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An investigation on NO removal by wet scrubbing using NaClO$_2$ seawater solution

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Abstract

The experiments were conducted to investigate the NO removal by wet scrubbing using NaClO$_2$ seawater solution in a cyclic scrubbing mode. Results show that, when the concentration of NaClO$_2$ in scrubbing solution is higher than 10 mM, a complete removal of NO can be achieved during the cyclic scrubbing process. The breakthrough time for seawater with 15 mM NaClO$_2$ is enhanced by 34.3 % compared with that for NaClO$_2$ freshwater. The extension of the breakthrough time for NaClO$_2$ seawater is mainly ascribed to the improved utilization of NaClO$_2$ in the solution. The good buffering ability of seawater could suppress the acidic decomposition of NaClO$_2$ into ClO$_2$ effectively. The analysis of reaction products indicates that the main anions in the spent liquor are chloride ions and nitrate ions. The calculation of NaClO$_2$ utilization according to the ion chromatography also agrees well with the experimental results of breakthrough times.

Keywords: Nitric oxide, Scrubbing, Oxidation, Sodium chlorite, Seawater

Background

Air pollution is currently one of the major problems worldwide, resulting that more rigorous environmental laws are introduced. The main source of air pollution is the combustion process of fossil fuels used in power plants, vehicles, ships and other incineration processes (Skalska et al. 2010). Sulfur oxides (principally SO$_2$), nitrogen oxides (NO$_x$), particulate matter (PM) are the key combustion-generated air contaminants. Since NO$_x$ have been implicated in a variety of environmental effects such as acid rain, photochemical smog, tropospheric ozone layer depletion and even global warming, they are considered as the primary pollutants of the atmosphere (Wei et al. 2009a).

At present, the implementation of stringent regulations of NO$_x$ emission requires the development of new technologies and improvement of currently used methods for NO$_x$ removal from exhaust gas. Effective reduction of NO$_x$ emissions from both stationary and mobile sources poses a major challenge. Technologies for the NO$_x$ removal can be divided into combustion control and post-combustion treatment. Combustion control aims at reducing the formation of NO$_x$ during the combustion of fossil fuel (Adewuyi et al. 1999). Post-combustion control methods include a variety of techniques such as selective catalytic reduction (SCR) (Zhang et al. 2015; Jiang et al. 2015), selective non-catalytic reduction (SNCR) (Lee et al. 2008), thermal DeNOx and scrubbing. SCR can

remove NO_x with an efficiency of 80–95 % and it has been applied in power plants extensively. Up to date, SCR is also considered as one of the most promising techniques for ocean-going ships. But it requires additional space, high investment and operating cost. Another major concern of SCR is the deleterious effect of SO_2-laden flue gas on the life of catalyst which is an important factor of this technology's cost. SNCR approach requires high reaction temperature (900–1000 °C) with an elaborate temperature control to avoid ammonia slip and to achieve effective NO_x removal. Scrubbing method is one of the advanced air pollution control technologies. It has the ability of removing other acid gases and particulates simultaneously (Makansi 1990).

