of particles to agglomerate, thus also affecting output.

  - Electrical effects relating to temperature: The intensity of the field required to produce the corona effect (and hence the necessary potential) is directly related to gas density according to the square law. Thus, with a rise in temperature, the value of the potential needed to set off the particle charging mechanism drops considerably. Moreover, as the rise in temperature increases gas molecule kinetic energy owing to thermal agitation, charge transfer improves at lower potentials, yielding improved precipitator output.

It follows from the foregoing, that electrostatic precipitator output cannot be considered an absolute value, but needs to be understood as a function that depends on a series of parameters. Thus, electrostatic precipitator design involves assessing different configurations in different conditions, to enable verifying the combinations that yield the best efficiencies.

In order to keep precipitator design costs and time within acceptable limits, the design stage needs to be structured on the basis of a simple model, successively increasing the complexity of the design. This made it necessary to follow the design cycle detailed below, which sets out the features to be examined or controlled at each step.

First, a series of numerical simulations was performed to allow selecting the configurations that could a priori be expected to provide the most appropriate output and stability for the application. However, the great number of parameters that affect precipitator output means that precipitator behaviour can only be estimated in general lines with this type of simulation.

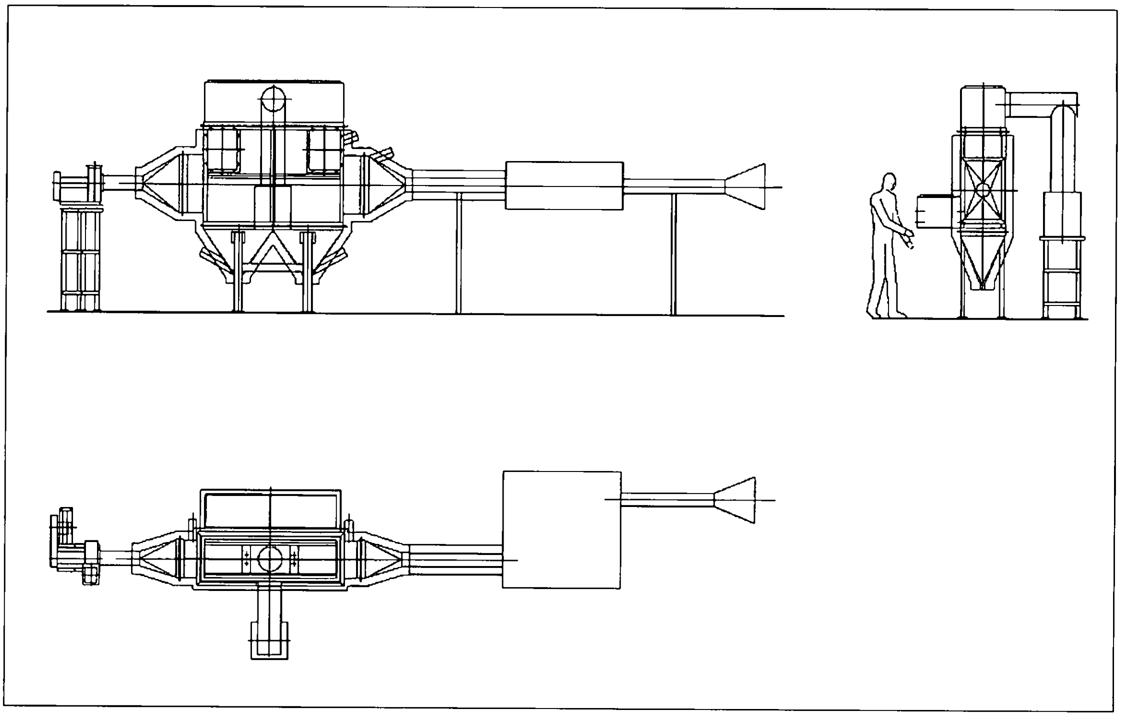

*Figure 1.*

A first numerical simulation, only taking into account electrostatics equations, enabled predicting electrode shape and distribution. Adding fluid dynamics equations and relating the effects of both then allowed estimating required field minimum length.

With the results of the simulation, a scale-model could be built with sufficient assurances to first of all enable verifying the similarity between the numerical results and the experimental ones. The choice of model building scale is no trivial matter and must be made keeping in mind that the resulting electrical, physical and chemical measurements data need to permit extrapolation.

It was decided to a build a model on a 1/10 geometrical scale, to have similar flows and perform the measurements under identical conditions to those of the actual prototype.

The trials to be run on the model were divided into two parts, workshop trials and *in situ* trials.

