

Humidification Feedback Control to Improve Performance of Dry Scrubbing for Power Plant Applications

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Introduction

Dry scrubbing applications, especially for utility coal-fired electricity generation, is experiencing a renewed interest primarily because of the recent emphasis placed on multipollutant control. With their integrated particulate collection device at the back end, dry scrubbers have a demonstrated advantage over their wet scrubber counterparts in particulate control and also condensable acid (SO₃) mist emissions. However, to meet the requirements of the marketplace dry scrubbers will have to go into an area where they typically have not been accepted - high SO₂ removal efficiency in medium to high-sulfur coal applications.

The dry scrubber technology is able to meet the performance requirements of this particular application, but to do so repeatedly and reliably will require a closer approach-to-saturation temperature or higher flue gas humidity conditions and the instrumentation to allow powerplant operators to go into this region safely without increasing risks of water condensation. As part of a project funded by the United States Environmental Protection Agency, Southern Research Institute has operated a circulating bed semi-dry scrubber with a H₂O on-line humidity sensor. The sensor was installed in the particulate control outlet to provide on-line humidity and dewpoint measurement and allow operators to push the flue gas humidity to maximize system performance without danger of exceeding adiabatic saturation and duct wall wetting.

Increasing Flue Gas Humidity to Improve SO₂ Collection

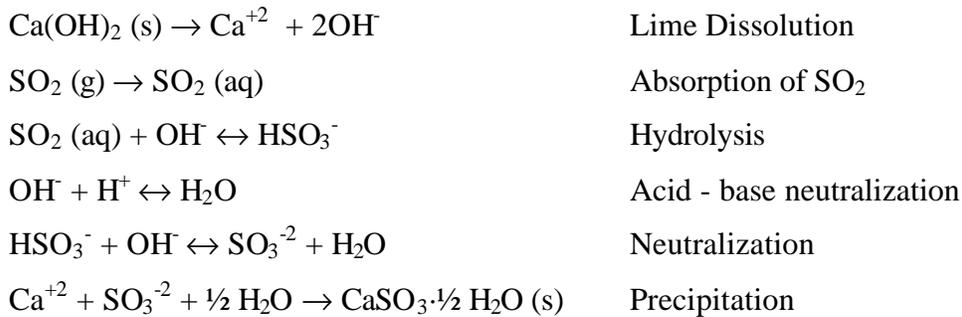
Dry Flue Gas Desulfurization Chemistry

The majority of the reactions required for SO₂ control in dry scrubbing take place in the aqueous phase. The SO₂ and the alkaline constituents dissolve into the liquid phase where ionic reactions produce relatively insoluble products.

The overall desulfurization reaction, using lime, may be written as follows:



However, the reaction pathway is best described as follows:



All but the first reaction take place in the flue gas; the first reaction occurs in the reagent storage tank. Without the injection of moisture, the reaction would proceed very slowly and it is well understood that an increased presence of water enables the reaction to proceed closer to stoichiometric completion.

By design the quantity of water in the atomized spray is limited so that it completely evaporates in suspension. The maximum amount of water injection is limited to that required for complete adiabatic saturation of the flue gas; beyond this point, the flue gas would not have any ability to absorb water, thus the downstream components would see droplet-laden flue gas. The flue gas temperature at complete adiabatic saturation is called the adiabatic saturation temperature.

Plant Operations

In the typical plant control system, operators monitor the reactor outlet temperature, trimming water injection to maintain a safe offset from the adiabatic saturation temperature. This offset, often called the approach-to-saturation or ATS, is a primary control variable, and in addition to reagent stoichiometry is an important parameter in optimizing SO_2 collection efficiency.

By reducing the approach-to-saturation it is possible for a plant to improve SO_2 collection efficiency and improve reagent stoichiometry without significantly increasing overall reagent consumption. Additionally, in previous work SRI studied dry sorbent reactivation and demonstrated that the dustcake properties were not adversely affected by low ATS, and in some cases could even improve.

