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HORIZONTAL IN-DUCT SCRUBBING OF SULFUR-DIOXIDE FROM FLUE GAS EXHAUSTS

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Abstract

Alcoa has conducted multi-year concept validation, pilot and full-scale demonstration studies to assess the technical feasibility of an energy efficient, horizontal gas-flow, co-current in-duct scrubber. The in-duct scrubber was designed and developed with the aim to significantly reduce capital expenditures and operating costs while providing >90% reduction of SO_2 emissions from aluminum smelters, anode bake furnaces, coke calciners and industrial boiler exhausts.

Pilot scale parametric testing of various spray nozzle types and configurations has been conducted to optimize the final scrubber design using a liquid solution for SO_2 scrubbing. More recently, a full scale commercial unit has been installed and is currently operating with SO_2 removal efficiencies greater than 92%. The scrubber treats the exhaust gases from an anode baking furnace with flows ranging between 120,000 and 150,000 cubic feet per min (cfm), liquid to gas (L/G) ratios ranging from 10-12 gallons/1000 acf (actual cubic feet) and an overall pressure drop across the scrubbing unit at or below 1.5 inch w.g. (water gauge). Future testing of this unit will entail detailed evaluation of the system's capability in removing fine particulates.

Introduction

The by Alcoa developed and patented in-duct scrubber (IDS) technology removes acid gases such as sulfur dioxide (SO_2) and particulate matter from flue gas, and is now in operation as part of a full-scale commercial demonstration at the Lake Charles Carbon Plant in Louisiana. The technology, developed by the Alcoa Technical Center (ATC) in collaboration with Alcoa's Global Primary Products' (GPP's) Technology Development Group, is designed with the aim to remove greater than 90% of the sulfur dioxide, >90% hydrogen fluoride and >80% total particulates contained in the flue gas of smelters, anode baking furnaces, petroleum coke calciners and industrial boilers in the 50-120 MW/unit range.

Most smelters worldwide have been able to meet current SO_2 emission regulations without having a scrubber system in place. However, SO_2 standards are becoming increasingly stringent in many parts of the world. In addition, the aluminum smelting industry is moving toward using petroleum coke with higher sulfur contents due to the reduced supply and higher cost of low-sulfur anode-grade petroleum coke. This will result in increased SO_2 emissions from potrooms and anode bake plants at a time when emission limits are decreasing. To address these growing challenges, Alcoa's researchers developed this innovative horizontal co-current sodium based wet scrubbing technology, which has a smaller physical footprint, lower capital costs, and 30-40% lower energy consumption. This is achieved by increased process and energy efficiencies for equal removal rates compared to conventional sodium or calcium based wet flue gas desulfurization (FGD) technologies. The system schematic is shown in Figure 1, which relates the simplicity of the system, e.g., no contactors or other mass transfer devices that consumes energy or contributes to scaling and increased maintenance.

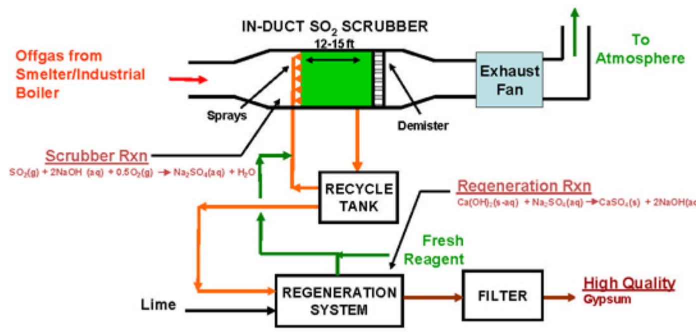

Figure 1: Alcoa's In-Duct Scrubber Technology.

A 1/15[th] scale pilot IDS system is housed in the campus of the Alcoa Technical Center, the largest light metals research facility in the world. Another 1/15[th] scale unit was used for demonstration purposes at the Alcoa Massena East smelter (shown in Figure 1) treating a slip stream of exhaust gases from the dry HF scrubber. Also, a 1/5[th] scale system is operated at test location in Canada.

