1. Summary

Stringent regulations further limiting environmental emissions are costing domestic refiners millions of dollars to remain in compliance or face severe economic penalties. In a refinery with a fluid catalytic cracking unit (FCCU), one common type of emissions control device is the ElectroStatic Precipitator (ESP) which attracts air borne catalyst particulates via electrical conduction. Catalyst resistivity is the measurable characteristic determining the relative likelihood a catalyst will precipitate out of the ESP.

A comprehensive study observing the effects of fresh catalyst versus equilibrium catalyst, metals levels, alumina content, environmental moisture content and operating temperature revealed ways to attenuate resistivity without requiring additional hardware. Considering the use of continuous chemical injection to further reduce resistivity, reviewing rapper frequency and adjusting operating voltage may also reveal new levels of improved ESP performance.

Identifying the significant operational and catalyst characteristics effecting catalyst resistivity will offer refiners several degrees of freedom to optimize and control the ESP operation.

2. Introduction

Over the past fifty years of fluid catalytic cracking, the evolution of refining technology has allowed refiners to debottleneck existing equipment. It is now possible for a recently revamped FCC unit to be processing twice as many barrels than when it was originally commissioned. Coupled to these expansions is an overload on downstream environmental mitigation equipment such as Electrostatic Precipitators (ESP). This equipment is designed to be on-line based upon a specific throughput and quality upstream. When upstream expansions occur, the ESP collection efficiency declines.

A methodical approach to improve collection efficiency or regain lost efficiency by lowering catalyst resistivity is presented. A basic but informative discussion of ESP design, operations, maintenance and troubleshooting is reviewed first. Upon acquiring a general understanding of how an ESP works, resistivity attenuation caused by operational adjustments, catalyst considerations and additives use are then described.

Electrostatic precipitators

An electrostatic precipitator is a large structure housing several collection plates and electrodes which are electrically energized to attract particles out of a gas stream. After a certain period of time, a film made up of small particles will cover the surface of the plates. When this occurs, a set of rappers are dropped on the collection plates knocking off the accumulated particulate matter. This material falls to the bottom of the precipitator where it ends up in a hopper bin for future transport and disposal.

Electrostatic precipitators work in corrosive, abrasive, high temperature environments. Close adherence to the manufacturer’s recommendations regarding unit operation and routine maintenance defines the foundation for optimizing collection performance and extending the run length of the ESP.

Design information

In the manufacturer’s Operating and Maintenance manual of each custom-made ESP unit should be specific information on design considerations such as gas volume, % entrained solids, temperature range and pressure. Included in this information should be mechanical descriptions of the hardware such as quantity and type of collection plates, electrodes, rappers, transformers, etc. This information is useful during all maintenance turnarounds when parts are being refurbished or need replacement. It is recommended not to deviate from the list of preferred suppliers when acquiring specified replacement parts.
The theory behind how an ESP works is defined by Ohm’s Law: \( V = IR \). Tiny particles of catalyst carrying minute charges (\( V_{\text{catalyst}} \)) are attracted to the electrically energized collection surfaces (\( V_{\text{plate}} \)) inside an ESP. An induced current begins to flow through the building catalyst layer from the side of high electric potential to the lower side. The catalyst layer presents the resistance to current flow due to its chemical makeup, layer thickness and other conditions such as temperature and moisture content.

The resistance term in Ohm’s Law, expressed as a function of catalyst resistivity, will be the focus of this discussion.

**Operation, monitoring and troubleshooting**

When the ESP is properly sized to match the current FCCU operation, run lengths of three to four years are possible without serious decline in collection efficiency. However, in one commercial application where the ESP was originally designed for a 30 MBPSD FCCU which now runs 50 MBPSD, cleaning of the collection plates and electrodes is required every three to four months. As more refiners increase FCC capacity upstream, downstream equipment like the GasCon section, process units such as Alky and environmental control equipment such as a flare system, wet gas scrubber and precipitator running well over 100% design become the new limitations of the typical refinery.

Inlet conditions and internal conditions of the ESP determine the outlet results. Monitoring ESP performance is as important as monitoring any other process unit in the refinery considering the consequences. Being out of stack opacity compliance can force the shutdown of the entire refinery.