Nitric oxide (NO) is a major component of NO_x emitted from incineration processes and is of low solubility in aqueous solution, so it can not be removed easily from the flue gas by scrubbing. But a feasible method is to oxidize NO to other soluble NO_x species (NO_2, N_2O_3, N_2O_4, N_2O_5, etc.). For this purpose, various oxidants such as hydrogen peroxide (H_2O_2) (Liu and Zhang 2011), potassium permanganate ($KMnO_4$) (Chu et al. 2001a), peracids (Littlejohn and Chang 1990), ferrous-chelating agents (Wang et al. 2007; Yan et al. 2015), sodium hypochlorite (NaClO) (Chen et al. 2005) and sodium chlorite ($NaClO_2$) (Deshwal et al. 2008; Wei et al. 2009b) have been investigated to enhance the NO removal efficiency of the scrubbing solution. Among these oxidants, $NaClO_2$ has been found one of the most promising chemicals for NO oxidation. In the late 1970s, Sada et al. performed early studies on the absorption of NO_x in a $NaClO_2$ solution and proposed the overall reactions of NO and NO_2 with $NaClO_2$ in alkaline solutions (Sada et al. 1978, 1979). Brogren et al. studied the kinetics of the absorption of NO in an alkaline solution of $NaClO_2$ and found that the chlorite ion oxidized NO mainly to NO_2 or NO_2^- and NO_2 to NO_3^- (Brogren et al. 1998). Yang and co-workers conducted experiments with acid solution of $NaClO_2$ and determined the overall reaction of NO with $NaClO_2$ in acidic conditions (Yang and Shaw 1998). Apart from the considerable studies on kinetics of NO absorption with $NaClO_2$ (Hsu et al. 1998; Chu et al. 2001b), more and more research on simultaneously removal of NO_x and other pollutants (such as SO_2 and Hg) by scrubbing $NaClO_2$ solution has been conducted throughout the world (Jin et al. 2006; Huston et al. 2008; Zhao et al. 2010; Park et al. 2015). However, all of the work above-mentioned is focused on experimentations using $NaClO_2$ freshwater solution. Since seawater has some unique properties such as the natural alkalinity (pH 7.5–8.3) and good buffering ability, it has already been used to remove SO_2 from the flue gas of on-going ships and onshore power plants (Andreasen et al. 2007; Vidal et al. 2007; Lan et al. 2012). To the best of our knowledge, research on NO removal by using $NaClO_2$ seawater has not been reported yet. The purpose of this work is to use seawater to take place of fresh water as solvent and to study the effect of seawater on the NO removal of $NaClO_2$ solution. The experimental results showed that $NaClO_2$ seawater can remove NO from the simulated flue gas with a high efficiency. Besides, the breakthrough time for NO absorption with $NaClO_2$ seawater is obviously enhanced due to the buffering ability of seawater compared with that for $NaClO_2$ freshwater and the possible reaction mechanism has also been discussed.

Experimental

Materials

The reagents used in this investigation were: N_2 pure gas, NO span gas (10 %) with N_2 as the balance gas, $NaClO_2$, sodium chloride (NaCl), magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$), sodium sulfate (Na_2SO_4), anhydrous calcium chloride ($CaCl_2$), potassium chloride (KCl), sodium bicarbonate ($NaHCO_3$), sodium hydroxide (NaOH) and hydrochloric acid (HCl). All chemicals were analytical reagent (AR) degree without further purification. The deionized water was prepared in a two-stage ELGA PURELAB Option R15 purification system and had a resistivity of 15 MΩ·cm.