Figure 2. Massena East Smelter Pilot Scrubber

After the initial successes, a full scale in-duct scrubber is now constructed in Alcoa's Lake Charles facility in Louisiana, USA. This facility calcines green petroleum coke and then bakes carbon anodes that are send to smelters. The IDS system has been in operation since March of 2014 and is treating exhaust gases at a rate of about 150,000 acfm (a capacity equivalent to a 60 MW boiler unit) with a removal efficiency >90% for SO_2 and HF (hydrogen fluoride) gas. Testing during 4Q 2014 will include particulate removal assessment for PM 10 and PM 2.5. The current particulate control system includes a 20 year old wet Electrostatic precipitator (WESP) that will be decommissioned once the IDS unit has been completely tested and approved by a regulatory agency during 2Q 2015. Alcoa is pursuing on plans to make this technology commercially available worldwide beginning 2015. Figure 3 shows the IDS unit that is installed in Lake Charles, LA.

Figure 3. IDS treatment system at Lake Charles, LA facility

Description

With the IDS, flue gas from an emission source is directed into a horizontal spray chamber (Figure 1), where a sodium-based solution is sprayed using special energy-efficient nozzles. A set of vertical Chevron type mist eliminators downstream of the spray nozzles acts as the final demisting step. The surfaces of the mist eliminator blades are continuously kept wetted via wash sprays, thereby reducing the potential of scaling. The clean, saturated gas leaves the scrubbing chamber via wet centrifugal fans and is discharged from a wet stack. The sulfate-laden liquid discharge is directed into a recirculation loop. A portion of this liquid is blown down to control the chemistry and is further treated for either permitted discharge to the environment or conversion to a potentially value-added product, such as gypsum. For example, one can couple IDS with conventional dual alkali treatment process to generate a gypsum by-product, or one can treat the blowdown using a conventional water treatment system or engineered polishing wetland system for permitted discharge. The Lake Charles demonstration unit uses NaOH as the scrubbing solution and includes a small treatment system to treat the scrubber blowdown liquid (~20 gpm) prior to discharge onto surface waters.

The key intended reactions (SO_2 Removal and Oxidation) that occur in the scrubber system are as follows:

$$SO_2 + H_2O = H_2SO_3 \quad (1)$$

$$NaOH + H_2SO_3 = NaHSO_3 + H_2O \quad (2)$$

$$CO_2 + H_2O = H_2CO_3 \quad (3)$$

$$NaOH + H_2CO_3 = NaHCO_3 + H_2O \quad (4)$$

$$NaHCO_3 + H_2SO_3 = NaHSO_3 + CO_2(g) + H_2O \quad (5)$$

$$NaOH + NaHSO_3 = Na_2SO_3 + H_2O \quad (6)$$

$$Na_2SO_3 + SO_2 + H_2O = 2NaHSO_3 \quad (7)$$

Some of the oxygen from the flue gases oxidize the sulfites to sulfates:

$$Na_2SO_3 + 0.5\ O_2 = Na_2SO_4 \quad (8)$$

The undesirable reactions (Scaling and Solids Buildup) in the scrubber, which are regulated by carefully controlling the recirculation chemistry, are as follows:

$$Ca^{+2} + CO_3^{-2} = CaCO_3 \quad (9)$$

$$Ca^{+2} + SO_4^{-2} + H_2O = CaSO_4 \bullet 2H_2O \quad (10)$$

$$Ca^{+2} + SO_3^{-2} + H_2O = CaSO_3 \bullet 0.5H_2O \quad (11)$$

The in-duct scrubber pilot at Alcoa Technical Center, PA is a fully integrated facility where the scrubber is coupled with a dual alkali blowdown regeneration system. In this system, lime is added to the blowdown to produce high quality gypsum, while the NaOH is regenerated. The liquor with the caustic soda is clarified and recycled back into the scrubber recirculation loop. By controlling the remaining moisture levels in the gypsum this process can be a true zero water discharge system. The principle regeneration reactions are as follows:

MAJOR:

$$Ca(OH)_2 + Na_2SO_4 = CaSO_4 + 2NaOH \quad (12)$$

After super saturation gypsum precipitates:

$$CaSO_4 + 2H_2O = CaSO_4 \bullet 2H_2O \quad (13)$$

MINOR:

$$Ca(OH)_2 + Na_2SO_3 = CaSO_3 + 2NaOH \quad (14)$$

After super saturation calcium sulphite crystals precipitate:

$$CaSO_3 + 2H_2O = CaSO_3 \bullet 2H_2O \quad (15)$$

The in-duct scrubber, however, can be used in a variety of scrubbing modes with different regeneration/treatment schemes in addition to the dual alkali process. The following scrubbing modes have been tested successfully via multiple pilot tests:

- Dilute Mode Dual Alkali (DDA) - Gypsum Byproduct;
- Concentrated Mode Dual Alkali (CDA) -Solid Waste for Disposal;
- Once Through Sodium – Direct Discharge of Na_2SO_4;
- Sodium promoted Lime – Slurry; and
- Seawater – Direct Discharge

The IDS unit is modular in nature and is very suited to retrofitting at existing facilities. Figure 4 depicts the compact scrubbing zone inherent to IDS as >90% of the removal is achieved within the first 6 feet in the scrubber.

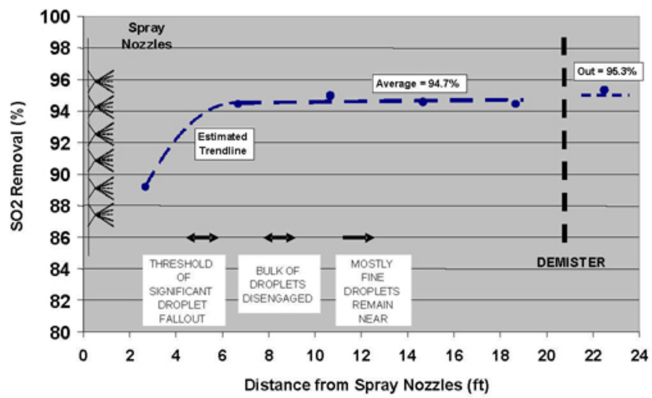

Figure 4. SO_2 removal as a function of distance from the spray nozzles (pilot and full scale operation data).

The full scale system at the Lake Charles facility has been operating since March of 2014 and is removing SO_2 consistently with an average removal efficiency of 92.5% (see Figure 5). As part of the system characterization and optimization tests, efforts have been made to operate the system in the most energy and cost efficient fashion while keeping the SO_2 removal rate above 90%. The following key outcomes have been consistently recorded as part of these field optimization trials:

- L/G ratio < 12 gallons/1000 actual cu. ft.;
- Nominal reagent nozzle pressure (~ 20 psi);
- Low overall pressure drop across the scrubber (~1 inch w.g.);
- >98% stoichiometric utilization of caustic; and
- Maintain gas flow velocities ~ 27 fps through the scrubber with minimum liquid carry-over from the mist eliminators

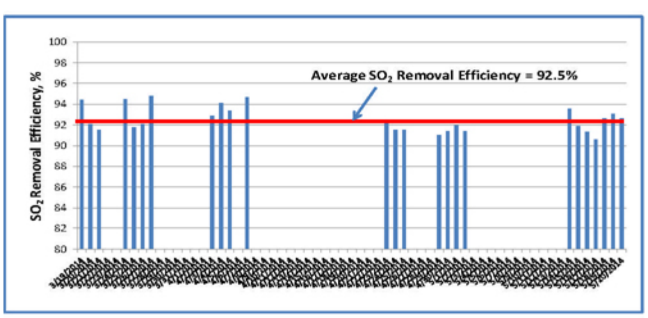

Figure 5. Average SO_2 removal efficiency data from Lake Charles full scale demonstration (excerpts of data from discrete monitoring events).

IDS is able to maintain >90% scrubbing efficiency over a wide range of inlet SO_2 concentrations (50 ppm to 2000 ppm) with a high turn down ratio. This is illustrated in Figure 6 which shows the SO_2 profile at the inlet and outlet of the Lake Charles unit as well as in Figure 7 which depicts the SO_2 removal from pilot testing at the test facility in Canada.