The most important conditions to monitor at the inlet are as follows:

1. Gas volume, velocity and uniformity
2. Gas temperature
3. Gas humidity
4. Dust concentration
5. Dust particle size distribution
6. Dust particle resistivity
7. Other FCCU operating conditions

The necessary data describing the precipitator internal conditions are as follows:

1. Electrical energization readings (rapper lift, rapper cycle, amps, voltage)
2. Voltage - current curves and wave form data
3. Particulate removal system operation
4. Internal inspection reports
5. Replacement parts log

Troubleshooting a problem on an ESP will become much smoother if frequent unit monitoring and accurate data recording are made a priority. A few select examples and possible causes are provided for the most common problems encountered with ESPs:

<table>
<thead>
<tr>
<th>Observation</th>
<th>Possible cause</th>
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</thead>
<tbody>
<tr>
<td>Volts transformer read abnormally low, AMPS precipitator reading at or above normal, hopper throat cool.</td>
<td>May indicate hopper plugged.</td>
</tr>
<tr>
<td>Volts transformer reading 0, AMPS meter reading high, hopper throat warm.</td>
<td>Broken discharge electrode Short across insulator.</td>
</tr>
<tr>
<td>Low - frequency, rhythmic fluctuation of meters.</td>
<td>Discharge electrode broken at bottom and whipping in gas phase.</td>
</tr>
<tr>
<td>Volts transformer and AMPS meters reading low.</td>
<td>Excessive catalyst build up on collection plates.</td>
</tr>
<tr>
<td>Volts transformer meter reading high, AMPS meter reading low.</td>
<td>Excessive build up on electrodes. High flue gas temperature.</td>
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</tbody>
</table>
Recommended ESP maintenance program
Performance and reliability of the ElectroStatic Precipitator is greatly influenced by a conscientious effort to follow a preventative maintenance program. The manufacturer provides maintenance advice on a daily, weekly, quarterly, semi-annual, annual and situational basis. An example of such a list is as follows.

**Daily:**

- Record electrical readings and transmissiometer data.
- Check operation of hoppers and catalyst removal system - insure particulate is not building up within hoppers and that the removal system is operating properly.
- Examine control room ventilation system.
- Compare meter readings. Deviations that may have been overlooked could indicate problems.

**Weekly:**

- Check and clean air filters.
- Inspect control set interiors.
- Check side access doors to insure gaskets are in place and doors closed tightly.

**Monthly:**

- Check operation of standby top housing pressurizing fan and thermostat.
- Check hopper level alarm operation.

**Quarterly:**

- Check transmissiometer calibration.

**Semi-Annually:**

- Clean and lube access door dog bolts and hinges.
- Clean and lube interlock covers.
- Clean and lube test connections.
- Check exterior for visual signs of deterioration and abnormal vibration, noise or leaks.

**Annual:**

- Conduct internal inspection.
- Clean top housing and all electrical insulating surfaces.
- Examine and clean all contactors and inspect tightness of all electrical connections.
- Clean and inspect all gasketed connections.
- Check and adjust operation of switch gear.
- Check and tighten rapper insulator connections.

**Situational:**

- Record air load and gas load readings during and after each outage.
- Clean and check interior of control sets during each outage of more than 72 hours.
- Clean all internal bushings during outages of more than five days.
- Inspect condition of all grounding devices during each outage over 72 hours.
- Clear all shorts during each outage.
- Check all alarms, interlocks and other safety devices during each outage.
- Check all collecting plate rapper rods connections for cracks, loosening during each outage.

3. Catalyst resistivity

One of many variables effecting the collection efficiency of the ESP is catalyst resistivity. It is defined as the ratio of the applied electric field across the catalyst layer to the induced current density. Independent laboratories follow the IEEE Standard 548-1984 procedure for laboratory measurements of resistivity. The units are ohm - cm which measures the affinity of the catalyst particle to accept an opposite charge and
catalyst and effects of alumina, rare earth, contaminant metals, carbon, ammonia injection, operating
temperature and moisture content is presented.

