Simultaneous Removal of NO and SO$_2$ from Flue Gas Using $[\text{Bmim}]_2\text{FeCl}_4$/Sulfolane Binary Mixtures

Liwei Li, Xiaoshan Li,* Yajun Bi, Bowen Lu, Wufeng Jiang, and Liqi Zhang

ABSTRACT: NO and SO$_2$ are the major pollutants of coal combustion. As superior absorbents, ionic liquids are environmentally friendly, are reusable, and can clean flue gases, such as CO$_2$, SO$_2$, and NO$_x$. However, NO and SO$_2$ absorption with low concentration in flue gases under normal conditions is rarely studied. In this work, $[\text{Bmim}]_2\text{FeCl}_4$ was synthesized and mixed with sulfolane for NO and SO$_2$ removal from flue gas. The investigated concentrations of NO and SO$_2$ were 1100 and 2500 ppm, respectively, which are close to real fuel gas conditions. Results showed that 30 wt % $[\text{Bmim}]_2\text{FeCl}_4$/sulfolane mixture performed the best absorption behavior. The presence of SO$_2$ could promote NO absorption by $[\text{Bmim}]_2\text{FeCl}_4$/sulfolane mixture. The 30 wt % $[\text{Bmim}]_2\text{FeCl}_4$/sulfolane mixture had removal efficiencies of 93.6 and 76.2% for NO and SO$_2$, respectively. This mixture also showed great reusability for NO and SO$_2$ after six cycles of absorption. Fourier transform infrared (FTIR) spectrum indicated that SO$_2$ and NO removal by $[\text{Bmim}]_2\text{FeCl}_4$/sulfolane binary mixture was due to the chemical reaction between NO and $[\text{Bmim}]_2\text{FeCl}_4$ and the physical absorption between SO$_2$ and sulfolane.

1. INTRODUCTION

The major source of NO and SO$_2$ emission is the combustion of coal and other fossil fuels.\(^1\)\(^-\)\(^3\) If these acid gases cannot be controlled, they can transform into acid rain and cause harm to the environment and citizen’s health. Hence, an effective way to control NO and SO$_2$ from fuel gas is necessary. Selective catalytic reduction (SCR)\(^4\)\(^-\)\(^6\) and wet flue gas desulfurization (WFGD)\(^7\)\(^-\)\(^9\) are applied in commercial coal-fired power plants to reduce NO and SO$_2$ emissions. However, the catalysts of SCR are of poor low-temperature activity, and some are poisonous. WFGD produces byproducts, such as gypsum or magnesium sulfate. A more convenient and financially sound method to control NO and SO$_2$ must be developed.

NO and SO$_2$ have been recently reduced by "wet" process that uses ionic liquids (ILs) and has great potential in absorbing acid gases such as CO$_2$, SO$_2$, and NO due to its excellent characteristics.\(^10\)\(^-\)\(^18\) Ionic liquids are environmentally friendly absorbent, with low vapor pressure and high thermal stability, and could avoid contamination and co-product during the simultaneous removal process compared with other liquid absorbents, such as NaClO$_2$ and KMnO$_4$. During regeneration, ionic liquids consume less energy, which is mainly sensible heat, due the lack of water in the absorbent. Hence, lowering the emission of NO and SO$_2$ using ionic liquids requires further studies.

Chen and co-workers\(^19\) suggested some nucleophilic atoms such as N or O with a strong interaction with SO$_2$, used $[\text{P}_{4442}][\text{Tetz}]$ to capture SO$_2$ under 2000 ppm SO$_2$, analyzed the reaction, and found that N in different positions of $[\text{Tetz}]^{-}$ could form an intense chemical bond with SO$_2$. The $[\text{Et2NEmim}][\text{Tetz}]$ designed by Yang and co-workers\(^20\) exhibited an efficient SO$_2$ absorption of 0.47 g SO$_2$/g ILs at 0.0101 MPa SO$_2$ partial pressure through the chemical reaction of SO$_2$ with both cation and anion. After several cycles, the characteristic and absorption capacity hardly changed. Ding and co-workers\(^21\) designed several dual-functionalized ionic liquids with metal chelate cations for SO$_2$ absorption and found that ionic liquids with a metal element have a high absorption capacity because of the combined physical and chemical interaction of SO$_2$. In addition, Huang and co-workers\(^22\) mixed sulfolane with an ionic liquid to reduce the viscosity and improve the SO$_2$ absorption rate.