The substitute ocean water, which is prepared according to an American national standard (ASTM 2008), is used as seawater solvent in the experiments. For simplicity, minor elements, occurring naturally in concentration below 0.2 g/L, are not included. The process for preparing the substitute ocean water is as follows: firstly, stock solution No. 1 is prepared by dissolving 11.11 g $MgCl_2 \cdot 6H_2O$ and 1.16 g $CaCl_2$ in 50 mL deionized water. Secondly, stock solution No. 2 is prepared by dissolving 0.695 g KCl and 0.201 g $NaHCO_3$ in 50 mL deionized water. Thirdly, dissolve 24.53 g NaCl and 4.09 g Na_2SO_4 in 900 mL deionized water and then add stock solution No. 1 and No. 2 slowly with vigorous stirring. Finally, adjust the pH value of the synthetic seawater to 8.2 with 0.2 M NaOH solution.
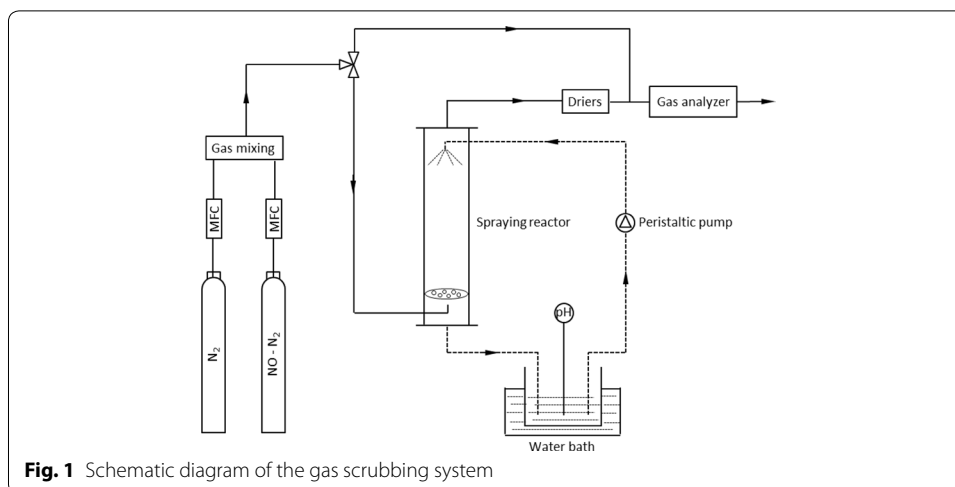
The scrubbing solution of various $NaClO_2$ concentrations (5, 10, 15 and 20 mM) is prepared by adding certain amount of $NaClO_2$ into deionized water and seawater, respectively. The initial pH values of $NaClO_2$ solution are listed in Table 1. In order to investigate the buffer capacity of $NaClO_2$ solution on the NO removal, 20 mM $NaClO_2$ seawater and freshwater solution are titrated with 0.2 M HCl, respectively.

Experimental setup

A schematic diagram of the experimental system is shown in Fig. 1. This system consists of a simulated flue gas supply unit, a countercurrent spraying reactor and a gas analyzing system. N_2 pure gas and NO span gas are provided from separate air bottles and metered through mass flow controllers (MFC). The synthetic flue gas is obtained from the feed gases by blending with an online mixer and then it is introduced into the countercurrent spraying column made of polymeric methyl methacrylate (PMMA). A spraying nozzle (B1/4TT-SS+TG-SS0.4, Spraying System Co.) is mounted at the top of the column. The size of liquid droplet sprayed from the nozzle is in the range of 80–100 μm. The height and inner diameter of the column are 25 and 5 cm, respectively. The simulated flue gas continuously flows through the column and the calculated residence time of flue gas in the column is about 19.6 s. After contacting with the flue gas in counter flow, the

Table 1 The initial pH values of the scrubbing solution of various $NaClO_2$ concentrations

$NaClO_2$ concentration (mM)	The pH value of freshwater solution	The pH value of seawater solution
0	7.09	8.20
5	9.62	8.11
10	9.88	8.41
15	10.1	8.42
20	10.5	8.61

**Fig. 1** Schematic diagram of the gas scrubbing system

scrubbing liquid is collected under the column in a beaker, from which the absorption liquid is pumped to the top of the column using a peristaltic pump. The total amount of the cyclic scrubbing solution is 0.2 L. The rotating speed of the peristaltic pump is set at 200 rpm, resulting in that the flow rate of the scrubbing solution is about 0.35 L/min. The scrubbing solution is kept at 20 °C by immersing the beaker in a water bath.

The scrubber gaseous effluent is analyzed with a Madur GA-21 gas analyzer which is a multi-functional flue gas analyzer. Electrochemical sensors are used for the measurement of gas concentration. NO and NO_2 are measured directly using the electrochemical cells while the NO_x concentration is calculated by the analyzer as a simple sum of measured NO and NO_2 concentration. In order to protect the flue gas analyzer, the simulated flue gas is dried by anhydrous $CaCl_2$ particles after being scrubbed. A pH meter is used to on-line monitoring the pH value and temperature of the scrubbing solution. After scrubbing, sample solution is withdrawn from the spent solution in the beaker for ion chromatographic analysis (Dionex ICS-1500).

