NO\textsubscript{X} and SO\textsubscript{X} Flue Gas Treatment System Based on Sulfur-Enriched Organic Oil in Water Emulsion

Alon Khabra, Gad A. Pinhasi,* and Tomer Zidki*

**ABSTRACT:** Nitrogen (NO\textsubscript{X}) and sulfur (SO\textsubscript{X}) oxides, the major gaseous pollutants emitted from fossil fuel combustion, have significant health and environmental concerns. Environmental regulations limit these pollutant emissions to tolerable levels. Currently, these pollutants are treated by flue gas desulfurization (SO\textsubscript{X} removal) and selective catalytic reduction (NO\textsubscript{X} removal) processes. However, these technologies require large footprints, use expensive catalysts, and operate under high working temperatures. A new catalyst is reported herein, based on sulfur-enriched oil emulsified with water, where the active catalytic species are sulfur-based oxides. The catalyst has been developed using O\textsubscript{2} as the oxidation reagent in a low-temperature wet scrubber rather than H\textsubscript{2}O\textsubscript{2} or O\textsubscript{3} that are presently used. The catalytically oxidized oxidation reagent in a low-temperature wet scrubber rather than H\textsubscript{2}O\textsubscript{2} or O\textsubscript{3} that are presently used. The catalytically oxidized pollutants are converted to produce ammonium fertilizers by NH\textsubscript{4}OH addition. As a result of treatment with this novel catalyst, we observed reductions in emissions of SO\textsubscript{X} and NO\textsubscript{X} of >85% and 23%, respectively. The catalyst production and the wet scrubbing process are discussed in detail.

1. **INTRODUCTION**

Nitrogen oxides (NO\textsubscript{X}) and sulfur oxides (SO\textsubscript{X}) are air pollutants emitted in large quantities from fossil fuel industrial plants, including power plants. Sulfur dioxide (SO\textsubscript{2}) is the predominant form of sulfur oxides. Two of the most common nitrogen oxides are nitric oxide (NO) and nitrogen dioxide (NO\textsubscript{2}). The nitrogen dioxide is in equilibrium with the colorless gas dinitrogen tetroxide (N\textsubscript{2}O\textsubscript{4}), Reaction 1:

\[
2\text{NO}_2(g) \rightleftharpoons \text{N}_2\text{O}_4(g)
\]

(1)

Currently, in most industrial processes, NO\textsubscript{X} and SO\textsubscript{X} are treated separately.\textsuperscript{4-9} Emissions of SO\textsubscript{X} are significantly reduced and completely removed from flue gases by a "wet scrubbing technology," which uses a slurry of alkaline sorbent (usually limestone or lime), or seawater to scrub gases. In this method, the SO\textsubscript{2} wet scrubbing product, calcium sulfite (CaSO\textsubscript{3}), is further oxidized to produce marketable gypsum (CaSO\textsubscript{4}·2H\textsubscript{2}O). This technique is known as forced oxidation, flue gas desulfurization (FGD), or fluidized gypsum desulfurization.\textsuperscript{10-13}

Although the flue gas desulfurization process achieves relatively high SO\textsubscript{X} removal efficiency, it is not effective in NO\textsubscript{X} removal. This is due to the fact that nitric oxide (NO) gas, which comprises more than 90% of NO\textsubscript{X} in the flue gas, is relatively insoluble in water.\textsuperscript{10-12} Therefore, removing NO\textsubscript{X} is mostly achieved via chemical reduction, in a process termed the "selective catalytic reduction" (SCR). The reduction yield of nitrogen oxides to nitrogen via the SCR is typically high, but this technique is extremely expensive.\textsuperscript{13,14} Other options include enhancing the removal efficiency of NO\textsubscript{X} in wet scrubbers by gas-phase oxidation of water-insoluble NO gas to water-soluble NO\textsubscript{2}, HNO\textsubscript{2}, and HNO\textsubscript{3}. This oxidation can be accomplished by using strong oxidation reagents like gaseous hydrogen peroxide (H\textsubscript{2}O\textsubscript{2}), ozone (O\textsubscript{3}), or nonthermal plasma. The oxidized NO\textsubscript{X} species may then be easily removed by caustic water scrubbing.\textsuperscript{15-17} Additional advantages of this process include the fact that both SO\textsubscript{X} and NO\textsubscript{X} can be removed simultaneously. The above process further comprises the step of contacting the oxidized NO\textsubscript{X} and SO\textsubscript{X} dissolved in a liquid phase, with ammonia to produce an ammonium nitrate NH\textsubscript{4}NO\textsubscript{3} and ammonium sulfate (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} mixture, which can be used as a nitrogen-contained fertilizer. The drawbacks of gas-phase oxidation are requirements of expensive reagents, corrosion-resistant systems, and specialized safety equipment to handle ozone and hydrogen peroxide safely.\textsuperscript{16,17} These additional requirements increase the cost of operations significantly.