For NO absorption, Chen\(^23\) concluded that azole-based ionic liquid has a high absorption capacity of about 4.52 mol NO per mol ionic liquids and could efficiently remove NO by forming a bond between N atoms and NO at multiple sites. Begel and co-workers\(^24\) investigated the reaction of iron (II) with NO in ionic liquids $[\text{emim}][\text{OTf}]$ and found Fe$^{2+}$−NO in the liquids and Fe$^{2+}$ was not oxidized by NO to form Fe$^{3+}$. Sun
and co-workers prepared metallic functional ionic liquid \([\text{Bmim}]_2\text{FeCl}_4\) to reduce NO. The mole ionic liquids could absorb 0.205 mol NO at 30 °C when NO concentration was 0.2% due to the reaction of Fe\(^{2+}\) and NO, indicating that NO could easily react with Fe\(^{2+}\). These works revealed that ionic liquids show good absorption performance for SO\(_2\) and NO. However, the simultaneous removal of NO and SO\(_2\) with low concentration in coal-fired flue gas conditions must be further explored.

Our group used imidazolium-based ionic liquids to remove NO and SO\(_2\) with low concentration at elevated pressures. The removal efficiency of SO\(_2\) and NO could reach 98.0 and 93.5%, respectively, under 1.0 MPa and 25 °C. Nevertheless, absorption in the ambient pressure and temperature with low gas concentration at real fuel gas conditions was not considered. Pure ionic liquids have the disadvantage of high viscosity that negatively affects the gas−liquid mass transfer. In the present work, an excellent solvent with a comparatively low viscosity was used to simultaneously remove SO\(_2\) and NO at real flue gas concentrations. Considering the high absorption capacity of \([\text{Bmim}]_2\text{FeCl}_4\), this ionic liquid was applied to absorb SO\(_2\) and NO in simulated flue gas under ambient pressure. The reaction of SO\(_2\) and NO with ionic liquid was investigated. In addition, to reduce the viscosity and improve the absorption efficiency, sulfolane was mixed with \([\text{Bmim}]_2\text{FeCl}_4\).

2. RESULTS AND DISCUSSION

2.1. Characterization of the Synthesized Mixture.

Figure 1 shows the Raman spectrum of the synthetic \([\text{Bmim}]_2\text{FeCl}_4\). The peak at 306 cm\(^{-1}\) was almost the vibration of FeCl\(_4^{2-}\) and those at 385 and 439 cm\(^{-1}\) were the result of the \([\text{Bmim}]^+\) vibration. Although the position of each peak was greater than that previously reported due to the influence of the testing environment and solvent, the sample synthesized in this work was confirmed to be \([\text{Bmim}]_2\text{FeCl}_4\).

The thermal stability of pure \([\text{Bmim}]_2\text{FeCl}_4\) and 30 wt % \([\text{Bmim}]_2\text{FeCl}_4/\text{sulfolane}\) was tested through thermogravimetric analysis (TGA), and the result is shown in Figure 2. Pure \([\text{Bmim}]_2\text{FeCl}_4\) starts to decompose at 250 °C. From 250 to 480 °C, the weight of the sample decreased rapidly because of \([\text{Bmim}]_2\text{FeCl}_4\) disintegration. When the temperature increased, the residue of the sample decreased gradually. The decomposition of 30 wt % \([\text{Bmim}]_2\text{FeCl}_4/\text{sulfolane}\) binary mixture included three parts with increasing temperature: sulfolane decomposition, \([\text{Bmim}]_2\text{FeCl}_4\) disintegration, and residue decomposition. The onset decomposition temperature of \([\text{Bmim}]_2\text{FeCl}_4/\text{sulfolane}\) binary mixture was 120 °C. The mass loss in the binary mixture from 120 to 250 °C in the first stage was about 70 wt %, which is consistent with the mass weight of sulfolane. The feature of the latter two stages at temperatures above 250 °C is nearly the same as pure \([\text{Bmim}]_2\text{FeCl}_4\) decomposition. The TGA result indicated that the binary mixture showed good thermal stability. If the regeneration temperature of the mixture is lower than the decomposition temperature of \([\text{Bmim}]_2\text{FeCl}_4/\text{sulfolane}\) binary mixture, almost no mass loss for absorbent would occur during the process of regeneration. Also, 80−120 °C should be a suitable temperature for absorbent regeneration.