As can be seen in the proceeding desulfurization reaction pathway, flue gas humidity plays an important role in the desulfurization reaction. By increasing the water injection rate the water droplets will remain in the flue gas longer, allowing the reaction to proceed further. Eventually the returns of increasing water injection will diminish as the flue gas SO_2 concentration decreases and the reaction becomes SO_2 -limited, but most plants would see an increase in SO_2 collection and also reagent stoichiometry by adjusting water injection to operate the system at a lower approach-to-saturation temperature. Plant performance improvements would be site-specific and would depend on several parameters: present ATS, coal sulfur, reagent quality, water quality, and reactor volume. Figure 1 presents typical plant SO_2 removal data, related to Ca/S ratio and also ATS. As can be easily seen, the SO_2 removal efficiency quickly increases as ATS is pushed lower through water injection. In fact, the increase in SO_2 removal efficiency per degree decrease in ATS is increasing. However, to push ATS downward requires an increasing water injection rate. The amount of water required to reduce temperature is fairly constant through most of the range, with the exception of the last few degrees above saturation (Figure 2).

Focusing in on the last 5 degrees ATS, the rate of change is approximately -145°F/(lb water injected/KACF dry flue gas), whereas through the preceding range the rate of change was steady at approximately -90°F/(lb water injected/KACF dry flue gas).

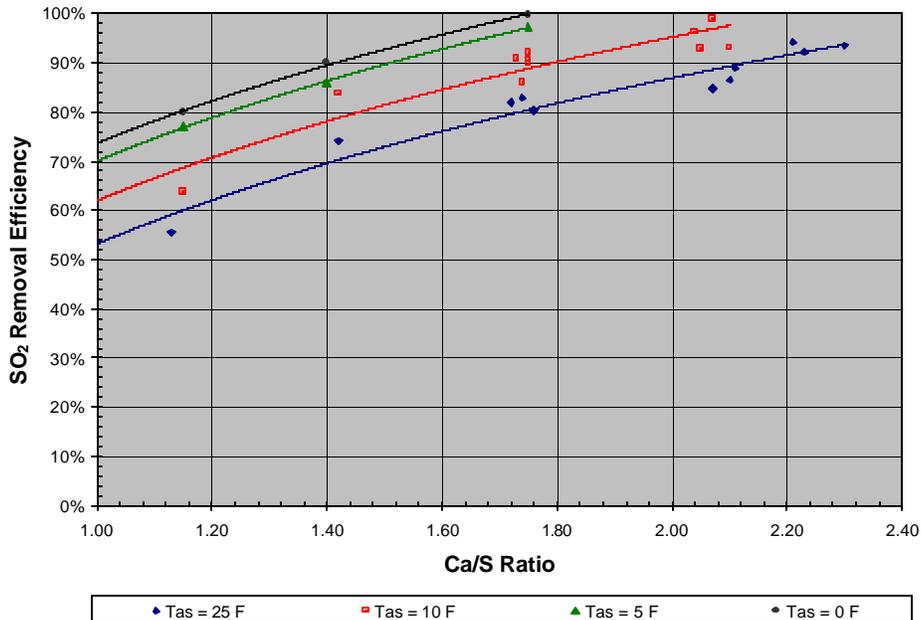


Figure 1. Typical Operational Data, showing relationship of SO₂ removal to Ca/S ratio and Approach-to-Saturation temperature.

