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Comparison of Thermoelectric and Permeation Dryers for Sulfur Dioxide Removal During Sample Conditioning of Wet Gas Streams

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Abstract

Flue gas conditioning for moisture removal is commonly performed for criteria pollutant measurements, in particular for extractive CEM systems at combustion sources. An implicit assumption is that conditioning systems specifically remove moisture without affecting pollutant and diluent concentrations. Gas conditioning is usually performed by passing the flue gas through a cold trap (Peltier or thermoelectric dryer) to remove moisture by condensation, which is subsequently extracted by a peristaltic pump. Many air pollutants are water-soluble and potentially susceptible to removal in a condensation dryer from gas interaction with liquid water. An alternative technology for gas conditioning is the permeation dryer, where the flue gas passes through a selectively permeable membrane for moisture removal. In this case water is transferred through the membrane while other pollutants are excluded, and the gas does not contact condensed liquid. Laboratory experiments were performed to measure the relative removal of a water-soluble pollutant (sulfur dioxide, SO₂) by the two conditioning techniques. A wet gas generating system was used to create hot, wet gas streams of known composition (15% and 30% moisture, balance nitrogen) and flow rate. Pre-heated SO₂ was dynamically spiked into the wet stream using mass flow meters to achieve concentrations of 20, 50, and 100 ppm. The spiked gas was directed through a heated sample line to either a thermoelectric or a permeation conditioning system. Two gas analyzers (Western Research UV gas monitor, KVB/Analect FTIR spectrometer) were used to measure the SO₂ concentration after conditioning.

Both analytic methods demonstrated that SO₂ is removed to a significantly greater extent by the thermoelectric dryer. These results have important implications for SO₂ monitoring and emissions trading.

Introduction

Flue gas conditioning for moisture removal is commonly performed for criteria pollutant measurements, in particular for extractive CEM systems at combustion sources and performance of EPA Methods 6C (SO₂), 7E (NO_x), and 10 (CO). These instrumental test methods require the gas sample to have low moisture because water vapor is an interferent in ultraviolet absorbance (SO₂), chemiluminescence (NO_x), and non-dispersive infrared (CO) measurements. Since industrial air emissions, particularly combustion process emissions, can have a high moisture content, sample conditioning is employed for moisture removal prior to instrumental measurement. The goal of sample conditioning is selective moisture removal while leaving the concentrations of other species unaltered.

Sample conditioning is usually performed by cooling the gas to approximately 35 °F (2 °C) to condense the water vapor and subsequently removing the condensate with a peristaltic pump. The concentrations of many emission matrix constituents can be affected by sample conditioning, either by condensation from cooling below the boiling point or by dissolution in the condensed water, and so cannot be accurately measured in a conditioned sample. It is well known, for example, the acids such as HCl and HF and polar organic compounds such as methanol are effectively removed from stack gas in a condensation-type conditioning system. Gas conditioning should have little impact on the concentrations of compounds with low boiling points and low water solubility, such as CO and NO. However, gas conditioning is used extensively for measurement of SO₂, which has a relatively high boiling point (-10 °C) and water solubility.

A laboratory evaluation was performed to compare the performance of two different sample conditioning systems for transport of sulfur dioxide (SO₂) in wet gas streams. The test objective was to measure the SO₂ concentration of several test gas mixtures after treatment by the sample conditioning systems and determine if SO₂ was lost in the conditioning process. This paper describes the experimental approach used to compare the sample conditioning systems and reports the results of the investigation.

Experimental

A laboratory evaluation program was conducted to measure the effect of two different types of sample conditioners (permeation and thermoelectric dryers) on SO₂ concentrations in hot, wet gas streams. The wet gas streams were generated by bubbling nitrogen gas at a flow rate of 5 liters per minute (lpm) through a series of water-filled glass impingers immersed in a variable temperature water bath. The gas stream moisture content was controlled by the bath temperature and the nitrogen flow rate. The conditions required to obtain moisture concentrations of 15 and 30% (±10%) were determined experimentally. Moisture content was measured gravimetrically using EPA Method 4. FTIR (Fourier Transform Infrared) measurements were used to verify that the moisture content remained consistent throughout the test program.

SO₂ (3067 ppm, 1% analysis, Scott Specialty Gases) was quantitatively spiked into the wet gas stream to achieve wet-basis concentrations of 100, 50, and 20 ppm at each moisture level. Electronic mass flow meters (Sierra Top-Trak, 0-250 SCCM and 0-10 LPM flow rates, 2% accuracy) were used to measure and control the spike and nitrogen flow rates. Spike dilution ratios ranged from 30:1 to 150:1 (wet stream:spike) using spike flow rates of 29-238 cubic centimeters per minute (ccm). The spike gas was preheated prior to injection into the wet stream to prevent moisture condensation.

The spiked gas was transported through a 50' heated sample line (300 °F, 148 °C) to the sample conditioning equipment. Following conditioning the SO₂ concentration was measured using a UV absorbance analyzer and an FTIR spectrometer. The SO₂ monitor was operated and calibrated as per EPA Method 6C. The FTIR measurements conformed to the EPA FTIR Protocol. The FTIR measured both SO₂ and moisture.

Separate test runs were performed at each moisture level using the two conditioning systems. FTIR measurements verified the gas stream composition remained consistent both during and between test runs. In order to ensure the proper operation of the equipment, adequate warm up and equilibration time was allotted under each test condition. Test runs were performed at two moisture levels (15 and 30%) using three SO₂ concentrations (100, 50, 20 ppm) and two separate gas conditioning systems. In addition, test runs were performed at two concentrations (50, 100 ppm) under dry conditions by bypassing the moisture generator and spiking the SO₂ directly into the nitrogen flow.