Results and discussion

The experiments of cyclic scrubbing the flue gas continuously by using different solutions to remove NO had been conducted. Figure 2 shows the changes of NO concentrations in exit flue gas during the scrubbing process. From the results, we can see that when seawater without $NaClO_2$ addition is used to treat the flue gas, NO concentration in exit flue gas nearly does not change, which demonstrates that seawater itself does not react with NO. For both freshwater and seawater, when there is 20 mM $NaClO_2$ added in the solution, NO concentration decreases sharply to zero within several minutes at the beginning of the scrubbing process. It suggests that NO in flue gas has been completely removed. With the proceeding of the cyclic scrubbing process, the complete removal of NO can last for tens of minutes. Finally, NO concentration increases fast to the initial level (about 1000 ppm), which indicates that $NaClO_2$ in the solution has been depleted.
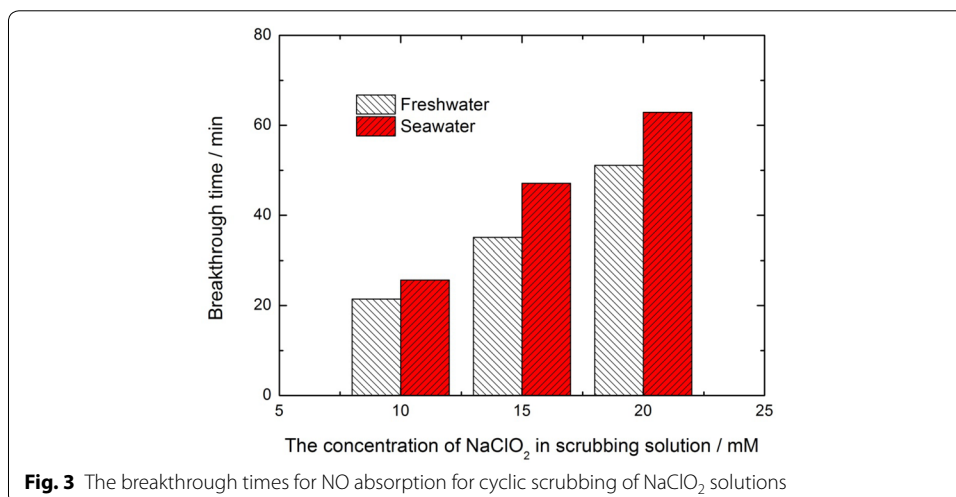
From Fig. 2, it can be seen that, with the same concentration of $NaClO_2$ in the solution, the breakthrough times, which refers to the duration of complete removal of NO from

