

# SPRAY DRYING FOR THE SIMULTANEOUS REMOVAL OF SO<sub>2</sub> AND NO<sub>x</sub> FROM FLUE GAS – EXPERIMENTAL RESULTS

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The implementation of the “New plant” emission limit values set in terms of section 21 of the National Environmental Management - Air Quality Act requires the reduction of emissions from a number of smaller operations, especially in the metallurgical field. Although apparatus for the control of particulate matter for such smaller operations has traditionally been designed and manufactured locally, there is less local experience with the control of SO<sub>2</sub> and NO<sub>x</sub> at small scale. In this paper, we report results from laboratory-scale work on the use of spray drying for simultaneous control of SO<sub>2</sub> and NO<sub>x</sub> using suspensions of commercially available dolomitic lime. In a 3 m high spray column, up to 70% of SO<sub>2</sub> could be removed in the absence of NO<sub>2</sub>; when both SO<sub>2</sub> and NO<sub>2</sub> were present, approximately 30% efficiency was achieved for both. The oxidation of NO to NO<sub>2</sub>, which is required where the NO<sub>x</sub> emissions are in the form of NO, was also investigated using ozone as the oxidant. Inconclusive experimental results were obtained, but sound literature data for the process design of this reaction exists.

**Keywords:** SO<sub>2</sub> removal, NO<sub>x</sub> removal, spray drying, NO oxidation.

## 1. Introduction

SO<sub>2</sub> and NO<sub>x</sub> are harmful components of flue gas produced from combustion and smelting related industrial activities. Consequently, safety and environmental authorities impose stringent, maximum allowable SO<sub>2</sub> and NO<sub>x</sub> emission limits for different process operations. A spray-dry operation using an aqueous, lime slurry can be employed to enable reaction of the SO<sub>2</sub> and NO<sub>x</sub> species. The process is intended to produce dry, solid products that are entrained within the flowing gas stream and can subsequently be removed using a common downstream solid-gas separator.

Robust operation of a gas cleaning spray-dry unit is inherently difficult as a consequence of the differently weighted and, in some instances, opposite effects of a number of key variables in attempts to improve SO<sub>2</sub> and NO<sub>x</sub> removal efficiencies and operational stability. These variables include spray pattern, droplet size, lime mass fraction and inlet gas temperature. The objective of the investigation was to gain insight into the nature and weight of effect of these variables and the mechanisms that govern the efficiency of SO<sub>2</sub> and NO<sub>x</sub> removal.

As nitrogen dioxide (NO<sub>2</sub>) is more soluble in water than nitric oxide (NO), increased NO<sub>x</sub> removal can be achieved if NO is first oxidized to NO<sub>2</sub>. Inconclusive experimental data were obtained on this subject. However, a brief study on the NO

oxidation reaction and mechanism has been included in this paper.

The spray-dry scrubbing experiments were conducted on a laboratory scale using a 3 m tall reaction column. Industrial flue gas was simulated by a heated stream of an air, SO<sub>2</sub> and NO<sub>2</sub> mixture. The effects of variation in spray pattern, slurry droplet size, slurry concentration and inlet gas temperature were tested.

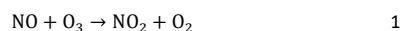
## 2. Theory

### 2.1 Oxidation of NO

NO reduction techniques on the basis of chemical reaction with ammonia (NH<sub>3</sub>) have been developed. However, on an industrial scale, these techniques often prove to be costly (Gostomczyk and Kordylewski 2010). The proposed alternative in this paper is the oxidation of NO using O<sub>3</sub> to produce higher derivatives of nitrogen oxides that are more soluble in water.

When the molar flow rate ratio of O<sub>3</sub> to NO is larger than one, higher derivatives are more likely to form (Sun *et al.* 2014, Li *et al.* 2015, Skalska *et al.* 2012). One setback might be the operation cost to produce ozone. Ellison (2005) determined that ozone was one of the most expensive oxidizing agents. Naturally, the alternative requiring the least O<sub>3</sub> would be the first consideration. It is a logical step to first contemplate whether the production of NO<sub>2</sub> is

favourable. The study of NO oxidation in this paper revolves around the following chemical reaction:



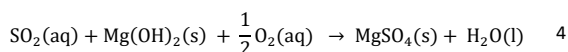
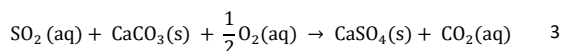
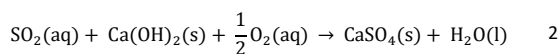
Gostomczyk and Kordylewski (2010) found that the optimal oxidation of NO was at reaction temperatures between 80°C and 90°C. In addition, increased NO oxidation was observed at larger residence times and when larger molar ratios of O<sub>3</sub> to NO were fed to the reactor. This is as expected from basic reaction kinetics.