The viscosities of pure ILs and 30 wt % \([\text{Bmim}]_2\text{FeCl}_4/\text{sulfolane}\) binary mixture under four temperature points of 30 ± 0.1, 40 ± 0.1, 50 ± 0.1, and 60 ± 0.1 °C were detected by a viscometer, and the results are shown in Figure 3. The viscosity was inversely proportional to the temperature for both samples. The pure \([\text{Bmim}]_2\text{FeCl}_4\) had higher viscosity than 30 wt % \([\text{Bmim}]_2\text{FeCl}_4/\text{sulfolane}\). At 30 °C, the viscosity of pure \([\text{Bmim}]_2\text{FeCl}_4\) was 1303 cP, which is almost 56 times as large as that of 30 wt % \([\text{Bmim}]_2\text{FeCl}_4/\text{sulfolane}\) binary mixture at 23.4 cP. Even at 60 °C, the viscosity of pure \([\text{Bmim}]_2\text{FeCl}_4\) was still large, at 192.9 cP. However, the temperature had minimal effect on the viscosity of 30 wt %
With the temperature increasing from 30 to 60 °C, the viscosity of 30 wt % [Bmim]$_2$FeCl$_4$/sulfolane decreased from 23.4 cP to 10.2 mPa s. Low viscosity is beneficial for gas−liquid mass transfer, as it can enhance the absorption of NO and SO$_2$.

2.2. Effect of Different Ratios of [Bmim]$_2$FeCl$_4$ and Sulfolane on NO and SO$_2$ Removal.

Sulfolane was in a solid form and could hardly absorb SO$_2$ and NO under this low temperature. However, sulfolane could dissolve in [Bmim]$_2$FeCl$_4$, and a high ratio of sulfolane could decrease the viscosity of mixtures and enhance the absorption rate. Thus, the effect of different ratios of [Bmim]$_2$FeCl$_4$ and sulfolane on NO and SO$_2$ removal was investigated to determine the appropriate ratio of [Bmim]$_2$FeCl$_4$ and sulfolane. [Bmim]$_2$FeCl$_4$/sulfolane for single NO and single SO$_2$ removal was investigated at the atmosphere of 1280 ppm NO/N$_2$ and 2500 ppm SO$_2$/N$_2$, as shown in Figures 4 and 5, respectively. In binary mixtures, the mass ratio of [Bmim]$_2$FeCl$_4$ was chosen as 10−50 wt % and the mass ratio of sulfolane was 50−90 wt %. For NO and SO$_2$ removal, the reduction efficiencies of all absorbents decreased with the absorption time. The absorption ability of the absorbents

![Figure 4](image1.png)

**Figure 4.** Effect of different ratios of [Bmim]$_2$FeCl$_4$ and sulfolane on NO removal (temperature, 25 ± 0.1 °C; pressure, 0.1 MPa; atmosphere, 1280 ppm NO/N$_2$).

![Figure 5](image2.png)

**Figure 5.** Effect of different ratios of [Bmim]$_2$FeCl$_4$ and sulfolane on SO$_2$ removal (temperature, 25 ± 0.1 °C; pressure, 0.1 MPa; atmosphere, 2500 ppm SO$_2$/N$_2$).

![Figure 6](image3.png)

**Figure 6.** (a) Effect of temperature on NO removal efficiency. (b) Effect of temperature on SO$_2$ removal efficiency (30 wt % [Bmim]$_2$FeCl$_4$/sulfolane; atmosphere, 1100 ppm NO/2500 ppm SO$_2$/N$_2$; pressure, 0.1 MPa).
were conducted to evaluate the in