Gas Conditioning Systems

Two gas conditioning systems were compared in the evaluation. Both the thermoelectric and permeation conditioners were new and had been received from the manufacturer immediately prior to the laboratory evaluation. The M&C Model EC/ECU gas cooler is a 4-pass thermoelectric gas dryer. Hot, wet gas flows through a set of 4 glass impingers maintained at 41 °F (5 °C), with the condensed moisture continuously removed using peristaltic pumps. The conditioned gas has a residual moisture content of 0.84%.

The Perma Pure GASS (Gas Analysis Sampling System) conditioner is based on removal of moisture by selective adsorption and permeation through Nafion polymer. The GASS system contained two dryer tubes for optimal drying capacity. Hot, wet gas flows in one direction inside a bundle of Nafion tubes while a counter-flow of purge gas (nitrogen) passes exterior to the tubes. The purge gas flow rate was maintained at 25 liters/minute. A temperature gradient is imposed on the dryer, with the wet gas inlet at 194 °F (90 °C) and the dried gas outlet at ambient temperature. The purge gas carries away moisture removed from the treated gas. A permeation dryer provides more effective moisture removal and the conditioned gas dew point is lower than the thermoelectric dryer.

Pre-Test Preparations

Digital mass flow meters and needle valves were used to control the nitrogen and the spike gas flow rates. The nitrogen flow was maintained at 5.0 lpm and measured on a 0-10 lpm range flow meter. SO₂ spike gas flow rates ranged from 39 to 238 ccm and were measured with a 0-250 ccm range flow meter. The accuracy of the 0-250 ccm and 0-10 lpm flow meters was verified by comparing the meter readout with a calibrated bubble flow meter. Three point linearity tests demonstrated the meters were accurate to within 2% of the full scale value as specified by the manufacturer.

Gas streams containing 15% or 30% moisture were generated by flowing nitrogen gas through a series of 5 water-filled glass impingers immersed in a variable temperature water bath (Figure 1). The moisture output depends on the gas flow rate and the bath temperature, and in this study the gas flow rate was kept constant and the moisture output was controlled by adjusting the bath temperature. The moist gas generator system was calibrated by measuring the outlet moisture content as a function of bath temperature. Figure 2 displays the measured moisture content as well as the saturation vapor pressure of water. The figure demonstrates that the generator output tracks with the water saturation vapor pressure. Moisture levels of 15% and 30% were obtained by setting the bath temperature to 64 °C and 77 °C, respectively.

Test Procedure

At the start of each test day, the moisture generator impingers were filled with deionized water and the bath temperature was set appropriately for the desired moisture level. Nitrogen was allowed to

flow through the system for one hour to ensure a consistent moisture output. The gas conditioning system was also allowed to warm up (permeation) or cool down (thermoelectric) for one hour prior to testing.

Table 1 is a test matrix showing the order in which measurements were performed. Each test run was performed as follows:

- Pre-Run EPA Method 4 gas moisture content measurement
- Pre-Run FTIR Background Spectrum measurement
- Pre-Run FTIR Calibration Transfer Standard measurement
- SO₂ spike flow commenced; gas flows through conditioning system for 15 minutes
- Conditioned gas monitored by FTIR to verify conditioner output is stable (± 1 ppm)
- SO₂ UV analyzer calibration error and linearity checked at start of day using 4 gas standards. SO₂ calibration checked prior each run (zero, upscale)
- Conditioned gas directed to UV analyzer. Signal monitored till stable (± 1 ppm), then data collected for 15 minutes and averaged
- Conditioned gas directed to FTIR analyzer. Data collected for 15 minutes (3 spectra) and averaged
- Unconditioned gas directed to FTIR analyzer. Data collected for 10 minutes (3 spectra) and averaged
- Post-Run UV analyzer calibration check (zero, upscale). UV analyzer data corrected for drift
- Post-Run FTIR Calibration Transfer Standard measurement
- Spike flow removed. Post-Run Method 4 gas moisture measurement. Pre- and Post-Run moisture readings are averaged

Sampling And Analytical Methods

Sampling and analytical procedures recommended by the United States Environmental Protection Agency were employed in the test program. The methods are briefly described below.

Moisture Measurement by EPA Method 4

Samples were withdrawn at a constant rate from the heated line using a Method 6 meter box. The hot, wet gas passed through four chilled midget impingers. The first two impingers each contained 10 mL of water, the third remained empty, and the fourth contained preweighed silica gel. Constant rate sampling was conducted and each run was 15 minutes in duration. The set of impingers was weighed on an electronic balance before and after the sampling run. The volume of water vapor collected was determined from the weight difference and entered into moisture content calculations.

Sulfur Dioxide Measurement by EPA Test Method 6C

EPA Method 6C was used for sampling and analysis of SO₂. The extractive monitor requires gas sample conditioning to eliminate any possible interference (i.e., water vapor and/or particulate matter) before being injected into the analyzer. The output from the monitor was connected to a computerized data acquisition system (DAS). A four-point analyzer calibration check was conducted at the start of each test day, and zero and upscale calibration drift was measured after each run. The calibration error ($\pm 2\%$), percent of span drift ($\pm 3\%$), and percent of span system calibration checks ($\pm 5\%$) were within acceptable limits. SO₂ readings were corrected for calibration drift.