Li *et al.* (2015) observed the decomposition of O<sub>3</sub> at temperatures higher than 200°C. In addition, they found that higher derivatives of NO<sub>x</sub> form when the O<sub>3</sub>:NO molar flow ratio was greater than one whilst optimal production of NO<sub>2</sub> was observed to occur at a ratio of one. Similar results were observed by Sun *et al.* (2014) and Skalska *et al.* (2012).

## 2.2 Spray-Dry Scrubbing

The spray-dry DeSO<sub>x</sub>-DeNO<sub>x</sub> method makes use of a counter-current spray of lime slurry which comes into contact with hot flue gas within a reaction column. As the slurry droplets fall down the column they absorb and react with the SO<sub>2</sub> and NO<sub>x</sub> content of the flue gas.

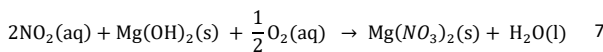
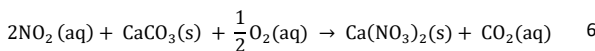
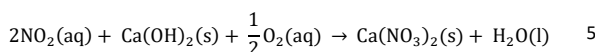
Depending on the composition of the lime source, the absorbed SO<sub>2</sub> will react in the aqueous phase according to one or more of the following irreversible chemical reactions:



The DeSO<sub>x</sub> mechanism can be divided into four processes (Nygaard *et al.*, 2004):

- Absorption: SO<sub>2</sub>(g) is absorbed into the slurry. SO<sub>2</sub>(aq) then dissociates to HSO<sub>3</sub><sup>-</sup> and SO<sub>3</sub><sup>2-</sup>.
- Oxidation: HSO<sub>3</sub><sup>-</sup> is oxidised to SO<sub>4</sub><sup>2-</sup>.
- Dissolution: The solids content in the slurry dissolves in the water. In the case of Ca(OH)<sub>2</sub>, ions of Ca<sup>2+</sup>(aq) and OH<sup>-</sup>(aq) form.
- Crystallisation: Ca<sup>2+</sup>(aq), SO<sub>4</sub><sup>2-</sup>(aq) and H<sub>2</sub>O combine to form CaSO<sub>4</sub>·2H<sub>2</sub>O(s). Heat transfer from the high temperature gas stream liberates the bound water to form anhydrous CaSO<sub>4</sub>.

Similarly, absorbed NO<sub>2</sub> will react in the aqueous phase according to one or more of the following irreversible chemical reactions:



The overall rate of SO<sub>2</sub> and NO<sub>x</sub> removal is controlled by the resistance of the slowest mass transfer effect between gas-liquid film mass transfer, liquid-side mass transfer and sorbent dissolution. The actual chemical reaction is comparatively instantaneous (Toole-O'Neil, 1998: 50).

## 3. Experimental

### 3.1 Spray-Dry Scrubbing

#### 3.1.1 Apparatus

Industrial flue gas was simulated by a heated mixture of air, SO<sub>2</sub> and NO<sub>2</sub> to a single inlet at the bottom of a 3 m tall, insulated reaction column. The interior of the column was lined with a refractory. Two 5 kW electrical elements within the column enabled heating of the gas to a maximum temperature of 300°C. An E instruments, E5500 portable industrial emissions system, combustion gas analyser, retrofitted with a thermocouple, was used to display and store temperature and composition data of the outgoing gas stream at the top of the column.

A partially slaked dolomitic lime composed predominantly of MgO and CaO (28% and 46% by mass respectively) was used as the lime source. A garden variety spray-can was used to spray the mixed slurry. The spray can made use of a plunger which could be used, by hand, to apply a low air pressure (75 kPa<sub>g</sub>) to the contents. Three distinguishable sprays patterns and accompanying variations in droplet size could be obtained by manipulating the position of a nozzle. A graphical representation of these patterns is depicted in Figure 1. Pattern 1 produced a fine spray that was widely distributed across the area of gas flow whilst Pattern 3 produced a comparatively direct spray down the centre of the reaction column. Droplet size and rate of spray was largest for Pattern 3 and smallest for Pattern 1. Pattern 2 was intermediate in all regards, relative to Pattern 1 and Pattern 3.