In addition, the removal effi
temperatures of 35
the results are shown inFigures 6and 7. As shown inFigure 6,
SO2 (30 wt % [Bmim]2FeCl4/sulfolane; atmosphere, 1100 ppm NO/
From NO absorption, 30 wt % [Bmim]2FeCl4/sulfolane binary
absorption capacity decreased with the absorption time.
absorption capacity in the mixture. NO and SO2 removal at
the gas
[Bmim]2FeCl4/sulfolane binary mixture also exhibited the best
change. Considering its excellent absorption characteristic and
pure [Bmim]2FeCl4. Its denitri
mixture, thus negatively a
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increased from 35 to 65
°C. The average NO removal effi
fficiency througheq
2.3. Effect of Temperature on Simultaneous NO and
SO2 Removal. Temperature is an important factor in the
reduction of NO and SO2 from stimulated fuel gas and affects
the gas–liquid mass transfer, absorbent regeneration, and
absorption capacity in the mixture. NO and SO2 removal at
temperatures of 35 ± 0.1, 45 ± 0.1, 55 ± 0.1, and 65 ± 0.1 °C
were conducted to evaluate the influence of temperature, and
the results are shown in Figures 6 and 7. As shown in Figure 6,
the temperature had a substantial effect on NO and SO2
absorption. The average SO2 removal efficiency decreased
from 80.3 to 63.8% when the temperature increased from 35 to
65 °C. The average NO removal efficiency was also decreased
strongly from 84.6 to 65% when the reaction temperature
increased from 35 to 65 °C. The effect of temperature on NO
and SO2 removal was complex. On the one hand, the
molecular motion and reaction rate increased with the
temperature. On the other hand, the high temperature was
c comparable low cost, the 30 wt % [Bmim]2FeCl4/sulfolane
mixture, which was slightly
decreased at 77% in 120 min. In the 2 h absorption, the NO
removal efficiency was improved by 28% using 30 wt %
[Bmim]2FeCl4/sulfolane containing only 30% [Bmim]2FeCl4.
In addition, the removal efficiency of SO2 nearly did not
change. Considering its excellent absorption characteristic and
comparatively low cost, the 30 wt % [Bmim]2FeCl4/sulfolane
was chosen to be the most appropriate absorbent for NO and
SO2 removal.

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temperature. On the other hand, the high temperature was
c conducive to the disintegration of Fe2+ nitroxyl species22 and
sulfide and could reduce the solubility of NO and SO2 in the
mixture, thus negatively affecting SO2 and NO absorption.

2.4. Effect of SO2 and NO Concentration on Their
Simultaneous Removal. NO and SO2 concentration is one
of the important factors in their simultaneous removal. Experiments were conducted under SO2 concentration from
0 to 2500 ppm and NO concentration from 0 to 1100 ppm
investigate the mutual effect of SO2 and NO concentration
during the simultaneous removal. The results are shown in
Figures 8 and 9.

Figure 8a shows that the average NO removal efficiency
increased from 74.7 to 93.7% when the concentration of SO2
increased from 0 to 1920 ppm. However, when the SO2
concentration continued to increase to 2500 ppm, the average
absorption efficiency of NO decreased slightly from 93.7 to
93.6%. The increase in NO efficiency was due to the SO3
generated from the interaction of SO2 and water absorbed by
the ionic liquid. According to the experiment of Wang et al.,27
SO2−3 improves the average NO removal efficiency through eq
1.

\[
2\text{Fe(III)}\text{Cl}_4^{-} + \text{NO} + \text{SO}_3^{2-} \rightarrow 2\text{Fe(II)}\text{Cl}_4^{2-} + \text{SO}_4(\text{NO})_2^{2-}
\] (1)

Hence, the presence of SO2−3 had a positive effect on NO
removal due to the chemical reaction. However, when the SO2
concentration was more than 1920 ppm, SO2 would compete
with NO for the physical absorption in IL and sulfolane, thus
slightly decreasing the average NO removal efficiency.

The effect of NO concentration on SO2 removal is shown in
Figure 9. The presence of NO had minimal influence on SO2
absorption. The average SO2 removal efficiency decreased
by no more than 1% when the NO concentration increased
from 0 to 1100 ppm. This finding is attributed to the competition
between NO and SO2 absorption in IL and sulfolane.

2.5. Reusability Performance. Another crucial feature of
absorbent is the ability of absorption for repeated absorption.
The saturated mixture was heated at 80 ± 0.1 °C for 5 h under
N2 atmosphere to reproduce the absorbent. The mixture was
then used to reabsorb NO and SO2 at concentrations of 1100
and 2500 ppm, respectively, at 25 ± 0.1 °C. Also, the
reusability of NO and SO2 in the 30 wt % [Bmim]2FeCl4/
sulfolane binary mixture is shown in Figure 10. It shows that
after six rounds of absorption, the average NO removal
efficiency declined from 93.6 to 75.6%. The removal efficiency
maintained 80% removal ability of the initial absorption after
six cycles. However, the average SO2 removal efficiency
decreased from 76.2 to 48.8%, which maintained 64.1% removal
ability of the initial absorption after six cycles. The
water was hard to remove totally under 80 °C, so SO3−2 was
hard to be desorbed totally, which would affect the desorption
of NO because SO2−3 could interact with NO to form
SO4(\text{NO})_2^{2-}. Therefore, 30 wt % [Bmim]2FeCl4/sulfolane
binary mixture was reusable during NO and SO2 absorption.