The workshop trials were designed to verify the correlation between the numerical simulation and the model, optimising the mechanical design of the supporting structure and fastening of the electrodes, as well as electrode design, to ensure keeping their dimensional stability in temporary temperature changes, and performing materials selection tests (thermal, mechanical characteristics, etc.).

The in situ trials were designed to quantify field retention efficiency under a variety of temperature conditions and different particle compositions and concentrations. Another very important feature to be controlled in this type of test was particle aggregation phenomena at the electrodes, while also evaluating the potential problems of semi-melted particles sticking to the electrodes.

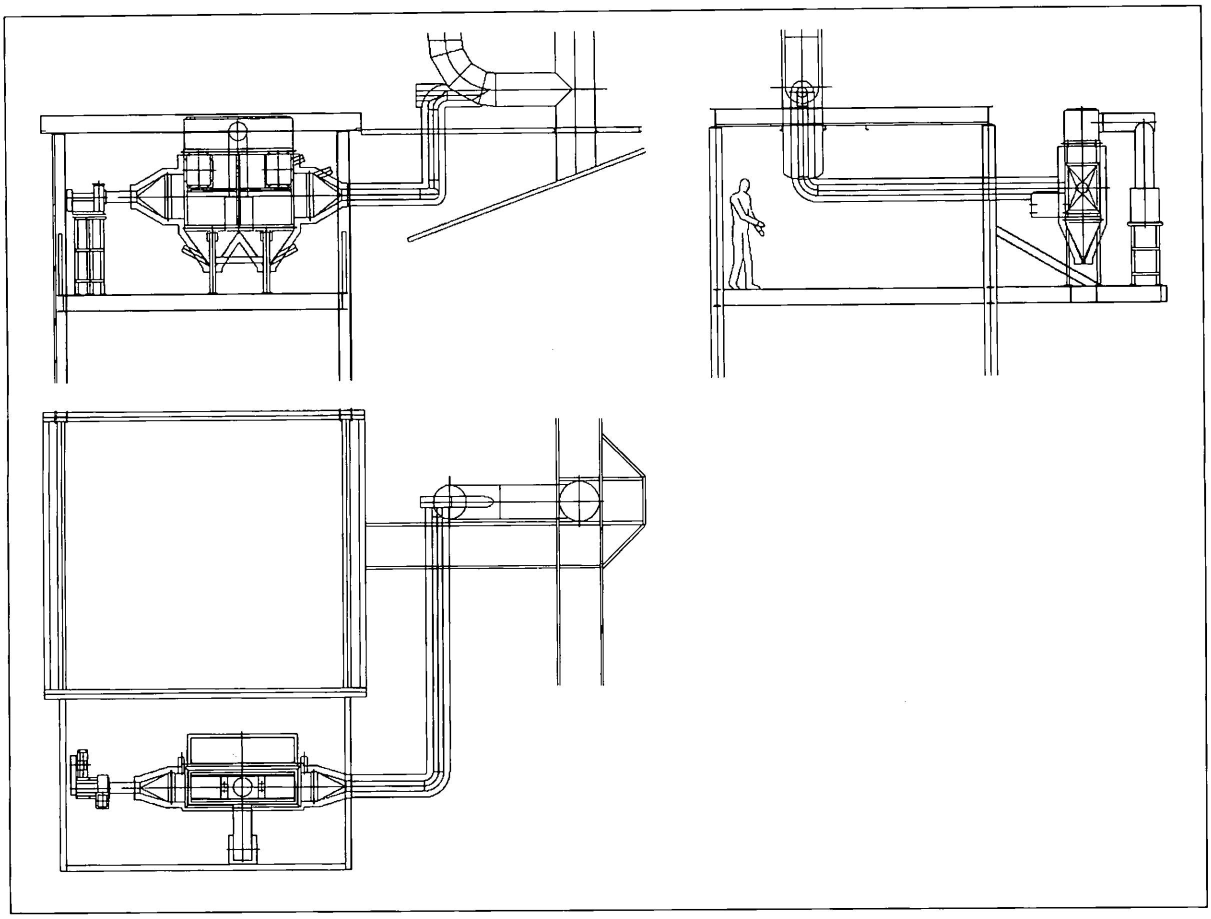

*Figure 2.*

After detailed analysis of the data obtained in the two foregoing stages, the true scale design of a precipitator prototype could be tackled, together with the necessary installation, equipping this with all the monitoring and analysis systems needed to enable verifying the facility's proper functioning under any kiln working condition on an industrial scale.