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The active catalytic species likely contain −SO3 (n = 1, 2), which can oxidize SO2 to SO3 and NO to NO2. The resulting −SO3− can be ultimately oxidized back to −SO4 using atmospheric O2 as the terminal oxidizing reagent. The organic phase functions both as the catalyst solvent and as an absorbing liquid (i.e., solvent) for nitric oxide (NO) since NO is only slightly soluble in water.10-12 The oxidations of nitric oxide to nitrogen dioxide and sulfur dioxide to sulfur trioxide are according to Reactions 2 and 3. The final oxidation products are nitric and sulfuric acids, which are soluble in the water phase and are formed via Reactions 4 and 5.

\[ 2\text{NO}_2(g) + \text{O}_2(g) \rightarrow 2\text{NO}_3(g) \]  
\[ 2\text{SO}_2(g) + \text{O}_2(g) \rightarrow 2\text{SO}_3(g) \]  
\[ 2\text{NO}_2 + \text{H}_2\text{O}(l) \rightarrow \text{HNO}_3(aq) + \text{HNO}_2(aq) \]  
\[ \text{SO}_3(g) + \text{H}_2\text{O}(l) \rightarrow \text{H}_2\text{SO}_4(aq) \]

As a result, the pH of the resulting suspension decreases. In the following stage, ammonia solution (ammonium hydroxide, NH4OH) is injected into the working liquid to increase the pH and to produce ammonium nitrate NH4NO3 and ammonium sulfate \((\text{NH}_4)_2\text{SO}_4\) mixture via Reactions 6–8.

\[ \text{H}_2\text{SO}_4(aq) + 2\text{NH}_4\text{OH}(aq) \rightarrow (\text{NH}_4)_2\text{SO}_4(aq) + 2\text{H}_2\text{O}(l) \]  
\[ \text{HNO}_3(aq) + \text{NH}_4\text{OH}(aq) \rightarrow \text{NH}_4\text{NO}_3(aq) + \text{H}_2\text{O}(l) \]  
\[ 2\text{HNO}_2(aq) + \text{O}_2(g) + 2\text{NH}_4\text{OH}(aq) \rightarrow 2\text{NH}_4\text{NO}_3(aq) + 2\text{H}_2\text{O}(l) \]

The ammonium sulfate and ammonium nitrate are dissolved in the aqueous phase. Upon saturation of the aqueous phase, precipitation of the \((\text{NH}_4)_2\text{SO}_4/\text{NH}_4\text{NO}_3\) mixture occurs at the bottom of the reactor, and it can be used as a nitrogen-containing fertilizer with substantial economic value. The pH during the entire process must be maintained in the range of 4–7 to keep the reaction going and avoid alkaline solution, from which ammonia gas (NH3) may be emitted. The working temperature range is 50–90 °C after reaching thermal equilibrium of the hot gases in the scrubber.

### 2. EXPERIMENTAL SECTION

The proposed process requires selecting an organic component for the working liquid and a method to integrate the catalyst into the organic phase. The efficiency of each method was examined using a bubble column that has been developed to determine its effectiveness in eliminating the SO2/NOx contaminations from the flue gases.

#### 2.1. Materials

The organic catalyst is based on heavy oil, which contains sulfur compounds as the active species. Essential characteristics for the oil include the fact that it needed to be chemically inert and have a very low vapor pressure, i.e., both a high boiling and a high decomposition point. For use in spray-tower wet scrubbing systems, the oil requires a relatively low viscosity to reduce head losses and increase its fluidity. Furthermore, the oil—water emulsion working liquid should have a relatively short separation time between the two layers, so efficient separation processes for product collection are feasible.