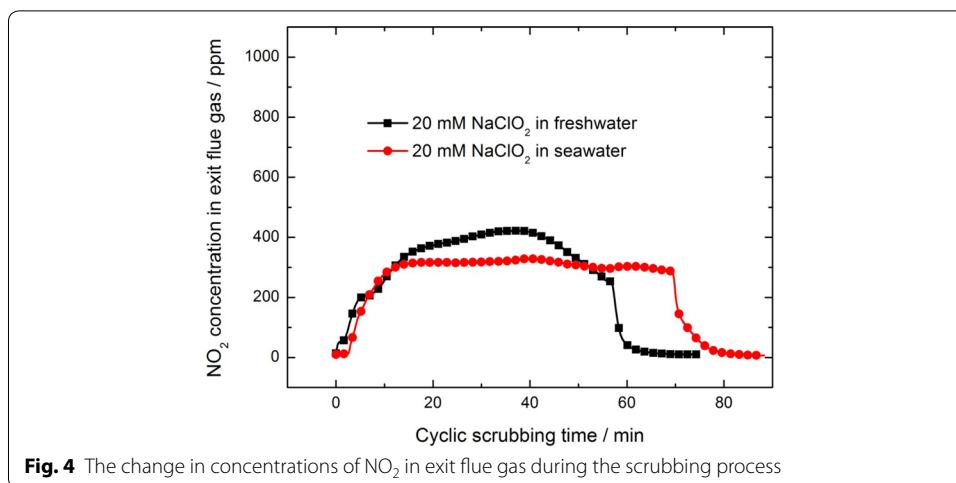**Fig. 2** NO absorption of 20 mM NaClO$_2$ scrubbing solution
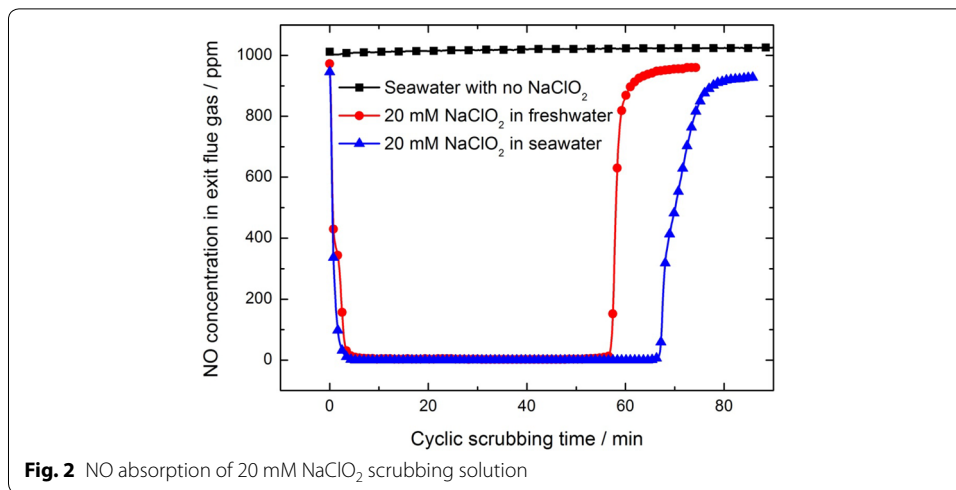
the flue gas, are obviously different from freshwater to seawater. The breakthrough times for NO absorption by scrubbing solution containing various concentrations (5–20 mM) of NaClO$_2$ are illustrated in Fig. 3.

When the concentration of NaClO$_2$ in the scrubbing solution is 5 mM, a complete removal of NO from the flue gas can not be achieved during the whole scrubbing process, so the breakthrough time is zero for 5 mM NaClO$_2$ solution. From Fig. 3, one can see that, the breakthrough times for NaClO$_2$ seawater solution have been enhanced obviously compared with those for freshwater solution of the same concentration of NaClO$_2$ oxidant. When the concentration of NaClO$_2$ is 15 mM, the breakthrough time for seawater can be improved by 34.3 % compared with that for freshwater. Since the breakthrough time for NO absorption during the cyclic scrubbing process represents the ability of NO absorption for the scrubbing solution, NaClO$_2$ seawater exhibits much higher NO absorption potential than NaClO$_2$ freshwater.

Figure 4 shows the change of NO$_2$ concentration in exit flue gas during the cyclic scrubbing process. As the simulated flue gas treated in our experiments is the mixture of

Fig. 3 The breakthrough times for NO absorption for cyclic scrubbing of NaClO$_2$ solutions

Fig. 4 The change in concentrations of NO_2 in exit flue gas during the scrubbing process

N_2 and NO, the initial concentration of NO_2 in exit flue gas is zero. With the start of the scrubbing process, the concentration of NO_2 in exit flue gas increases gradually due to the oxidation of NO into NO_2 by $NaClO_2$ (Brogren et al. 1998).

$$2NO + NaClO_2 \rightarrow 2NO_2 + NaCl \tag{1}$$

The equilibrium reaction between NO and NO_2 will occur simultaneously as in Eqs. (2) and (3).

$$NO + NO_2 \rightarrow N_2O_3 \tag{2}$$

$$2NO_2 \rightarrow N_2O_4 \tag{3}$$

It follows that some NO_x are absorbed via the hydrolysis of N_2O_3 and N_2O_4 as in Eqs. (4) and (5).

$$N_2O_3 + H_2O \rightarrow 2HNO_2 \tag{4}$$

$$N_2O_4 + H_2O \rightarrow HNO_2 + HNO_3 \tag{5}$$

Both N_2O_3 and N_2O_4 are very easy to react with H_2O, so most of them will be removed during the wet scrubbing process. To some extent, N_2O_3 and N_2O_4 can be considered as intermediate products. The NO_x in exit flue gas are mainly NO and/or NO_2. The reaction between NO and NO_2, as well as the hydrolysis of N_2O_3 and N_2O_4, will not affect the analysis result of NO_x absorption obviously.