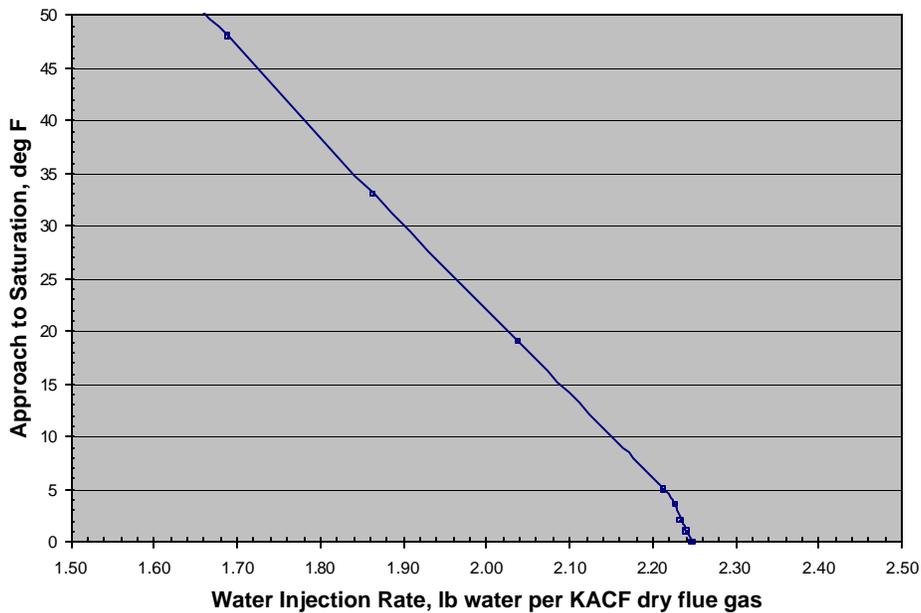


Figure 2. Water requirement for close ATS operation.

Humidity Variables within a Coal-fired Power Plant

The adiabatic saturation temperature for flue gas is dependent on the vapor pressure or volume fraction of water in the flue gas. So any ambient conditions or boiler auxiliary operations that change the flue gas composition will also alter the saturation temperature of the flue gas. Unit load, coal moisture variations, steam soot blowing, tube leaks and ambient air humidity changes will affect the flue gas humidity content. Typical dry bulb temperature measurements cannot detect changes in these humidity variables which result in less efficient and inherently higher risk scrubber operation. Unit load, coal moisture variations and soot blowing cycles can possibly change the moisture concentrations of the flue gas by 2 to 3% independently.¹ Ambient air humidity can change 1% by volume in a typical summer day (Table 1). It should be noted that the ambient air has a smaller effect on the flue gas moisture compared to the other variables.

Table 1. Typical Ambient Data - Summer.

<i>Time of Day</i>	<i>Dry Bulb Temperature, °F</i>	<i>Dewpoint, °F</i>	<i>Humidity, % vol</i>
Middle of Day	91	70	2.3
Late Night	72	55	1.3

Table 2. Flue Gas Dewpoint Variation (1% variation in ambient air).

<i>Humidity, % vol</i>	<i>Dry Bulb Temperature, °F</i>	<i>Dewpoint, °F</i>
13	199	135.3
14	199	138.2

If the flue gas humidity content were to increase by 1 % (Table 2) through any means, the operator would need to increase the scrubber outlet temperature by 3°F to maintain the same safety margin. This clearly demonstrates the need to monitor the humidity for improved scrubber efficiency as well as to maintain a proper margin for safe operations.

A humidity measurement is also very useful in identifying scrubber upsets such as nozzle erosion and plugging.

Feed Forward Scrubber Control

One method to improve operational control at a lower approach-to-saturation temperature is to install a flue gas moisture analyzer (H₂O Moisture Analyzer) and use the instrument output as a guide to control moisture injection. One approach is to install a humidity sensor prior to the dry scrubber, where the instrument can monitor the moisture variables within the process as well as provide the added benefits of improved heat rate calculations and tube leak detection. An outlet dewpoint temperature can be calculated from the scrubber inlet humidity and the temperature drop across the scrubber. Scrubber upset conditions will not be identified with this type of control though.

An alternative method, the one studied in this paper, is to install the instrument downstream of the scrubber and use the instrument's output to directly control the water injection. This method

¹ Redinger, Kevin, "Impact of Variable Plant Conditions on SDA Operation", 2001 Dry FGD Users Conference

has the advantage of being able to monitor scrubber upset conditions and detecting nozzle failures but will not be able to directly monitor tube leaks or other process variations at the scrubber inlet location. However, through careful monitoring of the system operators should be able to detect tube leaks from a decrease in water injection rate needed to maintain humidity levels.

With the improved control on moisture injection and the ability to monitor the flue gas humidity and flue gas dewpoint temperature in real-time, the plant should be able to increase SO₂ removal efficiency and improve limestone stoichiometry.

Instrument Description

A detailed description of the instrument is available in a previously published paper.² A typical unit is shown in Figure 3 and an installation in Figure 4.



