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Utilization of Water Utility Lime Sludge for Flue Gas Desulfurization in Coal-Fired Power Plants: Part III. Testing at a Higher Scale and Assessment of Selected Potential Operational Issues

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Abstract

The feasibility of lime sludge utilization for flue gas desulfurization was evaluated by continuing the previous laboratory-scale studies at a higher scale and investigating two potential operational issues, namely viscosity and metal corrosion. Two lime sludge samples and a baseline limestone sample, which were previously characterized and tested for SO₂ capture from a simulated flue gas at a laboratory scale, were first tested at a 10-fold scale with a simulated flue gas, and then tested with a slipstream of flue gas from a coal-fired power plant. The tested lime sludge and limestone slurries reduced the SO₂ concentration of the simulated flue gas from 2000 to <1 ppm, and they demonstrated similar Hg reemission profiles. Field-testing results revealed that the limestone and lime sludge slurries reduced the SO₂ concentration of the flue gas from ~1500 to <1 ppm. These experiments confirmed our previous smaller scale laboratory results that lime sludge can function as a suitable substitute for limestone for SO₂ removal from the flue gas of coal-fired power plants without negatively affecting Hg reemission. Two operational issues, namely viscosity and metal corrosion, were investigated to evaluate practical issues in the transition from limestone to lime sludge at power plants. Results of Marsh funnel viscosity experiments conducted at different solids contents and temperatures indicated the limestone and lime sludge slurries and their gypsum counterparts had similar flow characteristics. Carbon-steel, stainless-steel, and Hastelloy coupons were tested for corrosion by lime sludge and limestone slurries. Both stainless steel and Hastelloy were resistive to corrosion in slurries made from lime sludge or limestone samples or their gypsum counterparts. A considerable but similar amount of corrosion was observed for carbon-steel coupons exposed to lime sludge and limestone slurries. Adding 5000 ppm of Cl⁻ to slurries considerably increased the corrosion rate of carbon steel.

Keywords

flue gas desulfurization; limestone; lime sludge; mercury reemission; corrosion; viscosity

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1. INTRODUCTION

Wet scrubbers are widely used for removal of SO₂ from flue gas through reaction with limestone slurries.¹ A supply-demand evaluation and a life cycle assessment performed in Part I of this investigation, demonstrated that switching from limestone to lime-softening sludge can be highly beneficial to water treatment and power generation industries, both economically and environmentally.²

In Part II of this work, the feasibility of lime sludge utilization in the flue gas desulfurization (FGD) process was evaluated by conducting laboratory-scale tests with a simulated flue gas at a flow rate of 0.5 L/min (LPM).³ Eight lime sludge samples and a baseline limestone sample were evaluated for their performance capability to remove SO₂ from a simulated flue gas, while monitoring Hg reemission from the scrubber. These results confirmed the high performance of different tested lime sludge samples for SO₂ capture. Furthermore, replacing limestone with lime sludge did not increase Hg reemission or cause additional issues for leaching undesirable elements into the scrubber slurry.³

Testing at higher scales is needed to further demonstrate the performance of lime sludge for flue gas desulfurization application. Furthermore, potential operational issues should be addressed before lime sludge utilization is considered for large-scale implementation. Two potential operational issues (among others) are (1) mixing and pumping challenges resulting from the high viscosity of lime sludge slurries, and (2) the corrosion of metals (used in equipment manufacture) as a result of long exposure to lime sludge slurries.

The main objectives of this stage of our study were to (1) increase the scale of the previous laboratory scrubber system by a factor of 10 and test a prototype scrubber system with lime sludge samples for SO₂ capture from a simulated flue gas while monitoring Hg reemission during the scrubbing process; (2) use the prototype scrubber to test the performance of lime sludge samples for capturing SO₂ from a slipstream of flue gas from a coal-fired power plant; and (3) investigate the viscosity and corrosion characteristics of lime sludge slurries compared with a baseline limestone slurry case to address these two potential operational issues.