## 5. TEST STRATEGY

*5.1.- Numerical simulations:* Given the great complexity of the algorithms used in the calculations and the specific character of this stage, going into these in detail goes beyond the scope of the present paper. However, abundant references can be found in this regard in the literature.

*5.2.- Workshop trials with the model:* Figure 1 illustrates the assembly used in the workshop study. It consists of the installation of a hot-air generator, made up of an adjustable burner, fresh air mixing zone, a holding box and connecting duct fitted to the model inlet and a tail draw centrifugal fan controlled by a frequency regulator. The instruments fitted to control the gas parameters were thermocouples, Pitot tubes, and micro pressure gauges, for the electrical signals, a digital capturing oscilloscope and accurate efficient true value multimeters. The trials basically consisted of determining the electrical parameters at different temperatures and flow rates, and testing the mechanical behaviour of the precipitator by subjecting it to different temperature gradients, in both cases in steady and unsteady states.

*5.3.- In situ trials with the model:* The set-up used for the in situ trials involved mounting a provisional platform next to the existing structure on the kiln hall roof at Johnson Matthey, as shown in Figure 2. An air intake port was fitted in the duct connecting the kiln stack and the model, using a dilution valve. The connection between the systems (field controller, centrifugal fan frequency regulator and control computer) and the control computer position was made with a PROFIBUS DP network.

Besides using the systems mentioned in the foregoing section, the instruments used for the trials included the systems required to determine field output. Given the difficulty of performing isokinetic extractions in the assembly, it was decided to use the following procedure based on opacimetry:

The reduction in the intensity of a light source with a known value, on crossing a zone containing suspended particulates is expressed according to Lambert's law:

$$I = I_0 \bullet e^{-kxc}$$

where:

- I : Received light intensity
- $I_0$ : Source light intensity
- k : Constant depending on particle characteristics
- x : Optical distance
- c : Particle concentration in the optical path

The I to $I_0$ quotient is known as the transmittance, and is a value provided by opacimeters. Rewriting the foregoing equation gives:

$$\Theta = \frac{I}{I_0} = e^{-kxc}$$

If two opacimeters are positioned, one at the precipitator inlet and the other at the outlet, with the same optical distance, two transmittance readings will be obtained:

$$\Theta_s = e^{-kxc_s}$$

$$\Theta e = e^{-kxc_e}$$

Applying logarithms and relating these two equations gives:

$$\frac{\ln \Theta_s}{\ln \Theta_e} = \frac{-kxc_s}{-kxc_e}$$

As parameters k and c are eliminated, a relation is left between incoming and exiting concentrations, i.e., system output. Hence:

$$\eta = \frac{\ln \Theta_s}{\ln \Theta_e}$$

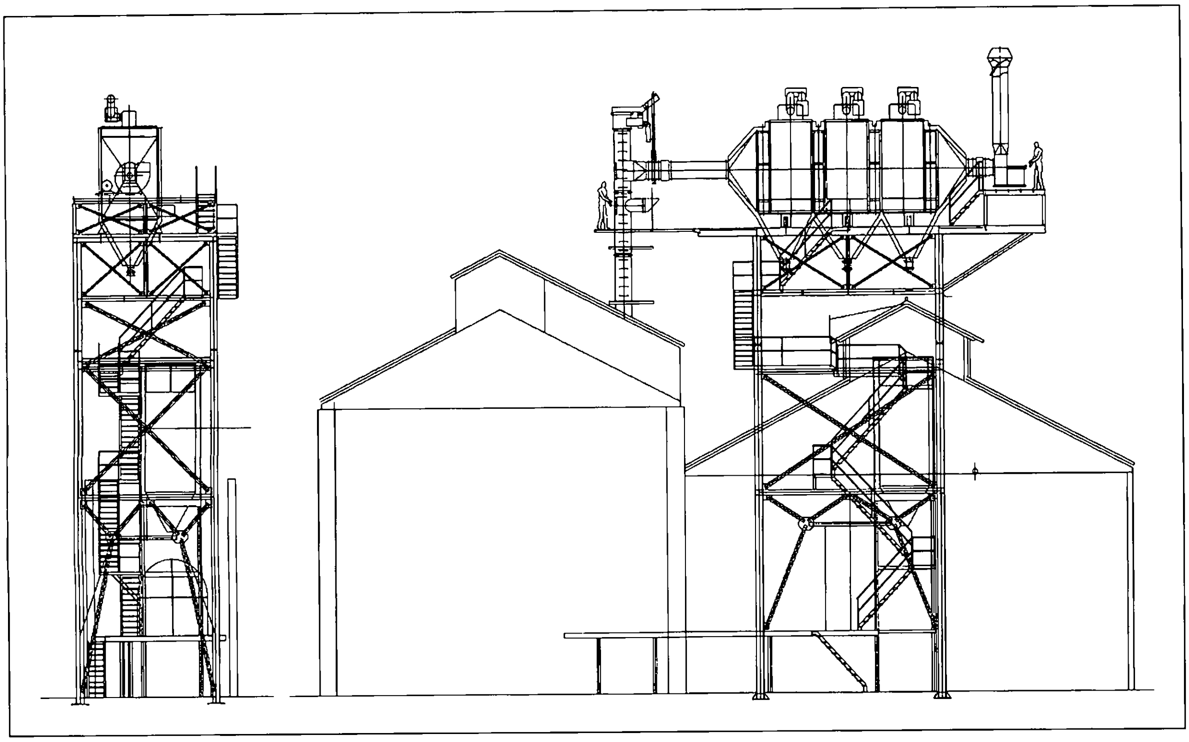

*Figure 3.*

Taking the measurements of both systems and deriving the quotient allows reliably finding the output value.

5.4.- *Prototype trials:* The prototype facility built is shown in Figure 3. In this facility great care has been taken to provide easily accessible inspection and sampling points. The systems are installed in such a way as to facilitate maintenance work on the actual recovery facility and on the associated kiln.

The possibility is also provided of collecting and weighing the waste near the kiln feeding system, to facilitate eventual reuse of the collected waste, if this is shown to be feasible.

The following tests will be run on the prototype, after installation:

5.4.1.- *Physical tests:* These are designed to study the mechanical and electrical behaviour of the precipitator, as well as verifying its operation. This part also includes the tests designed to study particle agglomeration and sticking.

5.4.2.- *Chemical tests:* owing to the probable relationship between kiln operating parameters and the type of frit being produced with emission characteristics, chemical analyses will be performed on the waste collected in the precipitator and on the gases exiting the precipitator, with a view to establishing possible relationships and improvements.

## 6. ANALYSIS OF THE RESULTS OBTAINED

Analysis of the workshop trials highlighted the need to make certain changes in the electrodes and in their fastening system to be able to reduce the model's heating and cooling times, without producing temporary or permanent deformations in the electrodes. Field stability also needed improving, while quite an acceptable correlation was found between the measured data and the data predicted by simulation.

The in situ trials with the model showed that the fields were correctly sized, as the measured efficiencies in most cases exceeded the expected efficiency for most of the tested frits. An incidental case was found in which the output was very close to the required minimum, so that it was decided to slightly increase prototype size. With regard to the analysis of the particulates collected in the model, when particle agglomeration occurred it favoured electrode cleaning, and when semi-solid particle sticking was found, everything indicated that the problems would not be hard to solve. In order to facilitate the operation of the prototype to be built, it was decided to integrate a database in the control software with adjustment points of the whole system, so that the system self-adjusted to optimum values for each product to be made. This characteristic is to be highlighted as it eliminates most of the errors that can endanger the integrity of the systems.

With regard to the electrical measurements, the electrical power consumed by the field was established. This value enabled sizing the prototype's installed power. Furthermore, the high immunity to electromagnetic interference was confirmed of the PROFIBUS DP industrial communications network as well as the simplicity of maintenance.

As regards the trials with the actual prototype, at the moment this paper is being written, only the trials performed in the workshop during the adjustment phase and field verification are available, which have been highly favourable.

## 7. CONCLUSIONS

Given the approach used in this paper, the conclusions relate to the characteristics of the designed facility and not to the results. However, we realise that it is of great interest to include real operating details, and though sufficient data are currently unavailable, actual data will be presented during the delivery of the paper.

In the absence of data on the continuous operation of the installed prototype, the available results appear to indicate that precipitator operation is highly stable, exhibiting notable advantages compared to systems based on filtering textile elements, both with regard to operating cost and maintenance, at a comparable purchasing cost.

It thus emerges from an analysis of the specifications and constraints, that a cleaning facility has been built, which is adequately sized to ensure problem-free service, while special attention has been paid to offering the end user a system that is easy to handle and maintain.

As indicative data, while awaiting actual facility consumption figures, it may be stated that the installed operating power per field for field operation is 3kVA, estimating an average real mean consumption of less than 50%. The installed electrical powder for the draw centrifugal fan is 15 kW, with an estimated maximum consumption of 75 %.

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