Figure 3. Typical H₂O System.



Figure 4. SRI H₂O installation.

The H₂O absolute humidity sensor is a direct measurement of the water molecule and the units are g/Nm³. The dewpoint temperature can then be calculated by the DCS system anywhere there is a dry bulb temperature measurement. The equations to convert absolute humidity to dewpoint are as follows:

Equation 1

$$P_d = \left(1 - \left\{0.0001 \times \left[\sqrt{(0.1 \times T) + 1} + 4\right]\right\}\right) \times 461.51 \times (T + 273.15) \times F \times 0.00001$$

where

$$F = \text{Absolute Humidity (g/Nm}^3\text{)}$$

² Kohler, Hans .M., and Mathew, A., Continuous in-situ and elevated temperature moisture measurement in high particulate reactive processes, ISA, 1996 - Paper #96-002 (1996)

P_d = Water Vapor Pressure (kPa)

T = Dry Bulb Temperature (°C)

Equation 2

$$DP = \frac{234.175 \times \ln\left(\frac{P_d}{6.1078}\right)}{17.08085 - \ln\left(\frac{P_d}{6.1078}\right)}$$

where

DP = Dew-point Temperature (°C)

Because the H₂O measurement provides a moisture concentration, dewpoint calculations can be done at any dry-bulb temperature location. The dry scrubber outlet (prior to the particulate collection device) is the safest and most accurate location to monitor and control the dewpoint temperature. Leaks across the particulate collection device will bias the humidity concentration on the low side, which would increase the rate of corrosion if the control was after the collection device.

The H₂O analyzer comes equipped with a ceramic surface filter, which allows the system to be installed at the dry scrubber outlet (prior to the particulate collection device). The pores of the ceramic filter are between 50-100 nm in size and the particles can not build up in the pores because they are larger than the pores. Installing the probe perpendicular to or in the direction of the process flow provides turbulence around the filter, causing a self-cleaning effect. Filter maintenance is not required, but H₂O does recommend a spare filter in case the ceramic filter is damaged or broken.

The probes will work reliably in temperatures up to 443°C (830°F). The probe is 76mm (3 in) in diameter and 1 meter (3.28 ft) long. The probe attaches to a 4 inch, 150 lb ANSI flange and is powered by a 110v / 10amp power source. The system comes equipped with a standard 4-20mA output.

The probe is heated to a constant temperature above the maximum normal operating process temperature and is directly introduced into the process stream. The heated probe enables the moisture measurement to be made at a constant temperature and minimizes corrosion of the probe components due to moisture condensation. Additionally, particulate build-up is reduced on a heated probe.

The sensor is a chamber which forms an open capacitor whose dielectric varies with the process environment. The moisture in the form of vapor diffuses through a membrane filter into the capacitor.

After a few minutes for stabilization, the transmitter unit displays the moisture value (in % volume or any user selectable unit) and provides an analog output for process control.

Linearization and mathematical correction of the sensor signal are not needed due to the direct physical measurement principle. The measured signal is directly proportional to the number of water molecules. A constant zero reference is provided by the hermetically sealed capacitor

provided in the probe. Thus, once the zero reference is established, only one other point of calibration is necessary for the entire range (0-100 % volume).

Operating Experience at Southern Research Institute Combustion Research Facility

In 2000-01, Southern Research Institute was studying, through two separate collaborative research and development projects funded by the US Environmental Protection Agency, the development of a low-cost, semi-dry FGD system targeted towards application in developing Asian nations and China. Details of the technology and the work are available in previous publications. The pilot system was installed at the Southern Company Services / Southern Research Institute Combustion Research Facility, located at Southern Research Institute's Birmingham, AL campus. The Combustion Research Facility is designed for up to six million Btu per hour firing on natural gas or coal, which is equivalent to 1.75 MW thermal or about 0.6 MW electric. The facility has been described in more detail in previous publications.³

Because of difficulties experienced in the first attempt (Summer 2000) to demonstrate the new technology at small scale, Southern Research Institute purchased a H₂O Moisture Analyzer monitor to assist operations through better determining approach-to-saturation temperature and also obtaining real-time measurements of flue gas humidity and adiabatic saturation temperature. The instrument was installed downstream of the semi-dry scrubber's particulate control system, and integrated in the plant control system. The unit was specified to report to the DCS the flue gas dewpoint in deg F. Modifications to the control package were made to display the dewpoint and to calculate the approach-to-saturation temperature from the fabric filter outlet temperature. As water was added to the flue gas through two routes - with the sorbent and as a trim - the DCS used the approach temperature as feedback control for trim moisture injection rate.

