Flue Gas Treatment by ESP: Realization and Optimization of an Emissive Electrode

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Abstract—Electrostatic precipitators (ESPs) are widely used in industries to remove fines particles contained in flue gases and to prevent health diseases. This study was inspired by the need to replace, because of industrial constraints, an active emissive electrode called “Heritrode” previously developed, by a new emissive electrode (NE). In order to design this one, electric field modelling and experimental results are conducted. We will investigate the ESPs efficiency of the new electrode by studying the collection efficiency, the impact of different dust and by conducting voltage tests, in order to have the better managed in an economic and efficient way. Experimental tests are carried out on a single stage pilot located in the SIAME laboratory to perform the filtration efficiency of the new electrode.

Keywords—Electrostatic precipitation, gas treatment, electric field modelling, gas discharge, collection efficiency

I. INTRODUCTION

In recent years, the CEA (Commissariat à l’énergie alternatives et aux énergies renouvelables) has worked on a process of incineration and vitrification called SHIV A. This process widely developed in papers [1], [2] uses plasma arc technology to treat many varieties of wastes (Fig. 1). However this reactor emitted flue gas containing dust particles which needed to be treated.

Indeed aerosol has a major role in air pollution problem ranging from environmental to health effect [3] and, because of prevention measures, this process and filtration need are increasingly important. One step of the gas treatment process used is the electrostatic precipitator (ESPs).

Electrostatic precipitators are used for a long time as industrial devices for gas treatment with an efficiency surrounding 99% and for a large scale of gas temperatures. They are widely used because of its profitability, ease of use and sustainability.

ESPs are equipped with a high voltage emissive electrode and a grounded collecting one. An electrostatic field generated by the emissive electrode charges the particles and finally these charged particles are deflected of the flue gas by the electric field and precipitated onto the collecting electrode. The latest is cleaned via rapping in dry ESPs or washing in wet ESPs.

This work is an investigation of the design of a new emissive electrode for the ESP placed after the SHIV A process and energized with a hybrid voltage (impulses superimposed on DC voltage).

II. MATERIAL AND METHOD

The experimental setup used to realize filtration tests with the new developed electrode is divided in 4 parts: a pilot, a power system, two particles counter (GRIMM) and particles injection system. To design the new emissive electrode called NE simulation of electric field and voltage/current experiments have been realized.

A. Laboratory scale pilot

The laboratory scale pilot located in SIAME laboratory (Fig. 2) is a single stage dry precipitator [1]. It is composed of a cylindrical grounded electrode for the collect (D = 30 cm) and a HV emissive electrode called Heritrode [4] which is used as reference for development of the new one. The pilot allows the study of different parameters as gas temperature (40°C to 160°C) and flow rate (60 m³/h to 240 m³/h). However in the case presented in the paper and in order to reproduce the SHIVA process conditions, we work with a gas flow of 120 m³/h and a temperature of 130°C.

B. Power system

To supply the ESP, we use an hybrid voltage system which improves particles collection. Hybrid voltage consists of high voltage pulses coupled to a background DC voltage. The superposition of both voltage types is obtained thanks to the electrical circuit introduced in Fig. 3.
We use two different DC power supplies: a SPELLMAN 100 kV - 12 mA and a TECHNIX 50 kV - 100 mA. One is connected to the thyristor switch to obtain the pulsed voltage and the other one is used to adjust the DC background; the repetition rate of pulses is fixed in this study at 1 kHz.

Hybrid voltage (Fig. 4) promotes the particle deflection with the DC voltage and gas ionization with the pulsed one.

C. Particle counter and injection

To determine the filtration efficiency (η), two spectrometers GRIMM 1.109 placed up and downstream are used. This portable counter model measures airborne particles concentration in sizes ranging from 0.25 µm to 32 µm in 31 different channels and returns these values as particle number and particle mass per liter of gas.

To calculate the collection efficiency (η), we use the following equation:

$$\eta = 1 - \frac{\langle p_{\text{out}} \rangle}{\langle p_{\text{in}} \rangle}$$ (1)

where $\langle p_{\text{out}} \rangle$ and $\langle p_{\text{in}} \rangle$ are respectively the average particle number at the outlet and at the inlet of the ESP (Fig. 2).