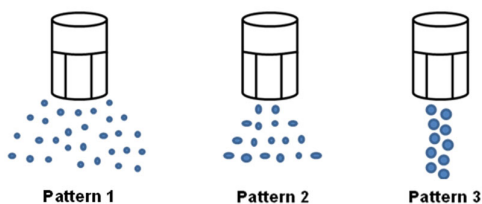


Figure 1: Spray pattern and droplet size variation due to nozzle manipulation

The SO<sub>2</sub> and NO<sub>2</sub> supply lines were fitted with rotameters for volumetric flow measurement, whilst the air flow rate was inferred from the measured pollutant concentrations within the column under the assumption of ideal gas behaviour. NO<sub>2</sub> (10% in N<sub>2</sub>) was introduced to the column at a flow rate of 30 L/min and the SO<sub>2</sub> (pure) was introduced at a rate of 3.6 L/min. The air flow rate was subsequently adjusted until the measured SO<sub>2</sub> and NO<sub>2</sub> concentrations were approximately 1 000 – 1 600 ppm. This ensured that the concentrations remained well within the span of the gas composition analyser.

The temperature and flow rate of the gas stream imposed a maximum limit on the water mass fraction of the slurry in order to ensure complete evaporation. However, the mass fraction of lime used was constrained to an upper limit of 0.20 due to nozzle blockage at higher concentrations. It was decided that lime mass fractions of 0.05, 0.10, 0.15 and 0.20 were to be tested at gas temperatures of 115°C and higher.

The performance of each experiment was quantitatively evaluated by the percentage reduction achieved in the SO<sub>2</sub> and NO<sub>2</sub> concentrations between the start of the experiment and a time at which the pollutant concentrations within the gas stream no longer changed significantly with time.

Each graph presented indicates an initial period before which the spraying of the slurry had started. A sudden and explicit decrease in SO<sub>2</sub> concentration is then observed, indicative of the start of the spray. The rate of spray was sustained at an approximately constant value by maintaining a constant pressure within the slurry reservoir. The volume of the reservoir was 1.5 L and consequently proved to be the limiting factor with respect to the duration of the experiments. During the middle period of each run a steady state is reached during which the measured SO<sub>2</sub> concentration no longer changes significantly with time. Any increase in SO<sub>2</sub> concentration at the end of each run signifies the point at which the spray-can was empty.

Due to the number of experiments conducted, each sub-experiment is described in the results

section. Each description is then immediately followed by the results for that experiment.

## 4. Results

### 4.1 SO<sub>2</sub> Removal

The following section details experimental results as obtained by Little (2014). These results pertain to the spray-dry scrubbing desulfurisation process in the absence of NO<sub>x</sub>. Residence time of the gas in the column was approximately 8 seconds.

#### 4.1.1 Effect of Spray Pattern and Droplet Size

Figure 2 and Figure 3 show the effects of the spray pattern on SO<sub>2</sub> removal using slurries with lime mass fractions of 0.20 and 0.15 kg lime/kg slurry respectively. The experiments were run with an initial gas temperature of 210°C.

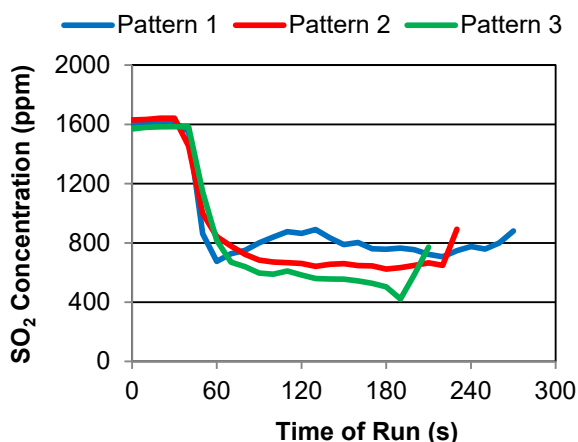


Figure 2: The effect of spray pattern on SO<sub>2</sub> removal using slurry with lime mass fraction of 0.20.