To prepare the catalyst, each oil has been thermally treated with ground elemental sulfur \((S_8)\). In the first step, the ground sulfur was added to the oil samples in various concentrations from 0.5 to 5 wt %, and the mixture was heated up to 140 °C and stirred for 1 h. The organic solution containing dissolved sulfur was slowly cooled to room temperature and visually checked for sulfur precipitation after 24 h. At the second step, the sulfur was dissolved at 140 °C, and its concentration was determined at room temperature.

### Table 1. Photophysical Properties of the Studied Oils and the Enrichment Results for Sulfur Concentration

| oil type                  | supplier                        | density (g/cm³) | viscosity 40 °C (cm²/s) | sulfur wt % (%) | separation time (s) |
|---------------------------|---------------------------------|-----------------|--------------------------|-----------------|---------------------|
| Paraffinic oils           | light paraffinic oil – 88       | 0.853           | 0.866                    | 0.52            | 80                  |
|                           | light paraffinic Oil—88 + diphenyl ether 10 wt % | 0.861           | 1.074                    | 0.92            | 37                  |
|                           | heavy Paraffinic oil—robull B34  | 0.905           | 5.1                      | 2.73            | 150                 |
| Synthetic oils—Synfluid PAO poly(a-olefin) cSt | PAO-6 | 0.8307 | 0.305 | 0.67 | 75 |
|                           | PAO-8                           | 0.8307          | 0.464                    | 0.86            | 78                  |
| Brominated waste vegetable oils | brominated vegetable oil 38-1-oxidized palm oil | 0.95   | >100                    | 1.5             | overspecification   |
|                           | brominated vegetable oil 39-2 canola oil | 0.95   | >100                    | 1.5             | overspecification   |

The sulfur was dissolved at 140 °C, and its concentration was determined at room temperature.

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oils with the highest sulfur concentration obtained, with no sulfur precipitate, have retreated with solid sulfur. The clearest sulfur-enriched oils without any elemental sulfur precipitate were analyzed for sulfur content.

Various oil types, paraffinic, synthetic, and brominated waste vegetable oils (these oils were tested to increase the sulfur solubility using the bromine heavy atom effect), were chosen for this study. These oils contain no sulfur as reported by the company database and confirmed by X-ray fluorescence (XRF) analysis (e.g., for oil 88, the sulfur content is <0.1%). A summary of the photophysical properties of the oils, including density and viscosity, is presented in Table 1, and the Fourier transform infrared (FTIR) spectra of these oils are presented in Figure 2 (see the Section 3).

To increase the solubility of the elemental sulfur in the organic phase, the addition of several solvents to the catalyst was tested.

The solvents were 1,2-dichlorobenzene, decabromodiphenyl ether (99% by Merck), quinoline (98% by Sigma-Aldrich), diphenyl ether, and diglyme (99% by Acros Organics). The elemental sulfur was supplied by Ziv Chemicals, and Frutarom Ltd supplied aqueous ammonia (25 wt %). The NO and SO2 gas cylinders (1% in a nitrogen atmosphere) were supplied by Airgas (an Air Liquide company). The water used throughout this study was ultrapure distilled water (UPDA) with a resistivity of >15 MΩ·cm.

2.2. Instrumentation. The sulfur concentrations were measured by X-ray fluorescence (XRF) model AXIOS mAX by Malvern Pananalytical with an X-ray power source (4KW), equipped with a gas purge unit for liquid analysis. IR spectra were recorded using a Fourier transform infrared (FTIR) spectrometer model ALPHA 2 by Bruker equipped with a platinum diamond attenuated total reflectance (ATR) module (the liquid samples were dropped on top of the ATR sample platform, and the FTIR spectra were recorded). The spectral resolution was set to 2 cm⁻¹, and 16 scans were taken per measurement. The analyses of NO, NO2, SO3, SO2, O2, and N2 were carried out using an OPTIMA 7—unit by MRU Instruments (based on electrochemical sensors). The accuracies of the sensors are NO ± 5 ppm, NO2 ± 5 ppm, and SO2 ± 10 ppm. The pH values of the solutions were measured with a glass electrode using a CyberScan Bench pH 500 pH meter. The gas flow rates were measured using a digital mass flow meter model M-SERIES V-Slpm-D/SV supplied by Alicat Scientific. The temperature controller was a digital temperature control system model BOX-3216 supplied by MRC.