2. EXPERIMENTAL SECTION

2.1. Lime Sludge and Limestone Samples

Two lime sludge samples (identified as “SL4” and “SL5”) were obtained from two water treatment plants in the states of Illinois and Ohio in the United States. Synthetic gypsum samples (identified as “SL4 gypsum” and “SL5 gypsum”) were prepared from lime sludge samples through reaction with H₂SO₄ according to a method described in our previous work.³ A high-purity limestone sample used in the FGD process and a gypsum sample (FGD by-product) were collected from a local power plant and identified as “limestone” and “gypsum” in this work. More details on these samples, including their characterization data, can be found in Part II of this work.³

2.2. Laboratory Testing with a Simulated Flue Gas

A setup that included various compressed gas tanks and a gas mixing unit, a 60 L Teflon-coated tank scrubber, pH controller and slurry pump, feed slurry container, external band heater, gas condenser/cold trap, Hg gas analyzer, and SO₂ gas analyzer, was used to evaluate the performance of the baseline limestone sample and the two lime sludge samples for SO₂ capture from simulated FGD slurries while monitoring Hg reemission (Figure 1a). A secondary limestone or lime sludge slurry (10 wt % solids) was prepared and used as a base reservoir for the pH pump to control pH during each run. All glassware and tubing were rinsed with 0.1 M HCl and deionized (DI) water, and then dried before reuse in experiments. A simulated flue gas with a composition of 5% O₂, 15% CO₂, and 2000 ppm of SO₂, balanced with N₂, and a total flow rate of 6 LPM, was bubbled in a slurry containing 5 L of DI water, 50 g of synthetic gypsum (or gypsum), and 10 g of dried lime sludge or limestone. A solution of HgCl₂ was added to the slurry at the beginning of each experiment to obtain an initial Hg concentration of 114 µg/L (114 ppb). Mercury concentration in the slurry was similar to the reported range of 50–194 ppb for 22 surveyed power plants.⁴ During the experiments, the slurry in the tank was held at a temperature of 57 ± 5 °C and pH 6 ± 0.5 . Mercury concentration in the gas stream was monitored continuously with a Tekran 2537X automated Hg analyzer (Tekran Instruments Corp., Seattle, WA). The concentration of SO₂ was monitored with a Nova 311WP analyzer (Nova Analytical Systems, Hamilton, Ontario). A condenser was used to capture condensed moisture from the treated flue gas before sending the gas to the Hg and SO₂ analyzers. Experiments were performed in duplicate to show the reproducibility of the results.

2.3. Field Testing at a Coal-Fired Power Plant with a Slipstream of Flue Gas

To conduct the field experiment at a local power plant, the prototype scrubber system was modified by adding a flue gas cooling vessel and vacuum pump (Figure 1b). Tests were performed with a slipstream of flue gas obtained from the exhaust duct of a coal boiler burning a high-sulfur Illinois coal. The duct used to sample flue gas was located downstream from the electrostatic precipitator and upstream from the FGD (scrubber) unit. A sampling port was installed to allow a vacuum pump to route ~6 LPM of flue gas out of the duct and into a scrubber tank filled with a lime sludge or limestone slurry prepared according to the method described in Section 2.2. Like the laboratory experiments, the tank was held at a temperature of 57 ± 5 °C and pH 6 ± 0.5 . The treated flue gas was then routed out of the scrubber tank, passed through a condenser flask and mass flowmeter, sampled continuously for SO₂ analysis, and finally returned to the flue gas duct. To inhibit ice clogging under extremely cold conditions, heating tapes were installed at critical points to prevent the formation of ice plugs within the gas flow path. A bypass line was installed to allow the SO₂ analyzer to sample flue gas directly to determine the concentration of SO₂ in untreated flue gas during each 1 h test run. Gas samples were taken from the treated gas stream in 1 L Tedlar sample bags (purchased from Restek, Bellefonte, PA) for Hg analysis at our laboratory with the Tekran 2537X Hg analyzer.

2.4. Marsh Funnel Viscosity

A Marsh funnel (MF) viscometer, obtained from Humboldt Mfg. Co. (Elgin, IL), was used to perform the viscosity measurements at room temperature ($\sim 23^{\circ}\text{C}$) and at 50°C based on ASTM Method D6910/D6910M-19.⁵ The MF viscosity measurement method consisted of measuring the time required for 1 qt (0.95 L) of slurry to flow through the funnel. Twenty-four slurries, which included limestone, gypsum, SL4 lime sludge, SL4 gypsum, SL5 lime sludge, and SL5 gypsum at four different concentrations (5, 10, 15, and 20 wt %), were prepared by stirring the mixture of each solid in DI water for 5 min with a magnetic stirrer before pouring the slurry into the MF. For samples tested at 50°C , the slurry was heated to this temperature on a hot plate with stirrer before the experiments. The average and standard deviation were calculated for each concentration from triplicate measurements.