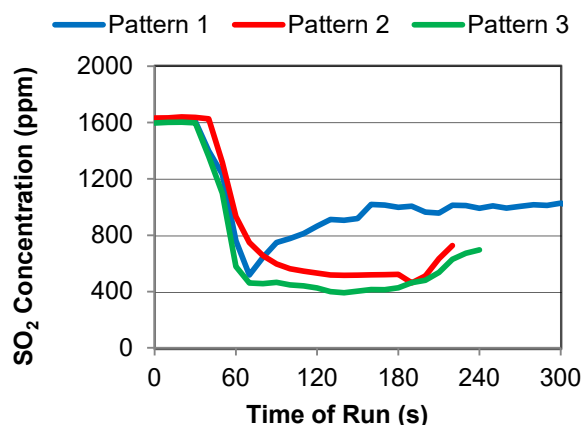


Figure 3: The effect of the spray pattern on SO<sub>2</sub> removal using slurry with lime mass fraction of 0.15.

The following percentage reductions in SO<sub>2</sub> concentration (molar) were achieved for the experiments depicted in Figure 2:

- Pattern 1: 51%
- Pattern 2: 60%
- Pattern 3: 64%

The following percentage reductions in SO<sub>2</sub> concentration (molar) were achieved for the experiments depicted in Figure 3:

- Pattern 1: 38%
- Pattern 2: 68%
- Pattern 3: 74%

Data from both sets of experiments indicate that Pattern 3 allowed for the best SO<sub>2</sub> removal whilst Pattern 1 affected the worst. The larger droplets of Pattern 3 fall a greater distance down the length of the column compared to the droplets of Pattern 1, before being completely evaporated. This results in a longer absorption section (longer length of spray) through which the gas has to migrate, subsequently allowing more SO<sub>2</sub> to dissolve into the aqueous phase for reaction. This is essentially a residence time effect. In addition, Pattern 3 results in a faster rate of spray to aid removal. This effect is accentuated in Figure 3 by the relatively poor removal achieved by Pattern 1, which underwent a significantly longer runtime before the spray reservoir was empty, as a consequence of a slower spray rate.

The one expected setback of Pattern 3 was that it does not cover the entire cross-sectional area of the reaction column. Unfortunately, observations could not be made to ascertain the exact spray behaviour. However, it is believed that the velocity of the gas and turbulence within the column allowed the droplets of the spray to spread out.

#### 4.1.2 Effect of Slurry Concentration

The mass fraction of lime (denoted as  $x$ ) in the sprayed slurry was varied in a sequence of experimental runs. The experiment was run with an initial gas temperature of 210°C. In addition, Pattern 3 was used, since it allowed for the best removal in the spray pattern tests. Figure 4 depicts the results obtained for this experiment.

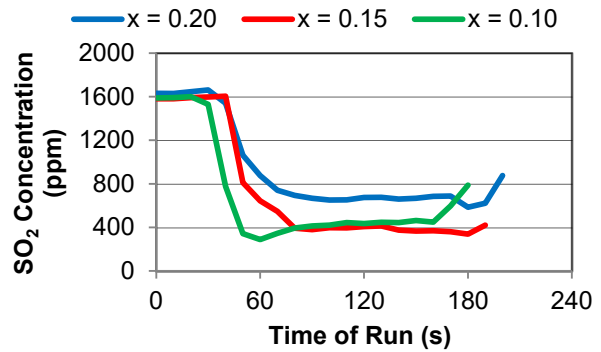


Figure 4: The effect of lime mass fraction on SO<sub>2</sub> removal using Pattern 3.

The following percentage reductions in SO<sub>2</sub> concentration (molar) were achieved for the experiments depicted in Figure 4:

- $x = 0.20$ : 59%
- $x = 0.15$ : 76%
- $x = 0.10$ : 73%

A small amount of slurry was collected at the bottom outlet of the reaction column for the experiment using the highest mass fraction of water ( $x = 0.10$ ). This did not occur for the other two experimental runs. Figure 4 indicates that the rate of spray was fastest for the experiment using  $x = 0.10$  and approximately equal for the experiments using  $x = 0.15$  and  $x = 0.20$ .