2.3. Sulfur Enrichment Tests. The sulfur enrichment in the oil was studied by using different protocols. A sample of the sulfur-enriched oil was analyzed for the sulfur content by the sulfur reduction method and XRF. The acid content of the S-enriched oil was tested by emulsification in water (water/oil = 1:1) and measuring the pH after separation of the organic emulsion’s phases.

2.4. Phase Separation Tests. The products of the studied process are ammonium sulfate and ammonium nitrate, which dissolve in aqueous solution. To separate them from the oil—water emulsion, they are first subjected to precipitation, followed by recovery of the ammonium salts from the spray column reactor via separation of the emulsion working liquid into two phases (aqueous solution containing the salts and the organic solution). The oil—water emulsion separation time for each oil was studied at 60 °C for each catalytic oil system.

Generally, in a wet scrubbing pilot facility, the product extraction process is carried out on a bleed stream separated from the fluid in a circulated working liquid. The “mother liquor,” the part of a solution that is left over after crystallization, is being returned to the circulated working liquid.

2.5. Bubble Test Column. The studied process and the proposed working catalyst liquid were studied with respect to the absorption efficiency of the two main pollutants, nitric oxide (NO) and sulfur dioxide (SO2), using a laboratory bubble column apparatus (Figure 1). The system consists of the main reactor; flow, temperature, and pH control systems; and a gas-composition measurement system. The main reactor is a vertical cylindrical tube with a 5 cm diameter and a gas inlet at the bottom; see the SI for further details. The reactor was filled with 500 mL of working liquid (the liquid level in the column was 30 cm). The working liquid was a catalyst emulsion with a 1:1 volumetric mixture of water and sulfur-enriched oil.

Gas mixtures were injected at the bottom of the reactor through a sparger to form fine bubbles. A fine thin Teflon wire in a packed formation was placed in the reactor to break the converging bubbles and enlarge the interfacial area. In preliminary tests, the gas flow rates were studied with respect to bubble size, gas hold-up, and pressure drop (Figures S1–S3). The operating parameters were set according to requirements for a 3 s residence time and to maximize the available interfacial area. The gas mixtures of a demonstration synthetic gas mixture: (NO 200–500 ppm/SO2 200–500 ppm in air) were injected into the reactor. The synthetic gas sources were 5 L cylinders of a 1% mass ratio (NO or SO2 balanced with nitrogen). The air and gas flow rates (NO/SO2) were measured using digital mass flow meters. The mixture flow rate and concentration were controlled using needle valves (V1 and V2 in Figure 1). The operational flow rate and concentration ranges were 0.5–1.5 LPM and 200–500 ppm, respectively. The gas mixture composition and the tested gas concentration...
before and after passing the reactor were analyzed using an Optima 7 gas analyzer. The tested gas conversion ($R_i[\%]$, $i = \text{NO}_x, \text{SO}_2$) for each case was calculated from the ratio between the inlet and outlet concentrations, where $C_{i,in}$ and $C_{i,out}$ referred to NO$_x$ or SO$_2$ gas concentrations, respectively, as shown in eq 9.

$$R_i[\%] = 100 \left(1 - \frac{C_{i,out}}{C_{i,in}}\right)$$

The reactor temperature was controlled by a PID controller digital temperature control system using textile glass heating tape (500 W, 250 °C) and K thermocouple for temperature sensing. The working temperature was kept at 60 °C. The acidity values were monitored by a pH electrode and controlled manually by the addition of 1.0 M ammonia solution to the reactor. Initially, the reactor was charged with a catalyst emulsion at pH 7.0.

3. RESULTS AND DISCUSSION

The results of the sulfur enrichment, phase separation tests, and bubble column tests are presented.

3.1. Sulfur Enrichment. Several procedures have been tested to dissolve elemental sulfur in the organic oil to produce the active catalytic species. The most efficient method was the following procedure: The organic oil was heated to 140 °C, elemental ground sulfur (S$_8$) was added to the stirred oil until a clear solution was obtained after ca. 1 h, and the sulfur-enriched oil was cooled slowly to room temperature. A sample of the sulfur-enriched oil was analyzed for sulfur content by the sulfur oxidation method and by XRF. The acidity of the S-enriched oil was tested by emulsification in water (water/oil = 1:1) and measuring the pH after the complete phase separation. The results of the sulfur enrichment are presented in Table 2.