Marsh funnel viscosity values of saturated CaSO_4 or CaCO_3 solutions (prepared from reagent grade materials) were also tested to determine whether the MF viscosity was affected by the difference in dissolution of CaSO_4 (gypsum) and CaCO_3 (limestone and lime sludge) in water.

All materials tested by using MF viscosity measurements were also characterized by particle size analysis with a Horiba Partica LA-950V2 laser scattering particle size distribution analyzer (Horiba, Kyoto, Japan). For each test, a small quantity (~ 0.5 g) of dry powdered sample was suspended in DI water, sonicated for 30 s to break apart large aggregates within the suspension, and tested to obtain a particle size distribution profile.

2.5. Corrosion Coupon Testing

Corrosion testing was performed according to ASTM Method G4-95.⁶ Corrosion coupons composed of three different alloys (C1018 carbon steel [CS], 316 stainless steel [SS], and Hastelloy C276 [HS]) with dimensions of $3 \times 0.5 \times 0.0625$ in. ($7.62 \times 1.27 \times 0.159$ cm) were purchased from Brown Corrosion Services Inc. (Houston, TX). The six slurries tested during these 6 week experiments conducted at 50°C were limestone, gypsum, SL4 lime sludge, SL4 gypsum, SL5 lime sludge, and SL5 gypsum.

During testing, the samples were kept in uncapped glass vials inside an oven set at 50°C equipped with a circulation fan. Samples in the oven were provided with a continuous flow of air from a hose connected to a compressed gas cylinder, which was fed into the oven through a vent port. All CS and SS coupons were tested in duplicate, whereas single coupons were used for tests involving HS. Each coupon was placed into a 60 mL glass vial, to which 50 mL of well-mixed 5 wt % slurry was added. Deionized water was added to each vial daily to compensate for water evaporation.

A separate series of corrosion coupon experiments were performed with only SS and HS coupons submerged for 4 weeks in slurries prepared from SL4 lime sludge, SL4 gypsum, limestone, and gypsum, both with and without the addition of 5000 ppm of Cl^- (from the addition of 8239 ppm of NaCl). Coupons were prepared and tested in the same manner as the first series, with duplicate coupons excluded and a blank sample included for each metal type and submerged only in DI water.

After the experiments were completed, the coupons were removed from the slurries, gently rinsed with DI water, and photographed. The coupons were then subjected to a 15 wt % HCl (trace metal grade) solution for 30 min at ambient temperature. Each metal type was cleaned in a separate acid bath to prevent any interaction between the different metal types and their corrosion products. Upon removal from the acid bath, each coupon was rinsed thoroughly with DI water, lightly brushed on all sides with a nylon brush, rinsed again under running DI water, and then allowed to air-dry at ambient temperature. The mass loss of each sample was calculated by subtracting the mass of each coupon after corrosion testing from its initial mass. Additionally, as a baseline measurement for the mass loss of unoxidized surface resulting from the cleaning procedure, 2 CS, 2 SS, and 1 HS as-received coupons were exposed to the same 30 min acid-cleaning procedure and their weight changes were recorded.

3. RESULTS AND DISCUSSION

3.1. Mercury Reemission during SO₂ Capture from Simulated Flue Gas

In the previous small-scale laboratory study, the reemission and fate of Hg during SO₂ capture by eight lime sludge slurries and a baseline limestone slurry were studied. The small-scale laboratory experiments were performed with 0.6 LPM of simulated flue gas and 0.5 L of slurry containing 114 µg/L of Hg. The previous results showed that all tested lime sludge samples exhibited a high reactivity and reduced the SO₂ concentration from 2000 to <0.5 ppm. Furthermore, the cumulative amounts of Hg reemission from the tested lime sludge samples were not higher than that of the baseline limestone sample.³

Among the lime sludge samples tested in the previous work, two samples (SL4 and SL5) along with the baseline limestone sample were selected for testing at a higher scale (i.e., 6 LPM of simulated flow gas and 5 L of slurry) with a tank scrubber. The main objective of testing at a larger scale was to further evaluate the performance of lime sludge slurries for SO₂ capture and Hg reemission at a 1 order of magnitude higher scale. Like the previous smaller scale tests, in all tank scrubber experiments using the SL4 and SL5 lime sludge slurries or the baseline limestone sample, the SO₂ concentration in the treated gas was less than the detection limit of the analyzer (1 ppm). These results confirmed that the prototype scrubber was effective in capturing SO₂ from the inlet level of 2000 to <1 ppm at the new testing scale.