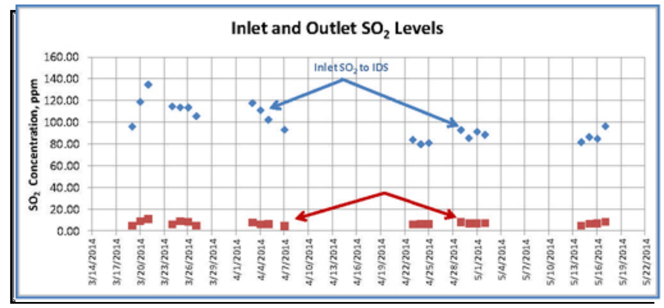

Figure 6. Inlet and Outlet SO_2 levels from the Lake Charles scrubber unit (excerpts of data from discrete monitoring events).

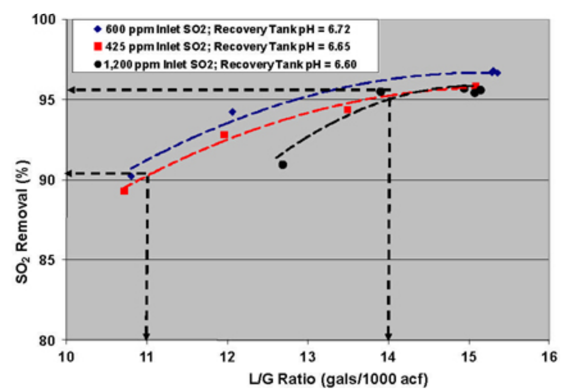

Figure 7. SO_2 removal plot as a function of L/G ratio under wide range of SO_2 inlet levels (data from pilot testing).

The type and orientation of the spray nozzle arrays contributes to optimum gas-liquid contact in terms of mass transfer surface area and mixing as well as the co-current placement of the nozzles that contributes to "aspiration effect", whereby the gas is pulled into the liquid spray zone along with a pressure rise, thereby resulting in lowering the overall pressure drop across the scrubber system. This is an advantage of a horizontal co-current spray system over conventional vertical counter-current scrubbers leading to lower overall energy consumption and smaller physical footprint.

Considerable testing has been conducted at the pilot test facility at Alcoa Technical Center, PA, where the dilute mode dual alkali process has been integrated with the in-duct scrubber. This process has the ability to further optimize the regeneration chemistry by adding lime to the scrubber blowdown to regenerate the caustic soda with minimum sodium losses while generating gypsum crystals with acceptable particle size and aspect ratio for easy dewatering. The key performance metrics that have been achieved in the course of this testing are as follows:

- No/Low Solids Scale or Buildup in the scrubber;
- Efficient Mist Eliminator Performance (expected droplet concentration after mist eliminator ~0.02 grains/dscf);
- High level of Oxidation $CaSO_3/CaSO_4$ < 2%;
- Absorber Liquor pH – 12.2 – 12.5;

- Maximum Gypsum Crystal – D_{50} > 80 microns;
- Maximum Calcium De-supersaturation – Calcium relative saturation of ~ 1.2;
- Lime Utilization > 98%; and
- Thickener Underflow Solids Content of 40-50% Attainable

Another important feature of this technology is the potential for higher efficiencies of particulate removal (PM 10 and PM 2.5). This is illustrated in Figure 8 which pertains to testing performed in a 10,000 cfm pilot unit with simulated anode bake oven flue gas. As stated earlier, a full suite of performance tests entailing PM 10 and PM 2.5 removal is planned at the Lake Charles full scale facility during 4Q 2014-1Q 2015 timeframe.