A Western Research Model 721AT2 analyzer was used to measure SO₂ by quantitative measurement of the absorption of UV radiation by SO₂ molecules. The analyzer uses a single light source which emits an appropriate wavelength, illuminating a cell through which the sample is continuously passed. Narrow band optical filters are rotated through the beam, and the radiation passed is detected by a single photodetector. The signal pulses from the photodetector are separated by a demultiplexor into a measuring channel and a reference channel. A log ratio amplifier computes the logarithm of the ratio of the input signals, producing a signal that is proportional to the

concentration of the SO₂. SO₂ concentrations are displayed on the front panel digital display meter and transmitted to the DAS.

Measurement of Gaseous Compounds by FTIR

Extractive FTIR spectroscopy was used to quantify SO₂ and H₂O according to the EPA document "Protocol for Applying Fourier-Transform Infrared (FTIR) Spectroscopy in Emission Testing." Pretest and post-test calibration procedures were performed as outlined in the FTIR Protocol.

During each sampling run, the gas continuously flowed from the gas conditioner (in dry measurements) or from the heated sample line (in wet measurements) to the FTIR gas cell. The test gas flowed through the cell as spectra were recorded. A Baratron capacitance manometer measured the gas cell pressure which was maintained equal to ambient atmospheric pressure during spectral measurements. Three spectra were measured at each test condition and the results were averaged.

The FTIR system included a medium-resolution interferometer (KVB/Analect Model RFX-40), a heated variable pathlength gas cell, a liquid nitrogen cooled mercury cadmium telluride (MCT) broad band infrared detector, and a PC computer. The nominal spectral resolution of the system was one wavenumber (inverse centimeter). The gas cell (Infrared Analysis, Inc. Model 5-22H) was maintained at 250 °F using heated jackets and temperature controllers. The inside walls and mirror housing of the cell were Teflon coated to minimize sample loss. The cell path length was set at 4.4 meters.

The theory of operation is based on the principle of absorbance of infrared radiation by gaseous organic and inorganic molecules. The gas is transported to a heated gas cell which is optically coupled to the FTIR spectrometer. The spectrometer transmits infrared radiation through the gas cell to an infrared-sensitive detector, and monitors the total infrared intensity as a function of wavelength over the entire mid-infrared region (approximately 2.2-20 microns). Molecules absorb infrared radiation in distinct patterns called spectra, where the intensity of absorbance is directly proportional to the concentration. By examination of the FTIR spectra the gas constituents can be identified and quantified. The quantification is performed on a personal computer using a mathematical analysis of the effluent spectrum. In this analysis the effluent spectrum is compared to carefully prepared, quantitative reference spectra of the effluent constituents. The FTIR spectrometer system is sensitive and capable of detecting numerous organic and inorganic species at levels in the low ppm range, though the detection limit is dependent on the compound and the gas matrix. The FTIR measurement is insensitive to gases such as nitrogen and oxygen (homonuclear diatomics). Some common gases, such as carbon dioxide and water vapor, can interfere with the analysis for certain pollutants when present at high concentration.

FTIR spectra were analyzed using the K Matrix method (least squares multicomponent analysis). Quantitative laboratory reference spectra of SO₂ (25.1, 48.2, 92.2, and 500 ppm) and water (three concentrations) were used in the computerized analysis. The SO₂ reference spectra were measured from the same protocol gas cylinders as used in calibrating the UV monitor. The FTIR analysis was verified to be accurate to ±1% by measurement of SO₂ cylinder standards and zero (nitrogen) spectra. The analytic routine was checked for cross-sensitivity between water and SO₂ and was demonstrated to measure each species independently.

A new FTIR background spectrum was measured prior to each test run by filling the gas cell with nitrogen and coadding 200 scans. Sample spectra used 100 coadded scans. Calibration Transfer Standard (CTS) spectra were measured before and after each test run as required by the FTIR Protocol. The CTS gas was 100 ppm Ethylene (balance nitrogen, ±1% analysis, Scott Specialty Gases). Spectra of SO₂ calibration standards and a zero gas (nitrogen) were measured several times during the test program to verify the FTIR accuracy.

Results

The results are summarized in Tables 2 and 3. The permeation dryer yielded a higher concentration of SO₂ under all test conditions, with the Percent Recovery ranging from 90.7% to 96.3% for the UV analyzer and 93.9% to 98.6% for the FTIR. The thermoelectric dryer, by comparison, had Percent Recovery values ranging from 86.7% to 91.8% (UV analyzer) and 87.8% to 92.5% (FTIR analyzer).

Discussion

The SO₂ data are plotted in Figures 3 and 4. Figure 3 compares the Percent Recovery of the SO₂ spike for the two analyzers and two conditioning systems as measured by the FTIR and UV analyzers. Figure 4 displays the Percent Difference in SO₂ recovery between the two conditioning systems. The Figures demonstrate that SO₂ is transported more effectively by the permeation dryer under all test conditions. The trend in this data indicates that SO₂ loss is independent of moisture content for the permeation system over the range of moisture levels tested, while for the thermoelectric system SO₂ loss increases with moisture content.

The readings from the FTIR and UV analyzers were in good agreement (average difference: 0.5 ppm) and displayed identical trends. The FTIR SO₂ measurements tended to be slightly higher than the UV measurements. The FTIR and UV analyzers were demonstrated to be accurate and linear for measurement of SO₂ by measurement of protocol gas standards. Measurement accuracy is expected to be comparable to the protocol gases used for calibration ($\pm 1\%$).