Mercury reemission during the SO₂ capture tests at the new scale was also measured continuously. Overall, the Hg reemission profiles and cumulative amounts of Hg released were similar for the two lime sludge samples and the baseline limestone sample tested (Figure 2). Figure 2a shows the average values and standard deviations for the reemission profiles from each of the three materials tested. Average peak values for the SL4 and SL5 slurries were within the same concentration range, and both SL4 and SL5 results showed overlapping Hg reemission values during the end of the profiles. The Hg reemission profile of the baseline limestone test showed an initial larger peak but lower tailing Hg reemission compared with the lime sludge profiles (Figure 2a). The cumulative amount of Hg released during all lime sludge and limestone tests was similar, despite any observable differences in the reemission profile (Figure 2b).

Relevant data from previous experiments with the small-scale laboratory test, which was 10 times smaller than the tank scrubber test, are shown in Figure 3. The general trend of the limestone sample exhibiting higher peak Hg reemission could be observed at both the tank scrubber and small laboratory scales (Figures 2a and 3a). The cumulative amount of Hg released from the tank scrubber was $\sim 23 \mu\text{g}$ (Figure 2b), which is approximately 10 times higher than the observed range of $1.7\text{--}2.7 \mu\text{g}$ for the laboratory scrubber (Figure 3b), in agreement with the 10 times scaling factor. Overall, the data trends observed for the prototype tank scrubber are in good agreement with the trends observed for the smaller scale experiments. Minor differences observed in the laboratory scrubber and tank scrubber results may have been caused by a difference in the operating temperature (i.e., 50 vs. 57°C), variations in the mixing and gas dispersion, differences in the scrubber size and material (i.e., 2 L glass flask for the laboratory scrubber vs. 60 L Teflon-coated stainless-steel tank for the prototype scrubber), and other factors.

3.2. Field Testing with a Slipstream of Flue Gas

Field tests with the tank scrubber were performed at a local coal-fired power plant with a slipstream of flue gas from the exhaust duct. The SO_2 concentration was measured continuously during each 1 h test run. An average SO_2 concentration of $\sim 1500 \text{ ppm}$ was measured in the slipstream that was fed to the scrubber. The concentration of SO_2 in the flue gas exiting the scrubber was $< 1 \text{ ppm}$ and practically identical regardless of whether lime sludge or limestone was used as the base source for the slurry. These results agreed with the previous small-scale laboratory data and similar tests conducted with a simulated flow gas (see Section 3.1), confirming that lime sludge could function as a suitable substitute for limestone for SO_2 removal from the flue gas of coal-fired power plants.

Mercury concentration in the treated flue gas was not measured continuously because of logistical issues. However, gas samples from each trial were collected for Hg analyses at our laboratory after completion of the field experiments. Results indicated that Hg concentrations of all treated gas samples (except two samples) were extremely low, at a range of $0.02\text{--}0.22 \mu\text{g}/\text{m}^3$. We were unable to measure the Hg concentration in the raw flue gas because of the high SO_2 concentration, but the typical concentration of Hg in coal combustion flue gas was reported to vary from 5 to $10 \mu\text{g}/\text{m}^3$.⁷

3.3. Marsh Funnel Viscosity Measurements

Marsh funnel viscosity results of slurries containing $5\%\text{--}20\%$ of limestone, lime sludge, or gypsum at 23 and 50°C are shown in Figures 4 and 5. The MF viscosity values of various slurries with $5 \text{ wt } \%$ solids measured at 23°C varied from 24.8 to 26.3 s . For comparison, the measured MF viscosity of DI water, a saturated CaCO_3 solution (representing limestone or lime sludge solutions), and a saturated CaSO_4 solution (representing gypsum solutions) were $26.0 \pm 0.2 \text{ s}$, $25.5 \pm 0.2 \text{ s}$, and $25.5 \pm 0.2 \text{ s}$, respectively. These results indicate that the MF viscosity values of $5 \text{ wt } \%$ slurries were similar to those of DI water or saturated solutions of CaCO_3 or gypsum.