Scala *et al.* (2004) provide an elegant explanation for the poorer performance of the slurry at the higher lime mass fraction of 0.20. According to them, as a droplet evaporates, the solids content of the droplet forms a porous “crust” at the surface which inhibits the absorption of SO<sub>2</sub>. The basic idea is that a lower water mass fraction will cause the droplets to dry in a shorter space of time. This event is undesirable since the removal of SO<sub>2</sub> is dependent on reaction within the aqueous phase.

The collection of slurry at the bottom outlet of the column implies that not enough thermal energy was transferred from the flowing gas stream to the sprayed droplets to allow for complete evaporation. Although this would effectively result in the longest spray length (the entire length of the column), which has already been shown to favour SO<sub>2</sub> removal, along with a faster rate of spray, another factor seems to favour the experiment for which  $x = 0.15$ . This factor could be the additive effect of good residence time and an improvement of rate-limiting gas-liquid film mass transfer. If an appreciable spray length forms as a result of the droplets being able to fall a significant distance down the length of the column before their motion is arrested by the upward momentum of the gas flow then the gas would have a considerable residence time within the spray of

slurry droplets. When the motion of the droplets subsequently reverses within the reactor, the flow of the streams will become more turbulent. An increase in the turbulence of the flow will decrease the thickness of the droplet gas-liquid film which will subsequently allow for faster migration of SO<sub>2</sub> into the aqueous phase.

#### 4.1.3 Effect of Gas Temperature

The effect of an increased gas temperature was analysed by allowing the reactor to heat up to a temperature considerably higher than 210°C. Figure 5 depicts the SO<sub>2</sub> scrubbing achieved when the initial gas temperature was 285°C. Two different slurry concentrations were tested and Spray Pattern 3 was used for both runs.

The data obtained from the experiment run at 210°C using Pattern 3 and a slurry solids concentration of 0.15 has been overlaid on the figure for qualitative comparison.

The following percentage reductions in SO<sub>2</sub> concentration (molar) were achieved for the experiments depicted in Figure 5:

- x = 0.15 (210°C): 74%
- x = 0.15 (285°C): 77%
- x = 0.10 (285°C): 81%

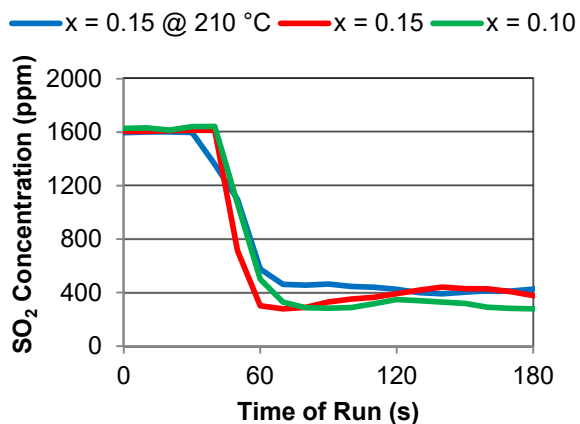


Figure 5: The effect of inlet gas temperature on SO<sub>2</sub> removal

At the increased gas temperature it was expected that the experiment using x = 0.15 would affect less scrubbing compared to the equivalent lower temperature experiment because the higher temperature would evaporate the droplets faster, resulting in a shorter spray length. Contrastingly, however, the spray performed better at the increased temperature at most times during the run. The superior performance is most likely due to enhanced mass transfer processes. At the increased temperature, the volumetric flow of the gas and subsequently, the gas velocity through the reaction column is higher. This, along with increased

turbulence within the column, would increase the rate of gas-liquid film mass transfer via a reduction in the thickness of the film length.

The best SO<sub>2</sub> removal was achieved using a slurry with x = 0.10. In this experiment no slurry was collected at the bottom outlet of the reactor column. Therefore, contrary to the previous experiment, where this solids concentration was used at a lower gas temperature, all of the sprayed content evaporated within the column. More SO<sub>2</sub> removal was allowed for using the slurry with x = 0.10 compared to x = 0.15 because the droplets were able to fall a greater distance down the length of the column as a result of their greater water concentration. In other words, the residence time of the gas stream within the spray was greater for the slurry of higher water mass fraction.

Another contributing factor to the superior performance of the slurry with the higher water mass fraction (x = 0.10) could be attributed to a higher concentration of ionised sorbent within the droplets. This would assist in counteracting the slow and dissolution process of the solids content into the aqueous phase.