With the improved control on moisture injection and some other system modifications, Southern Research Institute was able to demonstrate operation and performance of the technology in Winter 2001, meeting the objective of demonstrating greater than 95 % SO₂ collection. Frequency of forced outages due to reagent feed pluggage were reduced because the control modifications allowed us to inject more moisture in through the trim control, resulting in a drier reagent feed material. Also, frequency of forced outages due to reactor pluggage and solids buildup were also reduced, partly due to better moisture control.

Projected Cost Savings

Typical pro forma costs savings are shown in the following table. Costs savings are calculated for the first 12 months of operation, and are done for three different coal types or fuel sulfur loadings. Improvement in process performance is estimated, aiming for a 5 % reduction in excess lime consumption and a moderate SO₂ removal efficiency improvement. As can be seen from the table, annual cost savings and payback period will be directly affected by fuel sulfur content and the ability to sell or offset purchases of SO₂ allowances. Summary of the cost savings are shown graphically in Figure 5.

³ Monroe, L.S.; Clarkson, R.J.; Stallings, J., *Comparison of Pilot-Scale Furnace Experiments to Full-Scale Boiler Performance of Compliance Coals*, EPRI/EPA 1995 Joint Symposium on Stationary Combustion NO_x Control, Kansas City, MO, May 16-19, 1995.

Table 3. Projected first 12 months cost savings, by fuel type or fuel sulfur.

	<i>Coal Type</i>		
	Pratt Seam	Galatia	PRB
% S	1.48%	1.01%	0.49%
Plant Output, MW	300	300	300
Coal fired, lb/hr	257,108	244,610	292,887
SO ₂ , lb/hr	7,610	4,941	2,870
Calculation of Savings due to Reduced Lime Consumption			
<u>Baseline</u>			
Lime Stoichiometry	1.60	1.55	1.50
Lime, lb/hr (CaO basis)	7,414	4,663	2,622
<i>Anticipated Reduction in Excess Lime</i>	5%	5%	5%
<u>Close ATS</u>			
Lime Stoichiometry	1.57	1.52	1.48
Lime, lb/hr (CaO basis)	7,275	4,581	2,578
<u>Savings</u>			
Lime Savings, ton/yr	556	331	175
Lime Savings, \$/yr (at \$50/ton)	\$ 27,804	\$ 16,548	\$ 8,739
Calculation of Savings due to Avoided SO₂ Emissions			
<u>Baseline</u>			
SO ₂ Removal Efficiency, %	87.7%	85.0%	85.0%
SO ₂ Removed, lb/hr	6,674	4,200	2,440
<u>Close ATS</u>			
SO ₂ Removal Efficiency, %	93.9%	92.5%	92.5%
SO ₂ Removed, lb/hr	7,142	4,571	2,655
<u>Savings</u>			
Avoided SO ₂ Emissions, lb/hr	468	371	215
Avoided SO ₂ Emissions, tons/yr	1,872	1,482	861
Value of Credits (at \$115 per ton)	\$ 215,298	\$ 170,469	\$ 99,025
Total Savings	\$ 243,102	\$ 187,016	\$ 107,764
Reduction in Purchased Lime	\$ 27,804	\$ 16,548	\$ 8,739
Avoided SO₂ Credits Purchased	\$ 215,298	\$ 170,469	\$ 99,025