Moreover, at the inlet of the ESP before the GRIMM, the particle injection system is placed. Particles are injected with a flow rate between $2 \times 10^6$ and $4 \times 10^6$ particles/liter. Up to now, different dust mixtures provided by the CEA Marcoule coming from IRIS incinerator (dust 1 and 2) and by SIBELCO France (dust 3) are used for the experiments. The Fig. 5 shows the size distribution of dust particles used in the experiment and their chemical properties are given in the Table I:

### Table I: Chemical Characterization of Dust

<table>
<thead>
<tr>
<th></th>
<th>Dust 1</th>
<th>Dust 2</th>
<th>Dust 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (%)</td>
<td>0.2%</td>
<td>1.6%</td>
<td>99.2%</td>
</tr>
<tr>
<td>Cl (mg/kg)</td>
<td>16113</td>
<td>0.34%</td>
<td>Fe₂O₃ (330ppm)</td>
</tr>
<tr>
<td>Zn (mg/kg)</td>
<td>22125</td>
<td>&lt; 0.1%</td>
<td>Al₂O₃ (7520ppm)</td>
</tr>
<tr>
<td>P (mg/kg)</td>
<td>22740</td>
<td>0.5%</td>
<td>TiO₂ (220ppm)</td>
</tr>
<tr>
<td>Ca (mg/kg)</td>
<td>60999</td>
<td></td>
<td>CaO (110ppm)</td>
</tr>
<tr>
<td>Si (mg/kg)</td>
<td>88286</td>
<td></td>
<td>K₂O (60ppm)</td>
</tr>
<tr>
<td>Zn (mg/kg)</td>
<td>394572</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P (mg/kg)</td>
<td>158343</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

D. Electrostatic field simulation

To design the new electrode, preliminary simulations are conducted on electromagnetic calculation software called CST EM Studio™ (EMS). Simulations of the electric field (E-field) distribution in static conditions are performed for different geometries.

We simulate the two extremums of the hybrid voltage namely the background DC voltage and the maximum pulse voltage by applying respectively $-30$ kV and $-60$ kV to the emissive electrode. The choice of the applied voltage amplitude and polarity is based on previous study realized in the laboratory [5] and on the fact that corona discharges change to spark discharge for a voltage higher in negative than in positive polarity [6].

A tetrahedral meshing is used (Fig. 6) and the simulations are validated by performing a convergence study of the
maximum value of the electric field (V/m) depending on the mesh refinement. The new emissive electrode is validated by coupling the electrostatic results to the experimental tests.

III. RESULTS AND DISCUSSION OF THE EMISSIVE ELECTRODE DEVELOPMENT

The CEA Marcoule wants, because of industrial constraints, to develop a new emissive electrode (NE) and for that we use the multi-points Heritrode as a reference. The problem is that the new electrode (NE) will have a diameter larger than the previous one (Heritrode). Increase this diameter must have an impact on electric field distribution and on the effectiveness, so it has been decided to optimize the new one by making electric field simulations and experimental validation tests.

A. Modelling

1) Influence of the supporting tube on a point

First of all, we study the impact of the supporting tube on the field distribution around the point. We simulate and compare the following three configurations:

- 1 unique point without supporting tube
- 1 point + supporting tube of the Heritrode ($\phi = 2$ cm)
- 1 point + supporting tube of the NE

Fig. 7 shows the field enhancement at the extremity of the point and this simulation allows determining the maximal E-field at this location (Fig. 8).

We observe that adding a supporting tube or increasing its diameter leads to a reduction of the maximal electric field at the top of the point as a function of the gap (inter-electrodes distance).

In the same way, K. Parker showed, in studying the corona initiation field strength depending on wire radius, that increasing this parameter leads to a decrease of electric field strength [7].

According to this result, we need to compensate this loss in order to obtain a maximal electric field responsible of discharge initiation and therefore gas ionization.

To this end, we investigate the influence of other geometric parameters, to obtain a maximal electric field as high as the case of the Heritrode supporting tube.

2) Influence of points length

The first parameter playing on the increase the value of the electric field is the length of the point ($h_p$). We simulate the maximal electric-field by applying a voltage of $-60$ kV. The comparison is based on the two following configurations (Fig. 9):

- 1 point + supporting tube of the Heritrode
- 1 point + supporting tube of the NE

The results show that we need a point length of at least 3 cm for the NE to have a maximal electric field as high as in the Heritrode case.

However, we have to consider the average electric field which is responsible of particles deflection. Its value must stay lower than the value of negative streamers propagation in air throughout the inter-electrodes gap. The negative streamers propagation strength is evaluated to be around 14 kV/cm for a temperature of 130°C and for a constant reduced electric field ($E/N$) [6], [8], [9]. So, to avoid breakdown which will cause a decrease of the filtration efficiency, the new electrode configuration must have an average electric field lower than this value. We define as limit not to be exceeded 10 kV/cm.

To calculate the average electric field we use the following
where:

- $E_{090\%}$ is the value of the E-field localized from the supporting tube at 90% of the gap.
- $E_{\text{min}}$ is the minimal value of the E-field (out of 0).