Figure 4 also shows that, for 20 mM $NaClO_2$ seawater solution, the concentration of NO_2 in exit flue gas is more stable than that of freshwater solution, suggesting that seawater is better for balancing the NO absorption during the cyclic scrubbing process. Besides, for 20 mM $NaClO_2$ seawater solution, the total removal efficiency of NO_x (here it is the sum of NO and NO_2) can be approximately calculated as 70 % during the cyclic scrubbing process.

Compared with freshwater, artificial seawater used in our experiments contains 419.74 mM NaCl, 54.62 mM $MgCl_2$, 28.79 mM Na_2SO_4, 10.45 mM $CaCl_2$, 9.32 mM KCl

and 2.39 mM $NaHCO_3$. Apart from these six kinds of salts, there is a little NaOH used to adjust the mixture solution pH to 8.2. Here it can be seen that, although the components of seawater solution seem to be a little complex, it can be considered as a buffering solution, because it does not react with NO directly. In order to investigate the effect of the buffer capacity of seawater on NO absorption by $NaClO_2$ solution, the experiments of titrating 20 mM $NaClO_2$ solutions with 0.2 M HCl are performed. The changes in solution pH value with the addition of HCl are shown in Fig. 5.

It is known that water itself is a buffering medium, even in the absence of an added buffering reagent. Unlike water, seawater is of natural alkalinity, defined as the sum of the concentrations of the alkaline species contained in seawater. The value of alkalinity is not fixed, but changes according to the geographical area. In a general way, seawater alkalinity can be expressed as follows (Giuseppe et al. 2012):

$$A_T = \left[HCO_3^-\right] + 2\left[CO_3^{2-}\right] + \left[B(OH)_4^-\right] + \left[OH^-\right] + \left[HPO_4^{2-}\right]$$
$$+ 2\left[PO_4^{3-}\right] + \left[SiO(OH)_3^-\right] + \left[HS^-\right] - \left[H^+\right] - \left[HSO_4^-\right] - [HF] - [H_3PO_4]$$

(6)

where the first species HCO_3^- represents the dominating contribution to seawater alkalinity. It is related with the seawater buffer capacity directly.

As shown in Fig. 5, the initial pH value of $NaClO_2$ freshwater is about 10.5 and it drops sharply with the addition of HCl. An addition of 6.6×10^{-2} mmol HCl can make the pH value of 0.2 L $NaClO_2$ freshwater drop below 7. Whereas the initial pH value of $NaClO_2$ seawater is 8.6, which is just a little higher than that of seawater alone. With the addition of HCl, the pH value of $NaClO_2$ seawater drops slowly. It requires 1.14×10^{-1} mmol HCl to make the solution pH drop to 7. The result shows that, for $NaClO_2$ solution, seawater has a much better buffering ability in maintaining the solution pH than freshwater. It is well known that the buffering ability of seawater is mainly related with the bicarbonate salt which is only 0.48 mmol in 0.2 L seawater. Though the amount of HCl addition, that can make pH value of $NaClO_2$ seawater drop to below 7, seems to be much less compared with the molar quantities of bicarbonate salt and $NaClO_2$ (5 mmol) in the solution,