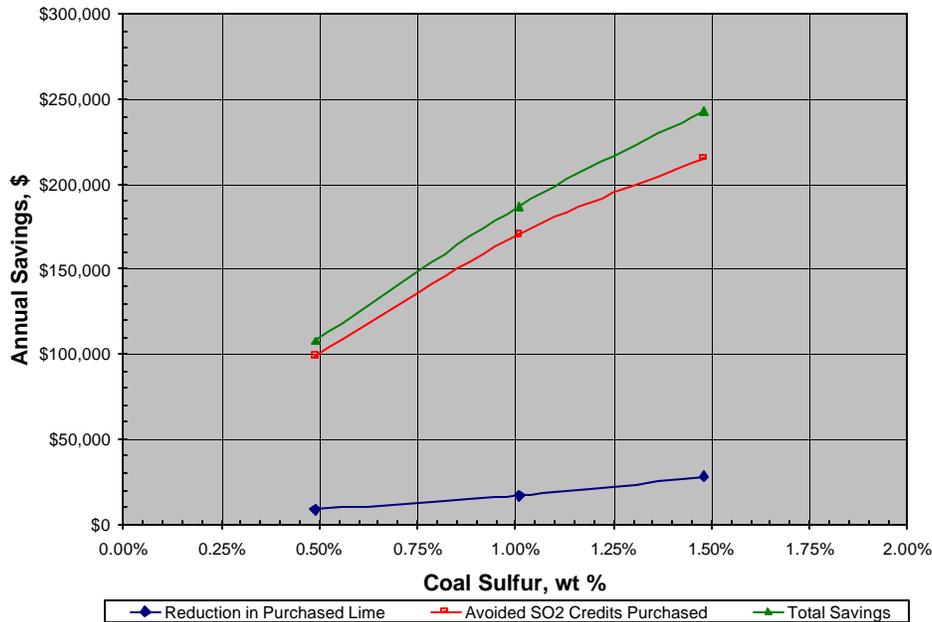


Figure 5. Projected Annual Cost Savings by Coal Sulfur Content.

Increasing Flue Gas Humidity to Improve SO₃ Control

An additional improvement in plant emissions can be gained through increasing flue gas humidity to reduce SO₃/H₂SO₄ emissions.

In coal-fired plants, H₂SO₄ vapor is created in the ductwork downstream of the boiler by the combination of water vapor and sulfur trioxide (SO₃), both of which are produced during the coal combustion process. Approximately 1/2 to 1 1/2 % of the total coal sulfur is converted to SO₃. After formation, some of the H₂SO₄ may condense and be emitted as an aerosol depending on the flue gas temperature. Although western coal consumers are not typically concerned with sulfuric acid mist emissions, primarily due to the low sulfur content of the coal and the usually alkaline nature of the flyash, sulfuric acid emissions are a concern for eastern coal-fired plants.

The most important mechanism responsible for the control and collection of SO₃ emissions is the heterogeneous SO₃/H₂SO₄ condensation onto existing particles when the local temperature is less than the dew point corresponding to H₂SO₄ vapor pressure in the gas phase. The portion of the H₂SO₄ that condenses from the vapor to an aerosol is a function of the total H₂SO₄ concentration, the flue gas temperature and the flue gas moisture content. In cases where the flue gas temperature exceeds the H₂SO₄ dewpoint, no acid aerosols are formed. However, when the flue gas temperature is at or below the H₂SO₄ dewpoint, an acid aerosol / vapor mixture is present. The dew point of H₂SO₄ is a function of the partial pressure of the H₂SO₄ and the moisture in the flue gas.

A typical SO₃ to H₂SO₄ conversion curve is shown in Figure 6 and a typical saturation curve shown for H₂SO₄ aerosol formation is shown in Figure 7. From examination of Figure 6, one can see that any SO₃ present in the flue gas at typical Dry FGD operating temperatures will be present as H₂SO₄, and that from Figure 7, if the flue gas temperature is low enough and if the

flue gas moisture content is sufficient enough, the H_2SO_4 will be present as an aerosol which can be collected by the outlet fabric filter.