All data are reported as measured, without any correction for possible variations due to the accuracy of the SO₂ spike gas ($\pm 1\%$) and the gas flow rates ($\pm 2\%$). Both conditioning systems were tested under identical conditions, using the same gas cylinders, flow meters, and gas flow rates. Inaccuracy in the SO₂ gas or flow rates will affect each conditioning system equally. Therefore, the experiments do not measure the *absolute* SO₂ removal for each system, but instead the *relative* SO₂ removal for the two systems.

One data point in Figure 4 requires additional clarification. At one test condition (0% moisture, 50 ppm SO₂), the FTIR measured a significant (6%) difference between the two dryers while the UV analyzer showed no difference, as would be expected in the absence of moisture. The reason for this discrepancy was the presence of residual moisture in the sampling and conditioning systems. Measurements on the thermoelectric dryer at the 0% moisture level were conducted immediately after completing 30% moisture runs, and low recoveries were encountered due to losses to condensate in the sampling system and dryer. The presence of residual moisture was confirmed by FTIR, which showed the thermoelectric dryer outlet moisture was 0.8% even though no moisture was entering the system. For the permeation dryer, FTIR and UV measurements were conducted at separate times. The FTIR measurement was made when the entire system had less residual moisture and SO₂ was transported more effectively. Residual moisture was present in the sampling system and permeation dryer during the UV measurement, thus reducing the SO₂ recovery. SO₂ recovery under these conditions would have been improved by ensuring no residual moisture was present in the sampling and conditioning equipment.

The experiments demonstrated that a condensation-type gas dryer effectively removes moisture from a hot, wet gas stream, but also reduces the SO₂ concentration in the conditioned gas. The permeation dryer, by comparison, is more effective in removing moisture from the gas stream while having a measurably reduced impact on the SO₂ concentration. The use of condensation conditioning systems at industrial sources could conceivably result in higher SO₂ losses than indicated by these experiments. For example, the lab evaluation examined the SO₂ loss in a matrix of deionized water, while the gas matrix at an industrial source will be considerably more complicated. In a combustion source, the condensate from gas conditioning can be highly ionic and acidic due to the presence of compounds such as SO₃ and HCl in the emissions. SO₂ solubility may be enhanced in this condensate compared with the neutral (deionized) water used in the current study. Secondly, the sampling flow rates at industrial tests are generally higher than the 5 liters/minute used in this

evaluation. At a higher flow rate, more condensate is formed during gas conditioning which would enhance SO₂ removal.

This study has important implications for measurement and monitoring of SO₂ emissions from industrial facilities. Condensation dryers are commonly used in CEM systems and source emission tests for criteria air pollutants. The results from these experiments indicate that losses of SO₂ from sample conditioning with condensation dryers can cause a low bias in emission measurements, particularly at high moisture sources. Industry emission permits and the system of SO₂ emission allotments and trading implemented in recent years rely upon accurate SO₂ emission measurements. More accurate SO₂ measurements can be obtained by using permeation drying systems for gas conditioning.

Conclusions

A laboratory comparison of permeation and thermoelectric gas conditioning systems was conducted to determine the relative transmission of a water soluble gas (SO₂) in the presence of 15% and 30% moisture. SO₂ was quantitatively spiked into hot, wet gas streams to achieve wet basis concentrations of approximately 20, 50, and 100 ppm and moisture concentrations of 0, 15, and 30%. The spiked gas was then treated by each conditioning system and the SO₂ concentration of the dried gas was measured by an ultraviolet SO₂ analyzer and an FTIR spectrometer. The experiments demonstrated that under all experimental conditions the permeation dryer was superior to the thermoelectric dryer for transport of SO₂, in particular at higher moisture levels.

References

EPA Protocol for the Use of Extractive Fourier Transform Infrared (FTIR) Spectroscopy in Analyses of Gaseous Emissions From Stationary Sources, EPA Document, Emission Measurement Technical Information Center (EMTIC) Bulletin Board, 1995.

Test Method 6C- Determination of Sulfur Dioxide Emissions From Stationary Sources (Instrumental Analyzer Procedure), Part 60, Code of Federal Regulations, 1996.

Test Method 4- Determination of Moisture in Stack Gas, Part 60, Code of Federal Regulations, 1996.

Calculations

This section summarizes the calculations used to determine the experimental conditions (gas flow rate, gas composition, spike flow rate). Flow rates were calculated to achieve wet basis concentrations of 20, 50, and 100 ppm at 15% and 30% moisture. The nitrogen flow rate was maintained at 5 liters/minute under all conditions.

Flow Rates

$$\% \text{ Moisture} = \frac{(\text{Moisture Flow Rate})}{(\text{Moisture Flow Rate} + \text{Nitrogen Flow Rate})} \quad 1$$

At 15% moisture, the moisture flow rate is 0.882 lpm, and the total flow is 5.882 lpm. At 30% moisture, the moisture flow rate is 2.143 lpm and the total flow rate is 7.143 lpm.

$$\text{Spike Flow Rate} = \frac{(\text{Total Flow Rate}) \times (\text{Target Spike Concentration})}{(\text{Spike Cylinder Concentration})} \quad 2$$

To obtain a spike concentration of 100 ppm in a 15% moisture gas stream from a spike cylinder containing 3000 ppm SO₂, the spike gas flow rate is 0.196 lpm or 196 ccm.