Fig. 10 illustrates the results obtained during the simulation of the hybrid voltage minimum ($U = -30 \text{ kV}$) and allows to observe the variation of the average electric field depending on the point length ($h_p$). According to these results, we conclude that the limit not to be exceeded of 10 kV/cm is reached for a point length of 7 cm. This conclusion converge with the one obtained during the maximal electric field study.

This modeling doesn’t achieve the NE design; we need, in addition to the length study, to determine the separation distance between the points.

3) Influence between surrounding points

We simulate 3 aligned points placed on the NE supporting tube to study the influence between them (Fig. 11). More the points are closed, more there is an overlapping of the field lines (Fig. 12). To obtain the behavior of three independent points, we must distance them from one another.

So we have to find the distance corresponding to the both following requirements:

- the maximal electric field of 3 independent points must be equivalent for each one to a single point configuration;
- the number of points along the support tube must be the most important as possible on the NE in order to have the most active zone.

To find this distance, we study the electric field distribution at the middle point of the three depending on the spacing between them (Fig. 13). This simulation shows the interaction between them. For a given point length, more the space increase, more the maximal electric field at the top of the middle point increase until a threshold, where the reached value tends to the value obtained with a single point. This distance is the one we are looking for to design the new emissive electrode. In the case of a point length of 3 cm or 4 cm, we need a distance higher than 5 cm.

Thanks to the Fig. 14, we logically observe that the average electric field is not significantly influenced by the space between points.

To conclude, CST EMS software allows to define two configurations for the new electrode design namely points length of 3 cm or 4 cm and distant from each other by at least 5 cm.

This simulation part of the work is completed by experimental tests to verify the modeling experiments and determine the
geometric configuration to adopt.

B. Experimental tests

The aim of this analyses is to evaluate the average current released in the precipitator which is responsible of gas ionization. We are looking for the higher value by taking into account the same geometric parameters.

First of all, we work on a point-to-plane configuration with the point placed on a NE supporting tube above a grounded plane. Fig. 15 illustrates the absolute value of the average current versus the applied DC voltage and shows that longer is the point, higher is the average current for a given voltage. For the two points length considered (3 cm and 4 cm), we observe that the difference between current values is not significant.

On the other hand, smaller is the point, higher is the gap distance and higher can be the applied voltage.

This curve also shows that the corona onset is at $-10\,\text{kV}$. According to that, other experiments concerning the spacing between points are essential.

As during the simulation study (III-A-3)), we evaluate the stabilization distance of the current for a given voltage (Fig. 16).

These results show that experimentally we need in order to have 3 independent points:

- for a point length of 3 cm, the separation distance is above 8 cm;
- for a point length of 4 cm, the space above 8.5 cm.

The experimental results dont show a big difference between these two configurations excepting for the current value, which is an important point. But considering the application in gas filtration, we decide to evaluate the free volume ($FV$) in the ESP. This free volume is an estimation of the free space and to determine it, we simplify the geometry of the electrode Fig. 17(a) to a large cylinder as show in Fig. 17(b). The volume of this cylinder (NE assimilated to a cylinder) depends on the tips length.

The free volume ($FV$) represents the free space between the collecting electrode and the NE cylinder, knowing that 100% of the free volume is when we have only the supporting tube and no tip, we calculate with the equation (3) the free volume.

We determine a difference about 10% between a 3 cm point length and a 4 cm one (Fig. 19). Based on this observation, we choose for the development of the NE a point length of 3 cm.

$$FV(\%) = \frac{V_{\text{collecting electrode}} - V_{\text{NE cylinder}}}{V_{\text{supporting tube}}} \times 100$$ (3)

A last experiment is realized for a point-to-cylinder configuration with points placed on the NE supporting tube. The aim is to reproduce the ESP (NE/cylinder) by making a revolution study. We place on a wreath a variable number of points ($h_p = 3\,\text{cm}$) and we evaluate the average current collected on the grounded cylinder. Fig. 20 illustrates the results obtained on which we can observe that the increasing behavior of the current can be divided in two zones.
In the Zone 1 (from 0 to 6 points per wreath) the current increase linearly. In the Zone 2 the points interact on each other and the current value not evolves more linearly, it seems to saturate.

To avoid the interaction between points and its influence on current value, the chosen configuration is made by 6 points \((h_p = 3 \text{ cm})\) per wreath on the NE.

**C. The new emissive electrode**

Finally, the new emissive electrode (Fig. 22(a)) have been optimized, developed and validated with the following geometric parameters:

- points length of 3 cm
- 6 points per wreath
- with a rotation of 30° every second stage.

This configuration is used to enhance the electric field and to promote the pulsed corona discharge and the particle deflection.

The results obtain Fig. 20 for 6 points are extrapolated to an entire electrode (120 points) and compare with the developed NE (Fig. 22(a)) placed in the ESP pilot.