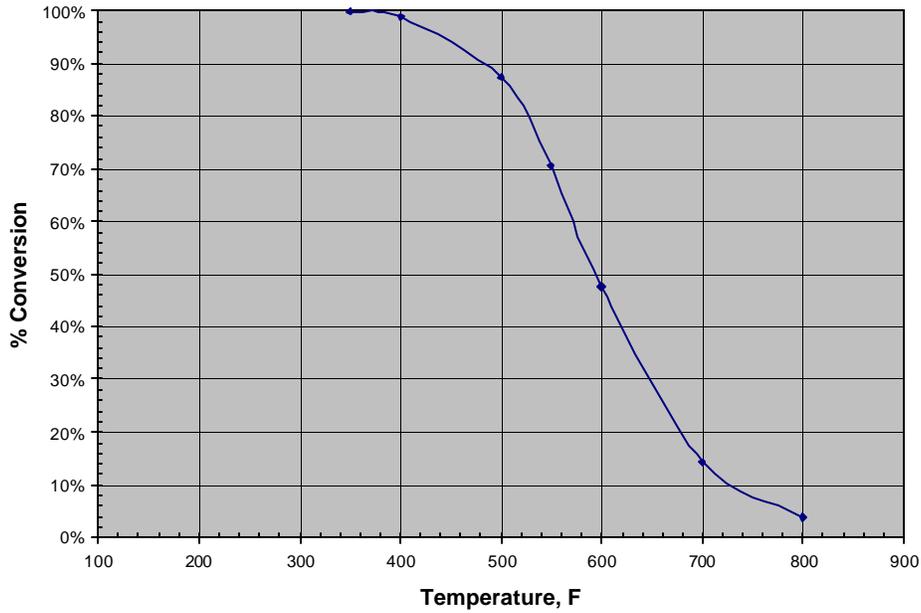


Figure 6. SO₃ to H₂SO₄ Conversion by Flue Gas Temperature.

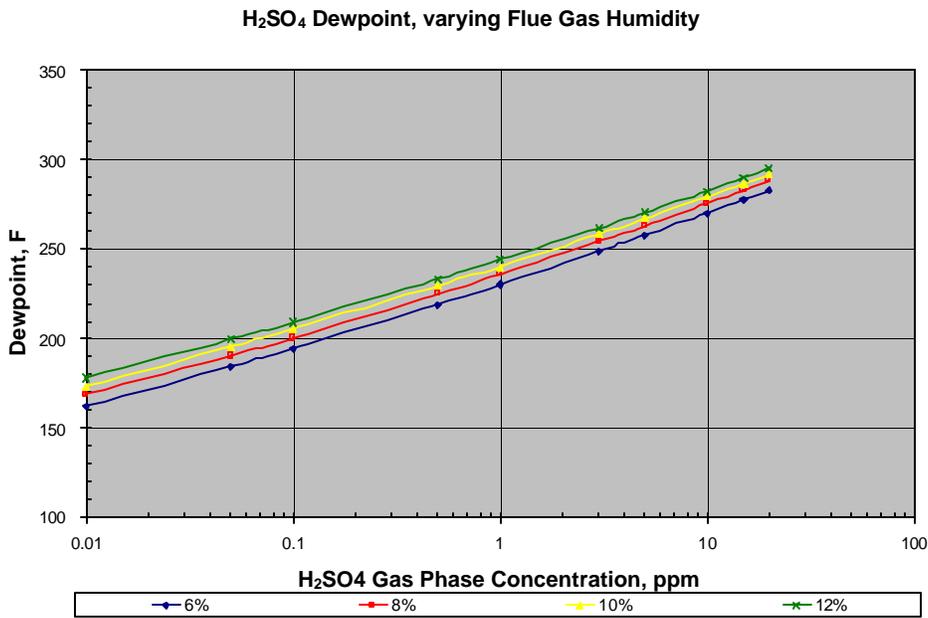


Figure 7. H₂SO₄ Dewpoint, by Flue Gas Temperature and Flue Gas Humidity.

Conclusions

Implementation of a real-time humidity sensor in a feedback control loop is an effective means to control moisture injection into a dry flue gas desulfurization system and to improve process performance. In particular, SO₂ collection efficiency and reagent utilization improve through system operation at high gas moisture contents (or closer approach-to-saturation temperatures). Through improvements in system performance it is possible to quickly recover installation and maintenance costs, yielding a net positive return on investment.

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Additional Resources

For more information regarding this work please contact:

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