Expected Concentrations (Wet and Dry Basis) and Spike Recovery

For each run, the expected spike concentration was calculated based on the true spike cylinder concentration (3067 ppm SO₂), the measured percent moisture (average of pre- and post-run measurement), and the nitrogen and spike flow rates.

$$\text{Spike Concentration (wet basis)} = \frac{(\text{Spike Flow Rate}) \times (\text{Spike Cylinder Concentration})}{(\text{Nitrogen Flow Rate} + \text{Moisture Flow Rate} + \text{Spike Flow Rate})} \quad 3$$

$$\text{Spike Concentration (dry basis)} = \frac{(\text{Spike Flow Rate}) \times (\text{Spike Cylinder Concentration})}{(\text{Nitrogen Flow Rate} + \text{Spike Flow Rate})} \quad 4$$

$$\text{Dry Basis Concentration} = \frac{(\text{Wet Basis Concentration}) \times (100)}{(100 - \text{Percent Moisture})} \quad 5$$

Data from the analyzers and two gas conditioning systems were compared on a dry basis. The ratio of the measured dry concentration to the expected dry concentration yields the Percent Recovery reported in Table 3. The ratio of the Percent Recovery for the two conditioning systems yields the Percent Difference in system performance listed in Table 3.

$$\text{Percent Recovery} = \frac{(\text{Measured Dry Basis Concentration}) \times (100)}{(\text{Expected Dry Basis Concentration})} \quad 6$$

$$\text{Percent Difference} = \frac{(\text{Permeation Percent Recovery}) \times (100)}{(\text{Thermoelectric Percent Recovery})} - 100 \quad 7$$

Table 1: Laboratory Test Matrix

Date	Time	Run Number	Test Condition (Spike Level, Moisture, Conditioner)
5/1/96	15:12-15:46	1	100 ppm SO ₂ , 15% Moisture, Permeation
5/1/96	16:31-17:06	2	50 ppm SO ₂ , 15% Moisture, Permeation
5/1/96	17:50-18:05	3	20 ppm SO ₂ , 15% Moisture, Permeation
5/2/96	11:25-12:17	4	100 ppm SO ₂ , 30% Moisture, Permeation
5/2/96	13:06-13:43	5	50 ppm SO ₂ , 30% Moisture, Permeation

5/2/96	14:32-15:15	6	20 ppm SO ₂ , 30% Moisture, Permeation
5/2/96	16:20-16:35	4A	100 ppm SO ₂ , 0% Moisture, Permeation
5/2/96	17:01-17:15	5A	50 ppm SO ₂ , 0% Moisture, Permeation
5/3/96	11:00-11:35	7	100 ppm SO ₂ , 15% Moisture, Thermoelectric
5/3/96	13:08-13:43	8	50 ppm SO ₂ , 15% Moisture, Thermoelectric
5/3/96	14:52-15:30	9	20 ppm SO ₂ , 15% Moisture, Thermoelectric
5/6/96	10:45-11:20	10	100 ppm SO ₂ , 30% Moisture, Thermoelectric
5/6/96	13:13-13:49	11	50 ppm SO ₂ , 30% Moisture, Thermoelectric
5/6/96	15:15-15:52	12	20 ppm SO ₂ , 30% Moisture, Thermoelectric
5/6/96	17:00-17:15	10A	100 ppm SO ₂ , 0% Moisture, Thermoelectric
5/6/96	17:48-18:02	11A	50 ppm SO ₂ , 0% Moisture, Thermoelectric

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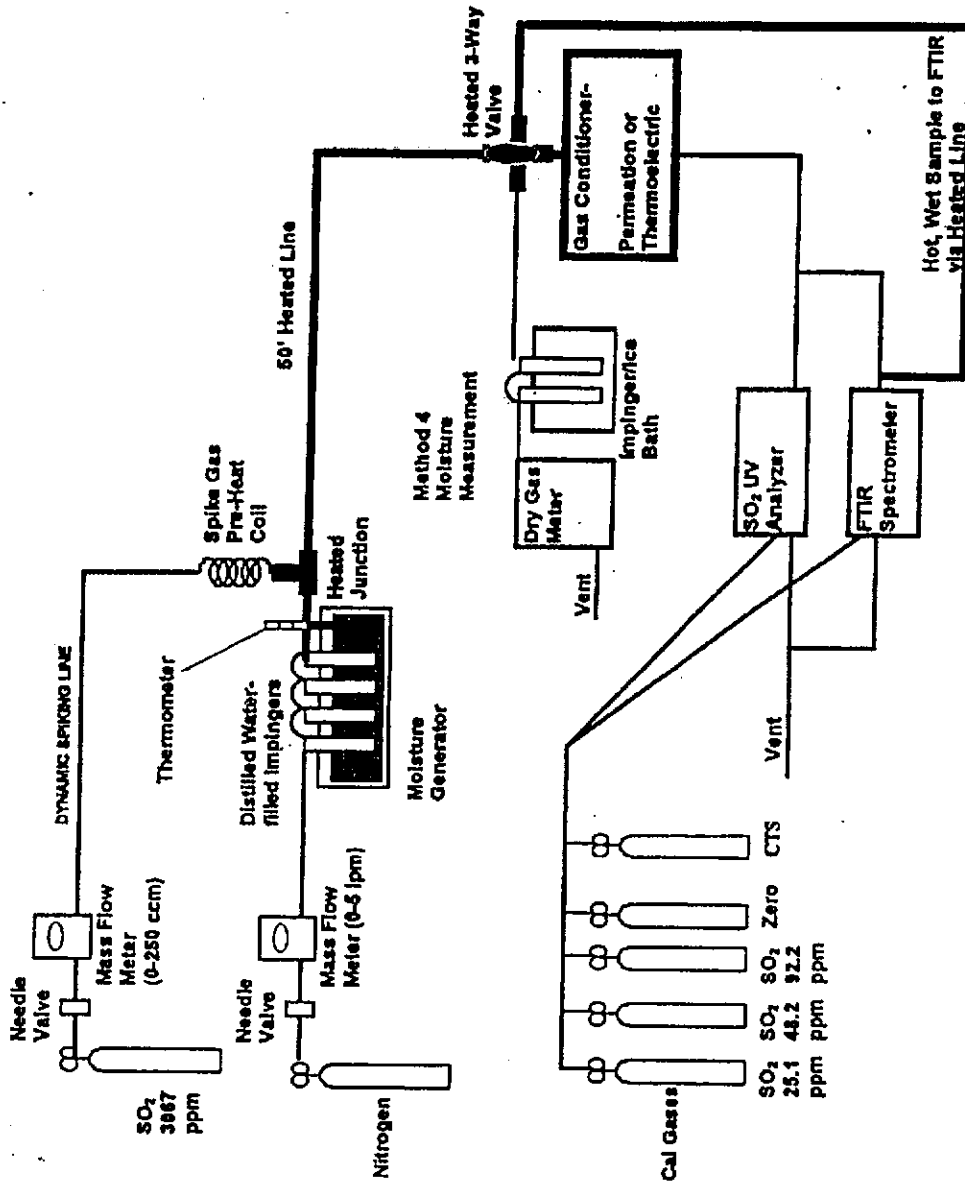