Current-voltage tests (Fig. 21) are realized without dust (WD) to compare the NE with the extrapolated results. Tests are realized with and without flow respectively “pilot on” and “pilot off”. The analysis shows that the “NE-pilot off” curve coincide with the extrapolation one and so this developed NE respect the small scale optimization data.

Also, we logically observe that, with the pilot switched-on (i.e. a flow of 120 m³/h and \(T = 130^\circ\text{C}\)), the current released for a given voltage is higher than when the pilot is switched-off, this can be explained by:

- the electric wind [10] which increased the charge mobility;

The corona onset voltage which is lower for higher temperature.

The following step is to proceed to filtration tests of the ESP with the NE and to evaluate the treatment efficiency of the process.

**IV. Precipitation of fine particles**

After a treatment tests session, the observation of the emissive electrode leads to two conclusions:

- The flow direction is visible on the NE thanks to the density of particles deposition on this electrode due to “back corona” [11],
- we can also notice that only half of the emissive electrode seems affecting the dust filtration when powered with a hybrid or pulse voltage, because the dust marks are only visible on the lower half part of the NE (Fig. 22(a), (b)). The explanation is still on study, but we suppose that the characteristic of the flow affect the filtration efficiency and promote the collect of dusts.

Concerning the collecting cylinder, we observe (Fig. 22(c)) that dust deposition is divided in two parts: a strong deposit of dust facing each point which is elliptic and a fine deposit easily removable which recovers all the cylinder including the space between the elliptic marks.

The NE efficiency is evaluated by comparing the results of the Heritrode and NE filtration efficiency for the dust 1 (Fig. 23) with a DC voltage supply. Compared to Heritrode, the NE filtration efficiency results are better for lower voltage and the
efficiency ratio of 98% is reached faster (at $U_{DC} = -10$ kV).

We also test the NE supplying by the hybrid voltage in order to improve the filtration efficiency for lower voltage. Using pulsed superimposed voltage increases the efficiency as observed with $U_{DC} = -7.5$ kV and the combination $-10$ kV DC/$-10$ kV pulsed seems widely enough to have a very high filtration efficiency for the dust 1 (Fig. 24).

These experiments validate the design of an effective NE. The final step of our study aims to verify if the hybrid voltage chosen allows similar results for dust with other electrical properties as dust 2 and dust 3.

To start, we analyze the filtration efficiency for the dust 2 and 3 with a DC power supply and compare the results to those obtained with dust 1 (Fig. 25). As well as dust 1, dust 2 and 3 show high filtration efficiency from $-10$ kV.

The choice of $-10$ kV as the background DC voltage seems to be enough to obtain a high filtration efficiency ($\sim 95\%$).

Considering that, we realize a study for dusts 2 and 3 for the hybrid voltage ($-5$ kV DC and $-5$ kV pulsed) to observe the influence of pulse frequency on the filtration. It seems (Fig. 26) that logically the filtration efficiency increase with the pulse frequency, but that there is a significant difference of the pulse frequency for the two different dusts (2 and 3).

This experiment shows that pulse frequency of 600 Hz with the hybrid voltage ($-5$ kV/$-5$ kV) allows to obtain 95% of filtration efficiency for the two dust studied.

Increasing the hybrid voltage couple will allow to reach a filtration efficiency of 99%. Fig. 27 shows that a pulse frequency of 100 Hz is enough for a hybrid couple of ($-7.5$ kV/$-7.5$ kV) and more. For higher hybrid voltage a lower pulse frequency is needed to obtain high filtration efficiency.

Now, hybrid voltage tests are still on study to determine the better configuration (power consumption, better filtration efficiency, operation time, etc... ) to adopt with the NE. More experiment and analysis have to be refined and mainly hybrid voltage tests on dust 2 and 3 have to be realized.

V. SUMMARY

In this work, we achieve the development of a new emissive electrode, usable on the ESP pilot for flue gas treatment and which shows high filtration efficiency.

The outlooks are: to finish the study for dust 2 with a hybrid voltage, to evaluate the efficiency for other dust samples. To complete this improvement of filtration efficiency of our ESP, a study on the optimization of pulsed superimposed voltage parameters (frequency, duty, voltage) will be performed. Finally, flow modeling have to be accomplish to argue our points distribution study.

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Fig. 23. Comparison of Heritrode and NE.

Fig. 24. Hybrid voltage on NE with dust 1.

Fig. 25. Filtration efficiency of the NE for three different dusts.

Fig. 26. Frequency study of the hybrid voltage (DC/pulsed) for dust 2 and dust 3.

Fig. 27. Performance of the new electrode for different hybrid voltage depending on pulse frequency for dust 3.
REFERENCES