2.6. Comparison of Removal Efficiencies of 30 wt %
[Bmim]2FeCl4/Sulfolane with Other Materials. The
removal efficiencies of different absorbents in previous reports
are summarized in Table 1. The NO removal efficiency using
common ionic liquids is extremely low under ambient pressure.
FeIIEDTA/urea and hexamminemcobalt(II)/iodide solution
can absorb NO and SO2 efficiently. However, the absorption
process consumes a large number of absorbents. The water and
NH3 in solution would be lost during absorption, which limits
their application in NO and SO2 absorption. Compared with those
absorbent, 30 wt % [Bmim]2FeCl4/sulfolane shows high
NO and SO2 removal efficiency without the drawback of those
absorbent in the previous literature.

2.7. Removal Mechanism. The mechanism of simulta-
neous removal of NO and SO2 by 30 wt % [Bmim]2FeCl4/
A sulfolane binary mixture was investigated by Fourier transform infrared (FTIR) to analyze the change in the chemical structure among the fresh mixture, mixture after NO and SO2 absorption, and regenerated mixture. The result is shown in Figure 11, indicating the chemical interaction between absorbent and acid gases. The peak from 990 to 1090 cm$^{-1}$ was due to the vibration of SO$_3^{2-}$. Hence, a new peak at 1050 cm$^{-1}$ represented the appearance of SO$_3^{2-}$, which could be the reaction between SO$_2$ and water absorbed by the ionic liquid.

It should be noted that a new peak at 1798 cm$^{-1}$ was found after absorption and disappeared completely after desorption. The new peak at 1755 to 1805 cm$^{-1}$ was the result of the stretching vibration of ferrous nitrosyl complexes. Hence, the peak at 1798 cm$^{-1}$ was related to the $v$(N–O) in [Bmim]$_2$Fe(NO)Cl$_4$. The reaction might be

$$[\text{Bmim}]_2\text{FeCl}_4 + \text{NO} \rightarrow [\text{Bmim}]_2\text{Fe(NO)Cl}_4$$  

(2)

This reaction did not affect the structure of IL and sulfolane. In addition, the structure of the mixture before absorption and after desorption was almost the same, indicating that the mixture is reusable.

### 3. CONCLUSIONS

In this work, a mixed absorbent of [Bmim]$_2$FeCl$_4$/sulfolane was first used to simultaneously reduce NO and SO$_2$ in low concentrations. The best ratio between [Bmim]$_2$FeCl$_4$ and sulfolane is 3:7. The 30 wt % [Bmim]$_2$FeCl$_4$/sulfolane binary mixture showed superb NO and SO$_2$ absorption performance. The efficiency of NO and SO$_2$ removal was comparatively high at low temperatures. The average reduction efficiency could reach 93.6 and 76.2% for NO and SO$_2$ at 1100 and 2500 ppm concentrations, respectively, at 25 °C and ambient pressure after 2 h absorption. NO chemically interacted with [Bmim]$_2$FeCl$_4$ and partial SO$_2$ interacted with the limited water absorbed by IL. Owing to the interaction between SO$_3^{2-}$ and [Bmim]$_2$Fe(NO)Cl$_4$, the presence of SO$_2$ promoted NO absorption. In addition, the mixture also physically absorbed...
NO and SO2. Also, after six cycles, the mixture also showed good performance for NO reduction. Therefore, 30 wt % [Bmim]2FeCl4/sulfolane binary mixture could be an alternative absorbent for the simultaneous removal of low concentrations of NO and SO2 in real fuel gas.

4. EXPERIMENTAL SECTION

The characteristic of this solvent was analyzed by Raman and TGA. The [Bmim]2FeCl4/sulfolane binary mixtures showed high SO2 and NO removal efficiency under simulated flue gas. The best proportion of [Bmim]2FeCl4/sulfolane binary mixtures was selected. The effect of temperature and concentrations of SO2 and NO during the process was investigated. The reusability of absorbent was tested by cycling experiments. The NO and SO2 removal mechanism was analyzed through FTIR spectrum.

4.1. Materials.

In brief, 1.0 vol % NO/N2, 1.0 vol % SO2/N2, and N2 (99.9%) were purchased from Wuhan Huarwen Industrial Co., Ltd. 1-n-Butyl-3-methylimidazolium chloride ([Bmim]Cl, 99% in purity) was acquired from Qingdao Aolike New Material Technology Co., Ltd. Iron (II) chloride anhydrous (FeCl2, 99.5% in purity) and sulfolane (95%) were obtained from Wuhan Xinshenshi Chemical Technology Co., Ltd.