Figure 1: Experimental Apparatus for Evaluation of Gas Conditioning Systems

Wet Gas Generator Data

- ◊ Saturation Vapor Pressure
- ▲ Measured % Moisture

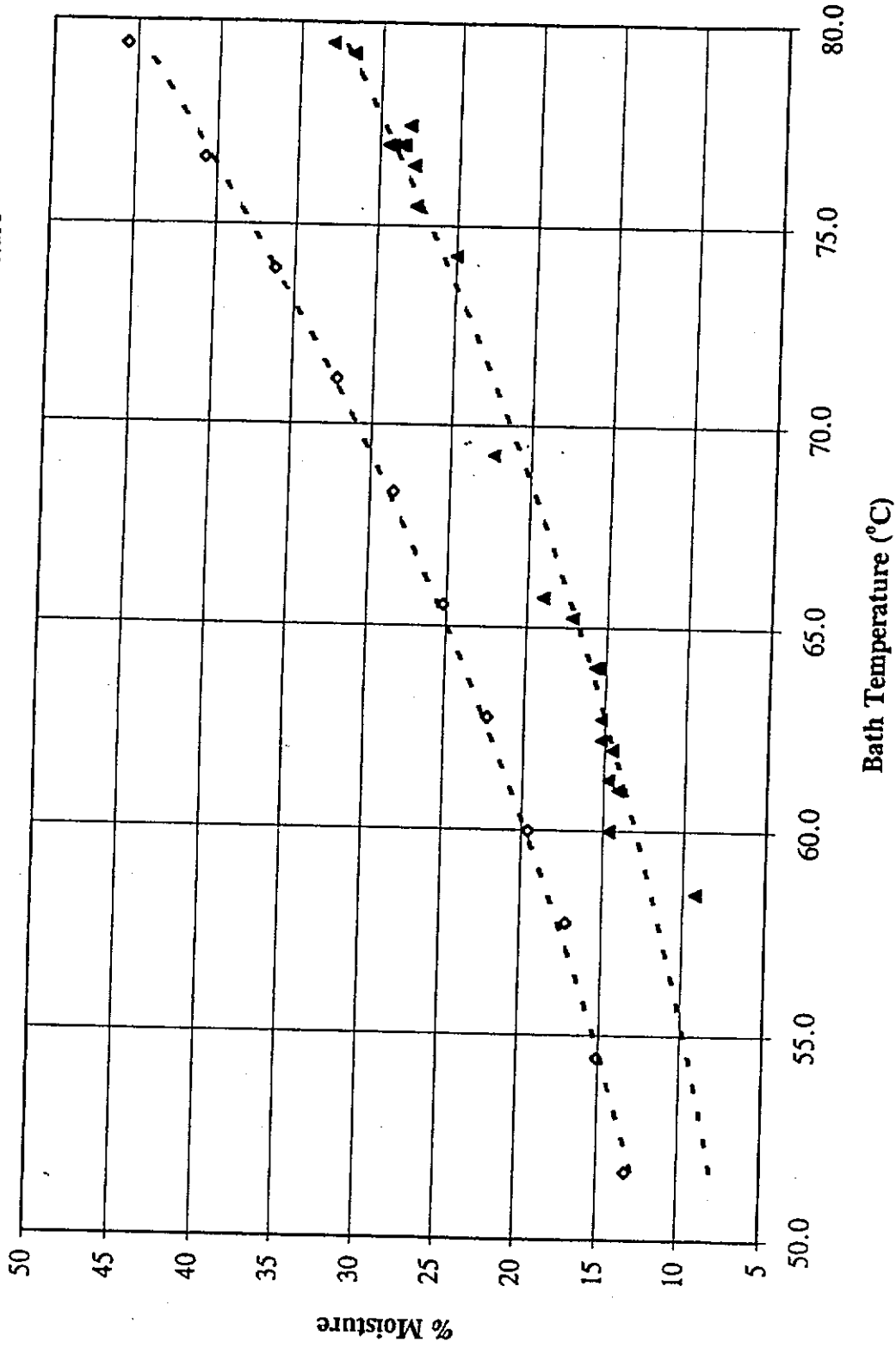


Figure 2: Wet Gas Stream Generator System Data

Table 2: Experimental Data, Permeation (PP) and Thermoelectric (TE) Gas Conditioners