As expected, all tested samples showed a lower viscosity at 50 °C compared with a similar measurement at 23 °C. Furthermore, the viscosity increased almost linearly with an increase in the solids content of the slurries.

Marsh funnel viscosity values of the baseline limestone and SL5 lime sludge were quite similar across the entire concentration range. The SL4 lime sludge showed slightly higher MF viscosity values at both temperatures tested when compared with the baseline limestone and SL5 lime sludge, with the disparity in MF viscosity measurements becoming increasingly larger at higher concentrations. However, even at the highest solids concentration of 20%, the MF viscosity of the SL4 lime sludge was only <10% higher than the MF viscosity of the baseline limestone or the SL5 lime sludge samples.

Gypsum viscosity measurements at 23 and 50 °C showed the SL5 gypsum to be more viscous. Marshall funnel viscosity values of the SL4 gypsum for solids concentrations above 5 wt % fell between those observed for the baseline gypsum and the SL5 gypsum for both temperatures tested. At the highest solids concentration of 20%, the MF viscosity of the SL5 gypsum sample was ~10% more than that of the baseline gypsum sample.

No clogging issues were observed during the flow of even the most concentrated lime sludge slurries through the MF orifice. Overall, flow characteristics of the limestone and lime sludge slurries appeared to be similar. Comparable results were also observed for gypsum samples.

To further understand the MF viscosity results of the tested slurries, the particle size distribution of each sample was measured and compared (Table 1). Except for the baseline limestone sample, all materials displayed single peaks in their particle size distribution profiles. The baseline limestone and gypsum samples had a wider particle size distribution. Median particle diameters were in a range of 12.8–16.5 µm for all the materials tested except for the baseline gypsum sample, which had a median diameter of ~80 µm. No correlation was found between the mean particle size and the measured MF viscosity values for the different slurries tested.

3.4. Corrosion Coupon Testing

To evaluate the performance of selected materials for prolonged contact with lime sludge slurries and the desulfurization by-product (i.e., gypsum), CS, SS, and HS coupons were subjected to six different slurries. Visual inspection of the metal coupons before and after exposure to various slurries showed the formation of a blackish-orange rust film on the CS coupons, whereas the SS coupons did not exhibit the formation of any visible metal rust but were only slightly stained (Figure 6). Figure 6 also shows that the HS coupons exposed to various slurries were not stained and kept their original shiny appearance. Figure 7 compares photographs of the CS and SS coupons exposed to different slurries with or without the addition of 5000 ppm of Cl^- . Chloride addition at this concentration made the CS corrosion worse, whereas it had no major visible impact on corrosion of the SS coupons during the 4-week test.

The mass losses of the CS, SS, and HS coupons exposed to two lime sludge slurries and one limestone slurry at 50 °C for 6 weeks are shown in Figure 8. The mass loss value includes the mass loss attributable to metal oxidation during the corrosion testing period and the mass loss of the unoxidized metal during the acid-cleaning stage. The mass loss of unoxidized coupons resulting from acid etching was estimated by measuring the mass loss of as-received coupons exposed to the same 30 min acid-cleaning process. These values are also shown in Figure 8 as the baseline.

The average mass loss of CS coupons after 6 weeks of immersion in different slurries varied in a range of ~120–370 mg, whereas the as-received CS coupons exposed to the same acid-cleaning process lost approximately 14 mg (Figure 8). This result suggests that more than 88%–96% of the measured mass loss occurred because of corrosion in the slurries. The average corrosion rate of CS coupons exposed to the selected slurries with or without the addition of 5000 ppm of Cl^- was also calculated and is shown in Table 2. Corrosion rates were calculated after applying the correction for corrosion of the as-received CS coupons subjected to the same acid-cleaning process. The high corrosion rate measured for the CS coupons was also consistent with the formation of the blackish-orange rust film observed on the CS coupons after exposure to the different slurries (Figures 6 and 7). As expected, Cl^- addition significantly increased the corrosion rate of CS and made the pitting corrosion more severe (Table 2, Figures 6 and 7).