4.2. Preparation for Mixtures.

[Bmim]Cl was dissolved in alcohol and dropped into FeCl2, and the mole ratio of FeCl2 and [Bmim]Cl was 1:2. After stirring at 50°C for 24 h, the alcohol in the solution was removed through the rotary evaporator to obtain the final product, [Bmim]2FeCl4. Sulfolane was directly added into [Bmim]2FeCl4 in different mass ratios to prepare [Bmim]2FeCl4/sulfolane binary mixture in various proportions.

4.3. Experimental Setup.

SO2 and NO removal was conducted under ambient pressure. The apparatus consisted of a flue gas simulation system, reaction system, and gas analysis system, which was the same as the apparatus in our previous work.26 For mixed gas preparation, several different gases were poured into the gas mixer with different flow rates controlled by flow meters with an accuracy of ±1.5%. The concentrations of NO and SO2 in the simulated gases could be set at 500–1100 and 1000–3000 ppm, respectively, by adjusting the flow rates. The values were close to the concentrations in the real fuel gas. After adequate mixing, the mixed gas was injected in a

| Table 1. Comparison of NO and SO2 Absorption by 30 wt % [Bmim]2FeCl4/Sulfolane with Other Materials |
|---|---|---|---|---|
| absorbent | temperature (°C) | pressure (MPa) | gas time | NO (% reusability) |
| 2 g 30 wt % [Bmim]2FeCl4/sulfolane | 25 | 0.1 | 2500 ppm SO2/1100 ppm NO | 93.6 yes this work |
| 30 g [C4mim][Ac] | 80 | 0.1 | 5.5% O2/1060 ppm NO | 18.4 yes 26 |
| 300 mL 0.014 mol/L FeIIEDTA + 5 wt % urea | 25 | 0.2 | 7% O2/3000 ppm SO2/500 ppm NO | 80 min 86.2 no 28 |
| 200 mL 0.1 mol/L hexammimecobalt(II)/iodide/NH3 solution | 50 | 0.1 | 5.2% O2/480 ppm NO | 3 h 70 no 29 |
| 200 mL 0.1 mol/L Fe(II)-EDTA/NH3 solution | 50 | 0.1 | 5.2% O2/480 ppm NO | 80 min 63 no 29 |
| 200 mL 10% H2O2/NH3 solution | 50 | 0.1 | 5.2% O2/480 ppm NO | 60 min 61 no 29 |

Figure 11. FTIR spectra of (a) fresh 30 wt % [Bmim]2FeCl4/sulfolane binary mixture, (b) mixture after NO and SO2 absorption, and (c) mixture after desorption.
reactor with a 100 mm long tube with a 20 mm inner diameter containing 2 g of binary mixtures. The temperate of the reactor was control by a water bath. The flow rate of the mixed gas in the inlet was 50 mL/min. After absorption, the outlet gas was mixed with 950 mL/min N2 and then placed in a flue gas analyzer (Multilyzer STe M60, AFRISO) to obtain the concentrations of NO and SO2 in the outlet. The relative standard deviations of the analyzer were determined to be 1%.

For the absorbent’s performance evaluation, the NO and SO2 removal efficiencies were defined as eq 3

\[ \eta = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \]  

(3)

where \( \eta \) is the removal efficiency of NO or SO2. \( C_{in} \) is the inlet NO or SO2 concentration, \( C_{out} \) is the outlet concentration of NO or SO2 after absorption.

The average removal efficiency of NO or SO2, \( \bar{\eta} \), was defined as eq 4.

\[ \bar{\eta} = \frac{1}{T} \int_{0}^{T} \eta(t) \, dt \]  

(4)

4.4 Characterization. The viscosities of pure [Bmim]2FeCl4 and [Bmim]2FeCl4/sulfolane mixtures were tested by a viscometer (Brookfield DV-C). The accuracy of the viscometer is 1%. The decomposition temperature of the solvent was detected using the thermogravimetric analyzer (STA449F3 NETZSCH). The sample was located in a pure N2 atmosphere, and the temperature increased from 20 to 800 °C at 10 °C/min. The Raman spectra of [Bmim]2FeCl4 were detected by a Raman spectrometer (Thermo Scientific DXR2) with wavenumbers from 100 to 4500 cm\(^{-1}\). The FTIR spectrum of the initial mixture and the absorbed mixtures was measured on an FTIR spectrometer (VERTEX 70, Brucker).

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Notes
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