Dryer	% H ₂ O	Expected (SO ₂ , Wet ppm)	Expected (SO ₂ , Dry ppm)	Measured UV (SO ₂ , Dry ppm)	% Spike Recovery	Measured FTIR (SO ₂ , Dry ppm)	% Spike Recovery
PP	0	50.0	50.0	45.3	90.7	47.3	94.6
PP	0	99.0	99.0	92.3	93.3	92.9	93.9
PP	14.5	20.2	23.6	22.3	94.3	22.2	93.9
PP	15.2	49.8	58.7	56.1	95.6	57.2	97.5
PP	15.2	98.2	115.7	110.8	95.8	111.1	96.0
PP	29.6	20.2	28.6	26.9	93.9	27.6	96.5
PP	29.4	50.4	71.4	68.7	96.3	70.3	98.6
PP	29.1	98.9	139.4	132.5	95.1	134.7	96.0
TE	0	50.1	50.1	45.4	90.6	45.1	90.1
TE	0	99.1	99.1	91.2	92.0	91.4	92.2
TE	15.7	19.8	23.5	21.0	89.3	21.2	90.3
TE	15.6	50.2	59.4	53.6	90.1	54.8	92.1
TE	15.4	97.9	115.7	106.2	91.8	107.0	92.5
TE	28.5	20.6	28.9	25.0	86.7	25.3	87.8
TE	28.6	51.0	71.4	63.2	88.5	65.1	91.3
TE	28.4	99.7	139.2	125.1	89.9	125.9	90.4

Table 3: Comparison of Permeation (PP) and Thermoelectric (TE) Gas Conditioner Performance

Test Condition		PP: % Recovery (UV)	TE: % Recovery (UV)	% Difference (UV)	PP: % Recovery (FTIR)	TE: % Recovery (FTIR)	% Difference (FTIR)
% H ₂ O	ppm SO ₂						
0	50	90.7	90.6	0.0	94.6	90.1	6.0
0	100	93.3	92.0	1.4	93.9	92.2	2.7
15	20	94.3	89.3	5.5	93.9	90.3	4.8
15	50	95.6	90.1	6.1	97.5	92.1	6.7
15	100	95.8	91.8	4.4	96.0	92.5	4.7
30	20	93.9	86.7	8.4	96.5	87.8	11.0
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30	100	95.1	89.9	5.8	96.0	90.4	7.2