The CS corrosion results suggest that exposure to none of the selected lime sludge slurries (i.e., SL4 and SL5) resulted in mass losses that were greater than the baseline limestone or gypsum slurries. Therefore, the transition from limestone to lime sludge at power plants would not be expected to increase the corrosion rate of equipment manufactured from CS.

Results of the SS corrosion tests after 6 weeks showed a small mass loss of ~8 mg, which was similar to the baseline mass loss of as-received SS coupons subjected to the same 30 min acid-cleaning process (Figure 8). The passive layer present on SS was susceptible to attack by HCl during the cleaning stage, so base metal penetration and removal occurred relatively quickly. Overall, the mass loss of SS coupons attributable to corrosion in the slurries was estimated to be <4 mg, which is 2–3 orders of magnitude less than the corrosive mass loss of CS coupons (i.e., ~106–356 mg). It should also be noted that when coupons were immersed in slurries that contained 5000 ppm of Cl^- , the SS coupons exhibited some staining (but not visible major corrosion) similar to the experiments with no Cl^- , whereas corrosion of the CS coupons became worse in the presence of Cl^- (Figures 6 and 7).

Hastelloy performed well when exposed to various lime sludge or limestone slurries. The mass loss observed for HS coupons during the 6-week immersion period was <1 mg. The as-received HS coupons also exhibited no measurable weight loss attributable to acid cleaning (Figure 8).

The overall result of corrosion coupon testing was that the SS and HS materials showed almost no corrosion in 5% slurries made from the SL4 and SL5 lime sludge or the baseline limestone or in 5% slurries made from their gypsum counterparts. Significant corrosion was observed for the CS coupons; however, the corrosion rate in slurries made from lime sludge

samples (or their synthetic gypsum counterparts) was similar to or lower than the corrosion rate of CS coupons exposed to the baseline limestone or gypsum slurry. It should be noted that the chemistry of scrubber solutions at power plants is more complicated than the simplified conditions used in this preliminary work. Depending on coal type and operational conditions, composition of a real flue gas is also more complicated than simplified composition of a simulated flue gas. For example, flue gas from the combustion of a low sulfur eastern bituminous coal can contain 13–16% CO₂, 5–7% H₂O, 3–4% O₂, 800 ppm SO₂, 10 ppm SO₃, 100 ppm HCl, 500 ppm NO_x, 20 ppm CO, 10 ppm hydrocarbons, 1 ppb total Hg, entrained particulates, and balance N₂, and some of these species can impact corrosion of the ductwork as well as mercury oxidation and reemission from wet scrubbers.^{8–12} The accumulation of Cl[−] (originating from Cl in the coal) in the scrubber solution is an important source of metal corrosion in the scrubbing system. Limited experiments performed with or without the addition of 5000 ppm of Cl[−] to the slurries demonstrated the impact of Cl[−] on CS corrosion. Chloride corrosion would be expected to have almost no impact on HS, more on SS, and much more on CS.

4. CONCLUSIONS

In this work, we continued our previous investigations of lime sludge utilization in the FGD process of coal-fired power plants by increasing the scale of the previous laboratory-scale studies and investigating two potential operational issues, namely viscosity and metal corrosion.

Tests conducted at a 1 order of magnitude higher scale than the previous laboratory tests confirmed that the lime sludge samples performed effectively for capturing SO₂ from a simulated flue gas containing 2000 SO₂ to <1 ppm. The Hg reemission profiles were similar for the tested lime sludge and baseline limestone samples. Furthermore, the cumulative amounts of Hg released from the tank scrubber were approximately 10 times higher than the observed value for the laboratory scrubber, which agrees with the 10 times scaling factor. Field testing of two lime sludge samples and a baseline limestone sample with a slipstream of flue gas from a coal-fired power plant also showed that lime sludge performed effectively for SO₂ capture. These results confirm that lime sludge can function as a suitable substitute for limestone for SO₂ removal from the flue gas of coal-fired power plants without negatively affecting the Hg reemission.

On the basis of the MF viscosity results, flow characteristics of the limestone and lime sludge slurries or the slurries prepared from their gypsum counterparts appeared to be similar. No clogging issues were observed during the flow of even the most concentrated lime sludge slurries through the MF orifice. Therefore, we would expect that equipment similar to that currently used for the mixing, pumping, and transport of limestone slurries could be used for lime sludge slurries.