**Fresh catalyst resistivity versus equilibrium catalyst resistivity (table 1)**

When catalyst resistivity is being measured, it is important to know that there are significant differences
regarding resistivity measurements between fresh and equilibrated catalysts. Figure 1 shows a resistivity
comparison between fresh catalyst and its equilibrated version at two different temperatures.

**Table 1. Fresh catalyst resistivity versus equilibrium catalyst resistivity**

<table>
<thead>
<tr>
<th></th>
<th>Fresh</th>
<th>Equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity</td>
<td>@ 350 °F (177 °C)</td>
<td>9.0 \times 10^{12}</td>
</tr>
<tr>
<td>Resistivity</td>
<td>@ 600 °F (315 °C)</td>
<td>1.3 \times 10^{11}</td>
</tr>
<tr>
<td>Nickel +</td>
<td></td>
<td>4.5 \times 10^{11}</td>
</tr>
<tr>
<td>Vanadium ppm</td>
<td></td>
<td>1.5 \times 10^{10}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,846</td>
</tr>
</tbody>
</table>
Fresh catalyst resistivity is always larger than the corresponding equilibrated catalyst resistivity. The presence of contaminant metals lowers catalyst resistivity one order of magnitude across the entire temperature range. Increases in temperature will continue to lower catalyst resistivity another order of magnitude relative to the measurement taken of the fresh catalyst at 350°F (177°C). Contaminant metals in combination with higher temperature represent the largest influences lowering catalyst resistivity by two orders of magnitude. These changes are delivered by feed quality shifts, reduced catalyst makeup rates, moving from partial to complete combustion and reducing the duty of the flue gas steam generator.

Clearly, equilibrium catalyst samples, not samples of fresh catalyst, should be used for resistivity measurements when troubleshooting an ESP efficiency problem because equilibrium catalyst is the major catalyst component in the unit. It is also recommended to evaluate catalysts known for stability in high metals and challenging thermal environments.

Catalyst alumina content
Two fresh catalyst samples were tested for resistivity to determine the effect of differing alumina content (table 2). Fresh catalyst samples were chosen to eliminate the effect of contaminant metals effects on equilibrated catalyst.

### Table 2. Alumina effect

<table>
<thead>
<tr>
<th>Catalyst A</th>
<th>Catalyst B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resistivity</strong></td>
<td><strong>Resistivity</strong></td>
</tr>
<tr>
<td><strong>Al₂O₃ content</strong></td>
<td>@ 392°F (200°C)</td>
</tr>
<tr>
<td><strong>wt%</strong></td>
<td>3.5 × 10¹²</td>
</tr>
<tr>
<td><strong>Resistivity</strong></td>
<td>40</td>
</tr>
</tbody>
</table>

**Catalyst A** contains 33% more alumina than **catalyst B**. Figure 2 shows that at 392°F (200°C), there is no difference in resistivity between the two catalysts. At elevated temperatures, the resistivity measurements are very similar and within the accuracy/repeatability of the test method.
Rare earth
Two fresh catalysts with differing amounts of rare earth were tested for resistivity to observe any differences (table 3). Again, equilibrated catalysts were not used to eliminate contaminant metals effects.

Table 3. Rare Earth effect

<table>
<thead>
<tr>
<th></th>
<th>Catalyst C</th>
<th>Catalyst D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity</td>
<td>@ 400 °F (204 °C)</td>
<td>3.9 \times 10^{12}</td>
</tr>
<tr>
<td>Resistivity</td>
<td>@ 600 °F (315 °C)</td>
<td>4.0 \times 10^{11}</td>
</tr>
<tr>
<td>Rare Earth content</td>
<td>wt%</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.6 \times 10^{12}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.4 \times 10^{10}</td>
</tr>
</tbody>
</table>

Not surprisingly, the higher rare earth catalyst has a lower resistivity at both temperatures. However, the difference is small and within the accuracy/repeatability of the test method (figure 3).
Contaminants level
As fresh catalyst ages in the FCCU circulating inventory, it picks up metals in the feed. These are primarily nickel, vanadium, copper and iron. If zirconium, tin, antimony or platinum additives are used, they too will accumulate in the catalyst inventory.