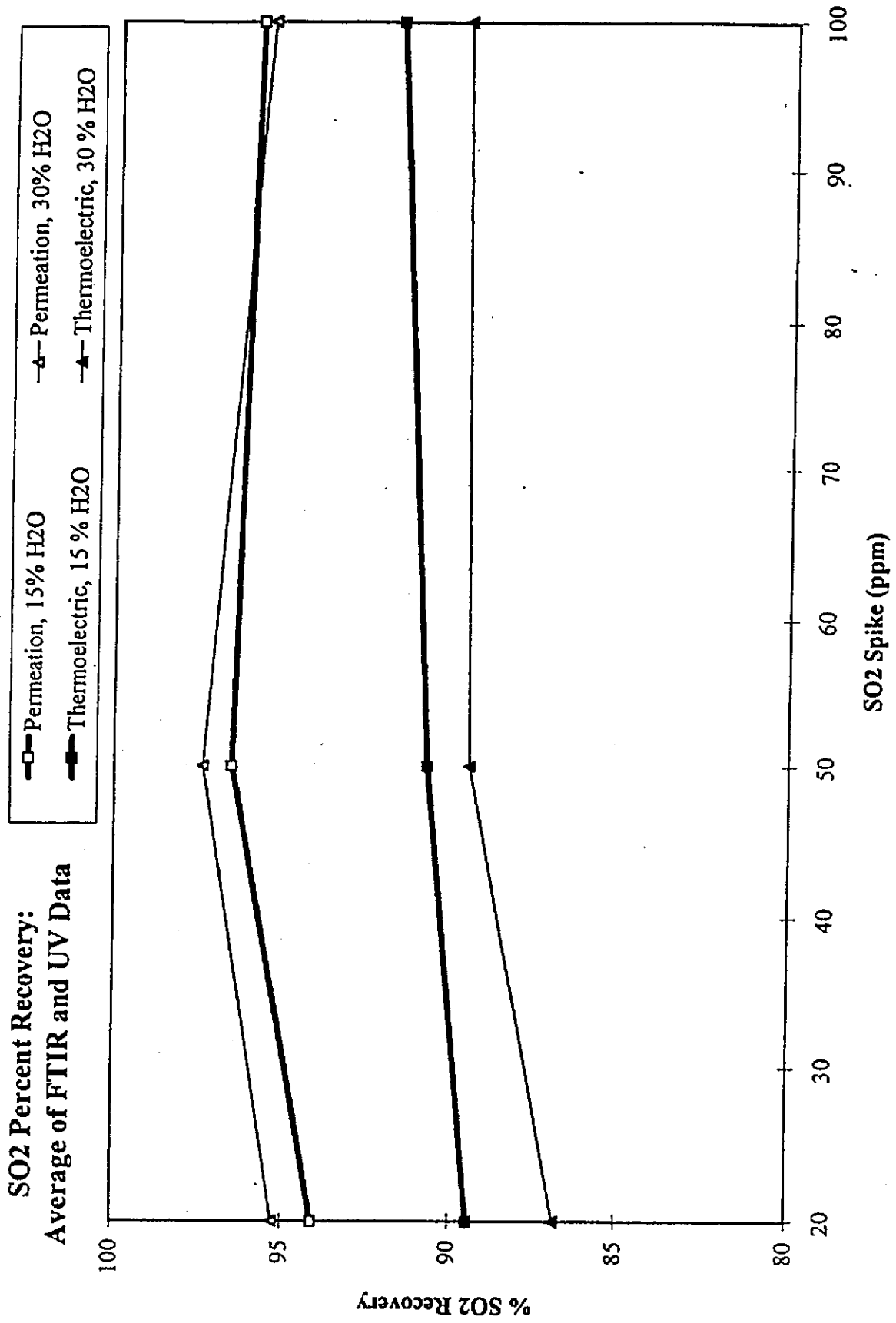
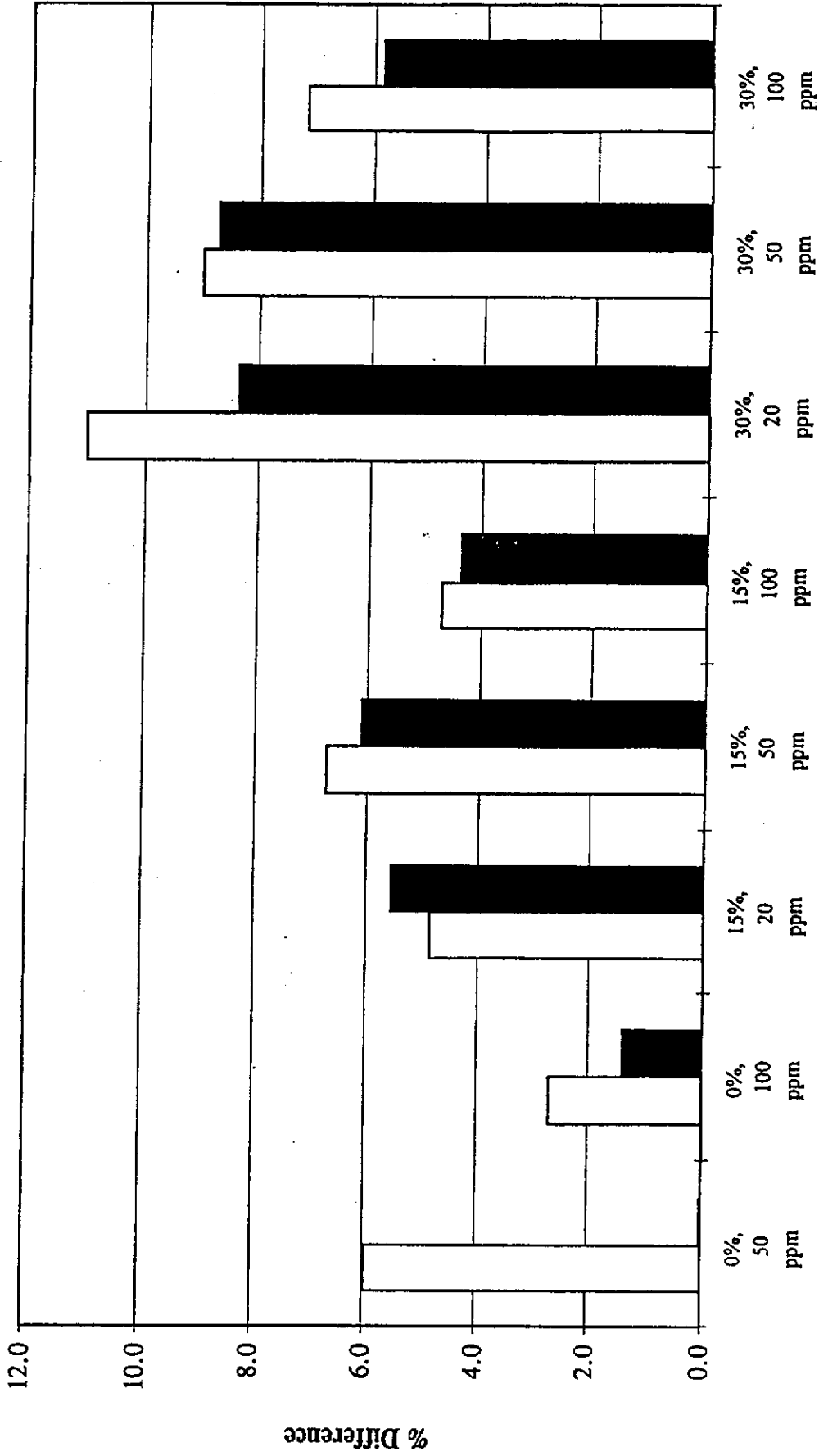


Figure 3: Graph: Percent Recovery of SO2 Spike

Percent Difference: SO₂ Recovery (Permeation Dryer Recovery Exceeds Thermoelectric Dryer)

□ FTIR Analyzer
■ UV Analyzer



Test Condition (% H₂O, ppm SO₂)

Figure 4: Graph: Percent Difference in SO₂ Recovery