According to the corrosion coupon tests, the SS and HS materials were resistive to corrosion in the lime sludge and limestone slurries and in the slurries made from their gypsum counterparts. Significant corrosion was observed for CS coupons; however, the corrosion rate in slurries made from lime sludge samples (or their synthetic gypsum counterparts) was

similar to or lower than the corrosion rate of CS coupons exposed to the baseline limestone or gypsum slurry. This result indicates that the same materials used for equipment manufactured for limestone slurry utilization could be used for lime sludge.

Future work can involve additional examination of the impacts of flue gas nitrogen oxides, sulfur oxides, hydrogen chloride, and entrained particulate on sulfur dioxide removal and mercury reemission when lime sludge slurries are used in wet scrubbers. Entrained fly ash particles can provide catalytic sites for oxidation of mercury and sulfur dioxide^{10,11,13}, and can impact mercury reemission.

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Figure 1.

Schematic diagram of the fabricated prototype scrubber system for (a) testing with simulated flue gas and (b) field testing. MFC, mass flow controller. See the Experimental Section for more details about the scrubber system.

Figure 2. Mercury reemission at 57 °C and pH 6 from the tank scrubber experiments conducted with 6 LPM of simulated flue gas when using limestone and lime sludge (SL4 and SL5) slurries. (a) Mercury reemission profiles, and (b) cumulative amount of Hg released during the 2 h desulfurization experiments.

Figure 3.

Mercury reemission at 50 °C and pH 6 from flask scrubber experiments conducted with 0.6 LPM of simulated flue gas when using limestone and lime sludge (SL4 and SL5) slurries.

(a) Mercury reemission profiles, and (b) cumulative amount of Hg released during the 2 h desulfurization experiments.

Figure 4. Marsh funnel viscosity values of limestone and lime sludge slurries with different concentrations at (a) 23 °C and (b) 50 °C.

Figure 5. Marsh funnel viscosity values of gypsum slurries with different concentrations at (a) 23 °C and (b) 50 °C.

Figure 6.

Photographs of metal coupons (CS, carbon steel; SS, 316 stainless steel; HS, Hastelloy C276) before (first row) and after (second row) immersion in different slurries at 50 °C for 6 weeks. Formation of a blackish-orange rust film on the CS coupons is visible.

Figure 7.

Photographs of metal coupons (CS, carbon steel; SS, 316 stainless steel; HS, Hastelloy C276) before and after immersion in different slurries at 50 °C for 4 weeks. The second rows of photographs represent sections of high magnification ($\sim 100\times$) of the same metal coupons. Formation of a blackish-orange rust film on the CS coupons, particularly in the presence of 5000 ppm of Cl^- , is visible at both centimeter and sub-millimeter scales.

Figure 8.

Average mass loss of carbon-steel (CS), 316 stainless-steel (SS), and Hastelloy (HS) coupons immersed in different slurries at 50 °C for 6 weeks. The average mass losses of as-received metal coupons subjected to the same acid-cleaning process (baseline values) are also shown for comparison. LS, lime sludge.

Table 1.

Particle Size Distribution of Limestone, Lime Sludge, and Gypsum Samples Used for MF Viscosity Measurements

Material	D ₁₀ (μm)	Mean size (D ₅₀) (μm)	D ₉₀ (μm)
Limestone	6.1	16.5	67.2
Gypsum	39.1	79.6	143.6
SL4	6.6	13.3	26.6
SL4 gypsum	8.2	12.8	20.4
SL5	7.4	14.4	27.4
SL5 gypsum	8.9	14.1	24.0

Table 2.

Average Corrosion Rate of Carbon-Steel Coupons Exposed to Different Slurries with or without the Addition of 5000 ppm of Cl^- (Equivalent to 8239 ppm of NaCl) at 50 °C for 4 Weeks^a

Slurry	Corrosion rate (mm/year) without Cl^- addition	Corrosion rate (mm/year) with addition of 5000 ppm of Cl^-
SL4 gypsum	0.088	0.115
Gypsum	0.092	0.130
SL4 lime sludge	0.052	0.083
Limestone	0.097	0.103

^a Corrosion rates were calculated after applying the correction for corrosion of as-received carbon-steel coupons subjected to the same acid-cleaning process.