## 4.2 NO<sub>2</sub> Removal

The following section details experimental results pertaining to the spray-dry scrubbing of NO<sub>2</sub> in the absence of SO<sub>2</sub>. Residence time of the gas in the column was approximately 2 - 3 seconds as calculated from the experimental parameters employed (Müller 2015). As will be observed in the following figures these experiments took a far longer time to establish equilibrium. This is attributed to the lower residence time, higher volumetric flow, of the gas through the column. With a higher volumetric flow of gas, the liquid-gas contact parameter (L/G ratio) is substantially smaller and consequently so are the gas-liquid mass transfer kinetics involved in the scrubbing process.

### 4.2.1 Effect of Spray Pattern

Figure 6 displays the trends obtained during experiments run at 115°C using lime slurry with a lime mass fraction of 0.05 kg lime/kg slurry.

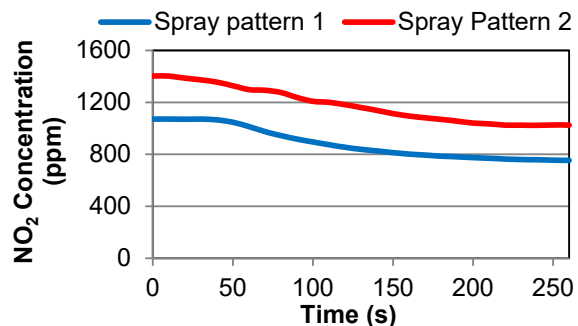


Figure 6: Effect of spray pattern on NO<sub>2</sub> removal

During this experiment no nozzle blockages occurred and no slurry accumulated at the bottom of the reactor.

The following percentage reductions in NO<sub>2</sub> concentration (molar) were achieved for the experiments depicted in Figure 6:

- Pattern 1: 30.1%
- Pattern 2: 29.5%

#### 4.2.2 Effect of Slurry Concentration

Figure 7 displays the trends obtained during experiments run at 180°C using Spray Pattern 2.

The following percentage reductions in NO<sub>2</sub> concentration (molar) were achieved for the experiments depicted in Figure 7:

- x = 0.05: 21%
- x = 0.10: 42%

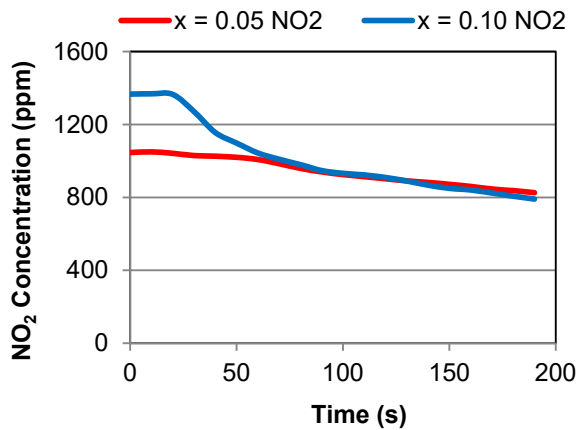


Figure 7: Effect of slurry concentration on NO<sub>2</sub> removal

#### 4.2.3 Effect of Gas Temperature

Figure 8 displays the trends obtained during experiments run using lime slurry with a lime mass fraction of 0.05 kg/kg slurry and Spray Pattern 2. The objective of the experiment was to observe the effect of temperature on NO<sub>2</sub> removal efficiency.

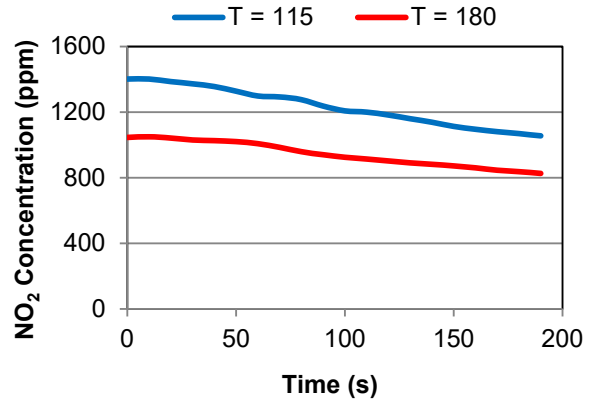


Figure 8: Effect of gas temperature on NO<sub>2</sub> removal

The following percentage reductions in NO<sub>2</sub> concentration (molar) were achieved for the experiments depicted in Figure 8:

- T = 115°C: 25%
- T = 180°C: 21%

#### 4.3 Simultaneous SO<sub>2</sub> and NO<sub>x</sub> removal

With the removal of NO<sub>2</sub> and SO<sub>2</sub>, the concentrations of these gases in the aqueous phase of the slurry can have a significant impact on the selectivity of the reaction. Figure 9 presents the results obtained with SO<sub>2</sub> in excess using Spray Pattern 2 and a slurry lime mass fraction of 0.05 kg lime/kg slurry.

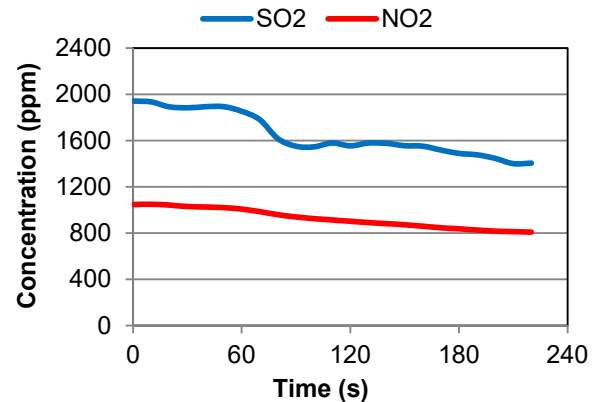


Figure 9: Simultaneous removal with SO<sub>2</sub> in excess

The removal of SO<sub>2</sub> was approximately 28%.

In the next experiment, the SO<sub>2</sub> and NO<sub>2</sub> are roughly equal in initial concentration, also using Spray Pattern 2 but with a slurry lime mass fraction of 0.10 kg lime/kg slurry.

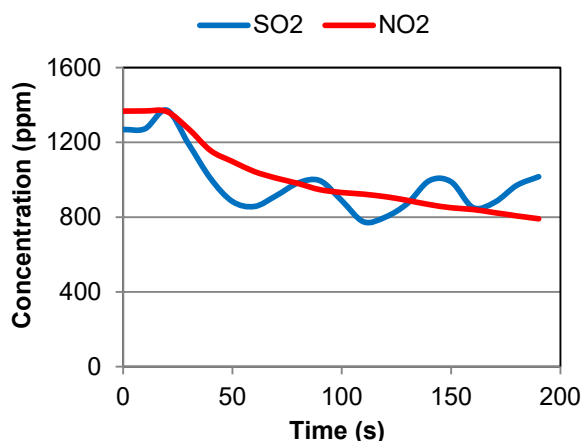


Figure 10: Simultaneous removal with equal initial molar quantities

The SO<sub>2</sub> concentration did not reach steady state, but an average removal of 31% was found.

- $x = 0.05$ : 21%
- $x = 0.10$ : 62%

## 5. Conclusions

Insight into the effect of variation in spray pattern, droplet size, lime slurry mass fraction and inlet gas temperature on the SO<sub>2</sub> and NO<sub>x</sub> removal efficiency of a counter-current spray-dry scrubber was ascertained.

Improved operation with respect to SO<sub>2</sub> and NO<sub>x</sub> removal occurs when the sprayed droplets are able to fall an appreciable distance down the length of the column before their motion is arrested and reversed by the upward momentum of the flowing gas. An additional increase in the performance of the spray-dry method occurs at high gas temperatures using slurry of relatively low solids mass fraction. This is a consequence of an enhancement of the rate-limiting gas-liquid film mass transfer mechanism. When the length of the spray is a significant fraction of the total length of the reaction column, the spray-dry scrubbing technique is able to effect a 70 – 75% reduction of the SO<sub>2</sub> concentration within the flowing gas stream with a residence time of 7 – 8 seconds. An 81% reduction was achieved during this investigation at an inlet gas temperature of 285°C using a large droplet spray of slurry with a 0.10 solids mass fraction.

To optimise the removal conditions for both SO<sub>2</sub> and NO<sub>2</sub>, the time the slurry droplets spend in the reactor should be maximised. The mass fraction of the alkaline powder in the slurry is critical in finding the balance between having enough water to prolong the residence time for each droplet and having enough surface area for the reaction to occur.