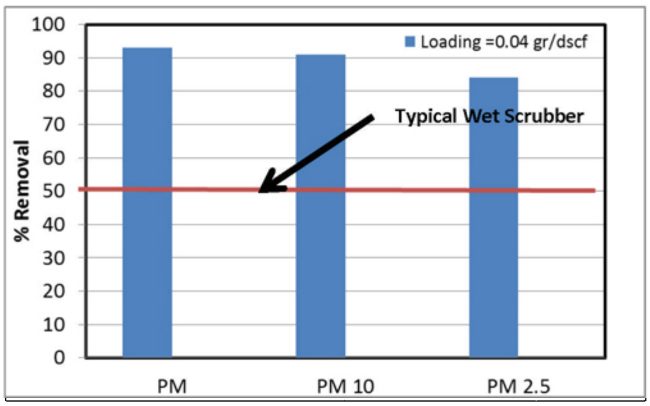

Figure 8. Particulate Removal from IDS Pilot Tests

Finally, the energy calculations from the Lake Charles IDS operation, combining the gas and the liquid side, indicates lower overall energy consumption when compared to traditional wet scrubbing devices, such as vertical counter-current spray tower or Limestone Forced Oxidation FGD units. There is at least the potential for 40-50% savings in overall energy consumption combining the gas and the liquid side as highlighted in the calculations presented in Table 1 for a typical 300,000 MTPY mid-size smelter. One unique advantage this renders IDS is the ability to place the unit after the fume treatment center (FTC) in the smelter courtyard without the need for installing additional fans. Because of the significantly low energy requirement on the gas side, the existing fans in the FTC should be able to push the gas through the IDS unit. This reduces the physical footprint of the installation leading to excellent retrofit opportunity and CAPEX reduction. Also, placing the IDS unit post FTC allows further polishing of the gas stream for any residual HF.

Table 1. Comparison of Key Energy Consumption Elements for Wet Scrubbing.

InDuct Scrubber Energy					
Fan Power			Pump Power		
Flowrate	Q scfm	1,500,000	Flowrate	Q usgpm	18,000
Delta P	ΔP "H2O	1.5	Delta P	ΔP psig	41.5
Efficiency	η (%)	80	Efficiency	η (%)	70
Power (hp)	≡Q x ΔP	442.5	Power (hp)	≡Q x ΔP	622.9
	6356 x η			1713 x η	
Power (kW)		330.0	Power (kW)		464.5
			TOTAL POWER (Kw)		794.5
			TOTAL POWER (hp)		1065.4

Vertical Scrubber Tower Energy					
Fan Power			Pump Power		
Flowrate	Q scfm	1,500,000	Flowrate	Q usgpm	37,500
Delta P	ΔP "H2O	4	Delta P	ΔP psig	30.0
Efficiency	η (%)	80	Efficiency	η (%)	70
Power (hp)	≡Q x ΔP	1180.0	Power (hp)	≡Q x ΔP	938.1
	6356 x η			1713 x η	
Power (kW)		879.9	Power (kW)		699.5
			TOTAL POWER (Kw)		1579.5
			TOTAL POWER (hp)		2118.1

Conclusions

Overall, the in-duct scrubber has shown to be an energy efficient wet scrubbing device for acid gases and particulates for a variety of applications. The scrubber is modular in design, which makes it very suitable for retrofits at brownfield locations. The scrubber can also be used in multiple scrubbing modes with different regeneration/treatment schemes.

In summary, the key attributes of the IDS system that make it attractive for applications in the target market segments indicated in Figure 9 are:

- No internal gas-liquid contacting device;
- Smaller droplet sizes (higher mass transfer surface area)
- High gas velocity (25-35 fps);
- Low L/G ratio (~10 gpm/1000acfm);
- Low delta P in the scrubber (~1 inches WG);
- Compact configuration (12-16 ft length of scrubbing zone);
- Modular (easy for retrofits);
- Can be coupled with multiple blowdown regeneration systems;
- Can be placed after the FTC in a smelter without the need for additional fans
- Multi-pollutant removal (SO_2, HF, PM10, PM2.5, VOCs); and
- Patented technology[1,2] available under license from Alcoa

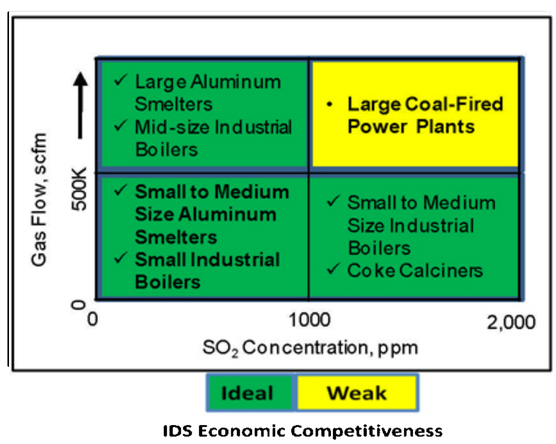

Figure 9. Operating Range (applicable market segments) for IDS technology.

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