Table 4. Contaminants metals effect

<table>
<thead>
<tr>
<th></th>
<th>Catalyst 1</th>
<th>Catalyst 2</th>
<th>Catalyst 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity</td>
<td>3.5 $10^{11}$</td>
<td>4.5 $10^{11}$</td>
<td>1.5 $10^{11}$</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
<td>7.0 109</td>
<td>1.0 1010</td>
<td>3.5 1010</td>
</tr>
<tr>
<td>Nickel +</td>
<td>34.3</td>
<td>39.1</td>
<td>38.8</td>
</tr>
<tr>
<td>Vanadium</td>
<td>8,680</td>
<td>2,846</td>
<td>532</td>
</tr>
</tbody>
</table>

The resulting effect on catalyst resistivity is predictable. The more metals on catalyst, the lower the catalyst resistivity. Table 4 clearly illustrates the effect on resistivity of different types of catalysts with different metals levels.
Carbon on catalyst
Resistivity is adversely effected by increasing carbon on catalyst levels because it acts as an insulator between the ESP collection plate and the charged particles on the surface of the catalyst. Safety concerns begin to emerge as carbon and possibly entrained hydrocarbon trapped in the catalyst pores may pose an explosion hazard under certain conditions inside the ESP especially when operating with > 4.0 mole% excess O₂. Carbon levels on catalyst should be minimized.

Ammonia injection
Ammonia has been a successful resistivity attenuation agent since the forties. The benefits of ammonia over other conditioning agents is that it is inexpensive and readily available. Also, only a small amount, ~6 ppm NH₄OH, is required to improve ESP collection efficiencies by reacting with existing SO₂ and SO₃ sulfur species to increase space charge effects and collection fields⁵. In one instance, using ammonia improved the ESP collection efficiency from 96% to 99.8%. Another commercial success for ammonia reduced one refiner’s stack opacity from 12 to 5.

It is also used to extend the cleaning frequency when the ESP is undersized. At some point, however, ESP collection efficiency will gradually degrade due to continued particulate buildup on the collection plates to the point where cleaning is required.

Moisture content
The moisture in the flue gas steam effects resistivity⁶. At cool operating temperatures between 200°F (93°C) and 400°F (204°C), increasing the environment’s moisture content slightly lowers resistivity. At higher temperatures, the moisture content has little influence on further lowering resistivity as the curves describing 0%, 6%, 9% and 15% moisture content resistivity data converge together (figure 5). The FCC regenerator is essentially a big steamer converting hydrogen in the coke and entrained hydrocarbon to steam when combusted with oxygen supplied by the main air blower. Altering the effectiveness of the catalyst stripper to remove hydrocarbon from the catalyst before it enters the regenerator is the main lever in adjusting the flue gas moisture content. Introducing steam immediately upstream of the ESP is a better option.
It is not recommended to sub-optimize the catalyst stripper efficiency to increase the moisture content and improve ESP collection efficiency at low operating temperature. This adjustment creates a very small effect.

**Other considerations**
If the above information does not prove successful in improving ESP performance, the decisions to increase rapper frequency and increase operating voltage needs to be made. Both options offer immediate results. This eventually comes at a cost via increased utilities usage and wear & tear on equipment.

4. Conclusion

The degree of success in implementing these suggestions is qualified by the physical condition and environment of the individual ESP. Maintaining a clean ESP is the best way to achieve high collection efficiencies.

Catalyst resistivity is one of the main factors effecting ESP performance because it can change by several orders of magnitude. The other variables do not change to the same degree as resistivity. Contrary to popular belief, alumina content does not influence resistivity. Rare earth and contaminant metals levels will not vary due to product yield and quality requirements and other limitations. Thus, if adjustments are made to these quantities then the impact on resistivity will be small.

Lowering resistivity via increased operating temperature, ammonia injection, increased rapper frequency and higher operating voltage can provide refiners with overloaded ESPs some immediate relief. These remedies, however, temporarily extend the cleaning cycle which is ultimately required to regain high collection efficiencies.

5. References