For NO<sub>2</sub> in air, the best removal achieved was 30% with a residence time of 2 – 3 seconds. The

optimal removal conditions for the SO<sub>2</sub> and the NO<sub>2</sub> were the same. When the NO<sub>2</sub> and SO<sub>2</sub> were introduced together into the reactor, the best removal was achieved when the slurry mass fraction was 0.10, the temperature was 180°C and spray pattern 2 was used. This actually increased the removal of NO<sub>2</sub> to 42% and decreased the SO<sub>2</sub> removal to 30%. It can also be noted that this removal was achieved when the mole ratio of NO<sub>2</sub> to SO<sub>2</sub> was roughly equal to one.

This study was able to demonstrate, using a relatively simple, inexpensive laboratory demonstration set up, the principles of reverse flow sorbent scrubbing. The apparatus was used to enable quantitative measurements to demonstrate the effects of varying various parameters, such as droplet size, flow rates and residence times. This data is beneficial to potential scrubbing devices suitable for small to medium boilers, which cannot justify the costs of modern complex (imported) gas scrubbing systems. This is valuable as a didactic tool for engineering technologists, to have hands on experience with the operating characteristics of gas scrubbing systems.

## 6. References

- Ellison W. 2005, 'Recent developments in the USA in the application of FGD-based technology for simultaneous SO<sub>2</sub>, NO<sub>x</sub> and mercury removal', In: *Radiation treatment of gaseous and liquid effluents for contaminant removal*, Proceedings of a Technical Meeting, Sofia, Bulgaria, 7–10 September 2004. IAEA, Vienna, IAEA TECDOC 1473, pp 77-92.  
[http://www-pub.iaea.org/mtcd/publications/pdf/te\\_1473\\_web.pdf](http://www-pub.iaea.org/mtcd/publications/pdf/te_1473_web.pdf).
- Gates S.J.F. 2015, 'The reaction kinetics of nitric oxide and ozone in the gaseous phase', *Research Report*, University of Pretoria.
- Gostomczyk M. and Kordylewski W. 2010, 'Simultaneous NO<sub>x</sub> and SO<sub>2</sub> removal in wet and semi-dry FGD', *Achivum Combustionis*, **30**:15-24.
- Li B., Zhao J. & Lu J. 2015, 'Numerical study of the simultaneous oxidation of NO and SO<sub>2</sub> by ozone', *International Journal of Environmental Research and Public Health*, **12**:1595-1611.
- Little, B.P. 2014, 'Desulfurisation of calcination kiln flue gas using spray-dry scrubbing', *Research Report*, University of Pretoria.
- Little, B.P. and Kornelius G. 2014, 'Flue gas desulfurisation using spray-dry scrubbing: A mechanical insight into key operating variables', *Research Paper*, University of Pretoria.
- Müller C. 2015, 'Simultaneous removal of NO<sub>2</sub> and SO<sub>2</sub> from a flue gas using spray dry scrubbing', *Research Report*, University of Pretoria.
- Nygaard H.G., Kiil S., Johnsson J.E., Jensen J.N., Hansen J., Fogh F. and Dam-Johansen K. 2004, 'Full-scale measurements of SO<sub>2</sub> gas phase

- concentrations and slurry compositions in a wet flue gas desulphurisation spray absorber', *Fuel*, **83(9)**:1151-1164.
- Scala F., D'Ascenzo M. and Lancia A. 2004, 'Modeling flue gas desulfurization by spray-dry absorption', *Separation and Purification Technology*, **34(1-3)**:143-153.
- Skalska K., Miller J.S. & Ledakowicz S. 2012, 'Intensification of NO<sub>x</sub> absorption process by means of ozone injection into exhaust gas stream', *Chemical Engineering and Processing: Process Intensification*, **61**:69-74.
- Sun C., Zhao N., Zhuang Z., Wang H., Liu Y., Weng X. & Wu Z. 2014, 'Mechanisms and reaction pathways for simultaneous oxidation of NO<sub>x</sub> and SO<sub>2</sub> by ozone determined by in situ IR measurements', *Journal of Hazardous Materials*, **274**:376-383.
- Toole-O'Neil B. 1998, *Dry Scrubbing Technologies for Flue Gas Desulfurization*, Kluwer, Boston.