Table 2. Sulfur Solubility in Organic Solvents at 60 °C

| organic solvent              | wt % sulfur |
|------------------------------|-------------|
| 1,2-dichlorobenzene         | 8.20        |
| quinoline                   | 11.1        |
| diphenyl ether              | 12.1        |
| diglyme                     | 12.3        |

"The solubility was measured by dissolving elemental sulfur in the compound at 60 °C and separating the excess undissolved sulfur by filtering the solid.

From the results of Table 2, it is clear that the best oil to increase the elemental sulfur content is the heavy paraffinic oil—Robul B34, in which a sulfur concentration of 2.73% was obtained. The second best was the brominated vegetable oil 38, which dissolved 1.5% of sulfur. These results are likely due to the fact that dissolved sulfur in the heavy organic oils reacts to form soluble sulfur compounds in the oil, which are the active species in the catalytic process. By contrast, the other oils are less able to provide the environment necessary for these reactions to occur.

The treatment of the heavy organic oils to produce the organic catalytic phase involves chemical changes and the formation of active sulfur species, which are the heart of the catalyst. Thus, it is expected that it will result in changes in the infrared spectrum. To verify it, the spectra of the catalyst compared to the untreated heavy oil have been measured, and indeed new absorption peaks have appeared at 1210–1240 and 1310–1330 cm$^{-1}$ that are absent in the untreated organic oils (Figure 2). The FTIR spectra in Figure 3 relate to the catalyst formed after the dissolution of elemental sulfur in the oil. In the inset, it is clear that two new absorption bands at 1225 and 1320 cm$^{-1}$ in the sulfur-enriched oil appear in the spectrum. These bands probably stem from the sulfur-active catalytic species, probably R-SO/R-SO$_2$ formed in the oil, which leads to S=O vibrations in the active species.

One of the advantages of using the heavy organic phase is that the solubility of molecular O$_2$ is much higher than in aqueous solutions. A plausible mechanism that might explain the sulfur-containing organic catalyst activity in the organic/aqueous emulsion is via Reactions 10–14.

$$\text{2R} - \text{SO}_{(org)} + \text{O}_2{(aq)} \rightarrow \text{2R} - \text{SO}_2{(org)} \quad (10)$$

$$\text{R} - \text{SO}_2{(org)} + \text{NO}_{(org)} \rightarrow \text{R} - \text{SO}_{(org)} + \text{NO}_2{(org)} \quad (11)$$

$$\text{2NO}_2{(org)} + \text{H}_2\text{O}_{(aq)} \rightarrow \text{HNO}_3{(aq)} + \text{HNO}_2{(aq)} \quad (12)$$

$$\text{R} - \text{SO}_2{(org)} + \text{SO}_3{(org)} \rightarrow \text{R} - \text{SO}_{(org)} + \text{SO}_4{(aq)} \quad (13)$$

$$\text{SO}_3{(org)} + \text{H}_2\text{O}_{(aq)} \rightarrow \text{H}_2\text{SO}_4{(aq)} \quad (14)$$

$^{23}$
The oxidized products are much soluble in water; thus, they will be transferred at the interphase layer of the emulsion from the organic phase to the aqueous solution, and in the presence of dissolved ammonia in the aqueous phase, a nitrogen sulfur mixture of NH₄NO₃/(NH₄)₂SO₄ will be produced.

### 3.2. Effect of Solvent Additives on the Sulfur Content

As the likely active species in the organic catalyst are sulfur-based species, we decided to study the effect of such compounds on the solubility of elemental sulfur by adding them to the heavy oil phase. The compounds chosen were 1,2-dichlorobenzene, quinoline, diphenyl ether, diglyme, and decabromodiphenyl ether; 10 wt % of each additive was added to 50 wt % of water/oil emulsion, and its ability to dissolve elemental sulfur was studied at 60 °C, since some of the compounds are volatile at 140 °C. Elemental ground sulfur was added to the organic solvent at 60 °C until maximum dissolution was obtained, and the organic phase was clear without any precipitated sulfur. The results of the saturated S concentration at 60 °C are given in Table 2.

As shown in Table 2, these compounds are efficient solvents for the dissolution of elemental sulfur, with a range of solubilities between 8% and 12.3%. To check the effectiveness of using these compounds, 10 wt % diphenyl ether was dissolved in oil 88 and the dissolution of elemental sulfur in the mixture was checked (Table 2). As expected, an appreciable increase (by almost a factor of 2) in the sulfur content of 0.92 wt % was achieved (compared with the pure oil 88 content of 0.52 wt %).

### 3.3. Catalyst Efficiency

Each catalyst oil was checked for its catalytic activity in two reactions: oxidation of NO to NO₂ and oxidation of SO₂ to SO₃ in the bubble column system. The typical NO or SO₂ gas concentrations at the inlet point were NO: 400–500 ppm, SO₂: 325–370 ppm, at low gas flow rates (for example, mixing 0.5 L/min air with 75 mL/min NO or SO₂ resulted in 450 ppm NO or 350 ppm SO₂). Upon operation of the bubble column system, the pH values of the water in the catalytic emulsions were decreased from 7 to 5.5 after 30 min of operation due to the oxidation of NO and SO₂. The oxidized products are much soluble in water; thus, they will be transferred at the interphase layer of the emulsion from the organic phase to the aqueous solution, and in the presence of dissolved ammonia in the aqueous phase, a nitrogen sulfur mixture of NH₄NO₃/(NH₄)₂SO₄ will be produced.

### Table 3. Percent Oxidation of NOₓ and SO₂ in the Pilot System: Wet Scrubber at 60 °C with Different Catalytic Systems.

| oil type                  | NOₓ oxidation, % | SO₂ oxidation, % |
|---------------------------|------------------|------------------|
|                           | pure solvent     | S-enriched catalyst | pure solvent     | S-enriched catalyst |
| water (only)              | 8.8              | 90               | 90              | 90               |
| light paraffinic oil—88   | 5.5              | 14.5             | 86              | 91.5             |
| heavy paraffinic oil—Robul B34 | 9.1         | 23               | 76              | 85               |
| PAO-6                     | 6.7              | 17.5             | 88              | 92               |
| PAO-8                     | 6.9              | 18.5             | 87              | 92               |
| brominated vegetable oil 38-1 | 9.5          | 24               | 70              | 76               |

**Typical inlet values: NO 450 ppm, NOₓ 60 ppm, and O₂ 20.5%; at the outlet of the reaction column: NO 411 ppm, NOₓ 26 ppm, and O₂ 18.9%; to get 14.3% oxidation. Typical inlet values: SO₂ 306 ppm and O₂ 20.5%; at the outlet of the reaction column: SO₂ 26 ppm, NOₓ and O₂ 18.8%, to get 91.5% oxidation.**

As the likely active species in the organic catalyst are sulfur-based species, we decided to study the effect of such compounds on the solubility of elemental sulfur by adding them to the heavy oil phase. The compounds chosen were 1,2-dichlorobenzene, quinoline, diphenyl ether, diglyme, and decabromodiphenyl ether; 10 wt % of each additive was added to 50 wt % of water/oil emulsion, and its ability to dissolve elemental sulfur was studied at 60 °C, since some of the compounds are volatile at 140 °C. Elemental ground sulfur was added to the organic solvent at 60 °C until maximum dissolution was obtained, and the organic phase was clear without any precipitated sulfur. The results of the saturated S concentration at 60 °C are given in Table 2.

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### 4. CONCLUSIONS

This study aimed to develop a catalyst that will eliminate SOₓ and NOₓ contaminations in flue gases using atmospheric oxygen as an oxidation reagent. The newly developed catalyst is designed as a potential replacement for the existing bulky and expensive wet scrubbing systems operating at a relatively high temperature (more than 350 °C) with much smaller, simpler, and cheaper combination systems operating at 50–90 °C. Additional feature of the studied system is that the dissolved sulfur species contribute to higher oxidation yields of NOₓ and SOₓ in flue gases and that higher sulfur concentration results in improved oxidation of the pollutant gases. Therefore, a simple and economic process providing a general method for the oxidation of NOₓ and SOₓ using atmospheric O₂ as an oxidation reagent while manufacturing fertilizers (such as ammonium nitrate (NH₄NO₃) and ammonium sulfate ((NH₄)₂SO₄) by ammonia injection) is achieved. However, the catalyst developed is very efficient for SO₂ oxidation (≥85% reduction) and still should be improved for NO oxidation (~24% reduction).

### ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c04485.

Operational characteristics of the bubble column (PDF)

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Notes
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