Fig. 5 The change of pH of $NaClO_2$ (20 mM) scrubbing solution with addition of HCl (0.2 M)
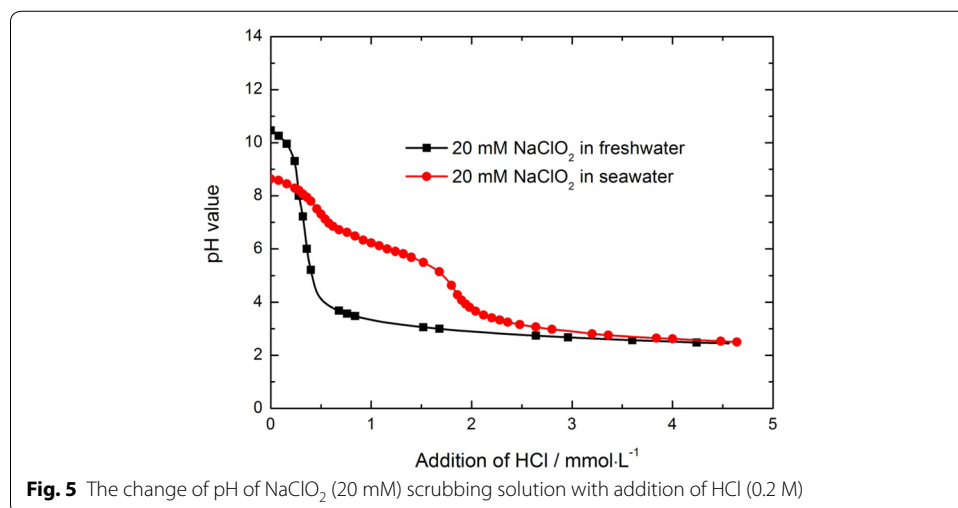
the buffering ability of seawater might be high enough to enhance the breakthrough time for $NaClO_2$ seawater during the cyclic scrubbing experiments.
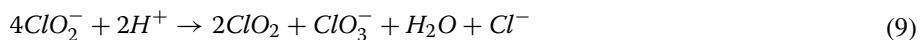
The changes of the solution pH during the cyclic scrubbing process are presented in Fig. 6. For 20 mM $NaClO_2$ freshwater solution, with the cyclic absorption of NO, the solution pH drops quickly to below 4, resulting that the majority of the NO removal process is in acidic condition. After scrubbing for several minutes, a greenish yellow color is observed in $NaClO_2$ freshwater solution, which is confirmed to be ClO_2. ClO_2 is formed by the acidic decomposition of $NaClO_2$ in Eq. (7) (Yang and Shaw 1998)

$$5NaClO_2 + 4HCl \rightarrow 4ClO_2 + 5NaCl + 2H_2O \tag{7}$$
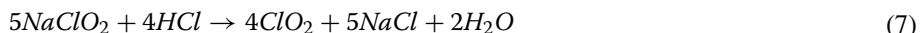
ClO_2 is found to be the active intermediate for NO oxidation. It does not react with water or ionize in solution, so it could remain as a dissolved gas or be stripped out from the liquid. ClO_2 escaped from the liquid contributes to the oxidation of NO to NO_2 in the gas phase

$$5NO + 3ClO_2 + 4H_2O \rightarrow 5HNO_3 + 3HCl \tag{8}$$

when the amount of ClO_2 is slightly in excess of that needed for the NO oxidation, NO will be absorbed completely during the breakthrough time. However, if the amount of ClO_2 is largely in excess of that needed for the oxidation of NO, the redundant ClO_2 will escape from the scrubber reactor without making contribution to the oxidation of NO. One can deduce from Figs. 2, 6 that, for 20 mM $NaClO_2$ freshwater solution, a certain amount of ClO_2 has possibly escaped into the atmosphere due to the low pH value during the majority process of NO absorption. In addition, it is reported that, in acidic medium (pH range of 3.5–4.0), a reaction will occur in Eq. (9) (Brogren et al. 1998).

$$4ClO_2^- + 2H^+ \rightarrow 2ClO_2 + ClO_3^- + H_2O + Cl^- \tag{9}$$

The formation of ClO_3^- consumes a small quantity of ClO_2^-, which makes no contribution to the oxidation of NO, too.

It can be seen from Fig. 6 that, for $NaClO_2$ seawater, the solution pH remains above 7 during the major part of the cyclic scrubbing process owning to the buffering ability of


Fig. 6 The change in solution pH value during the scrubbing process
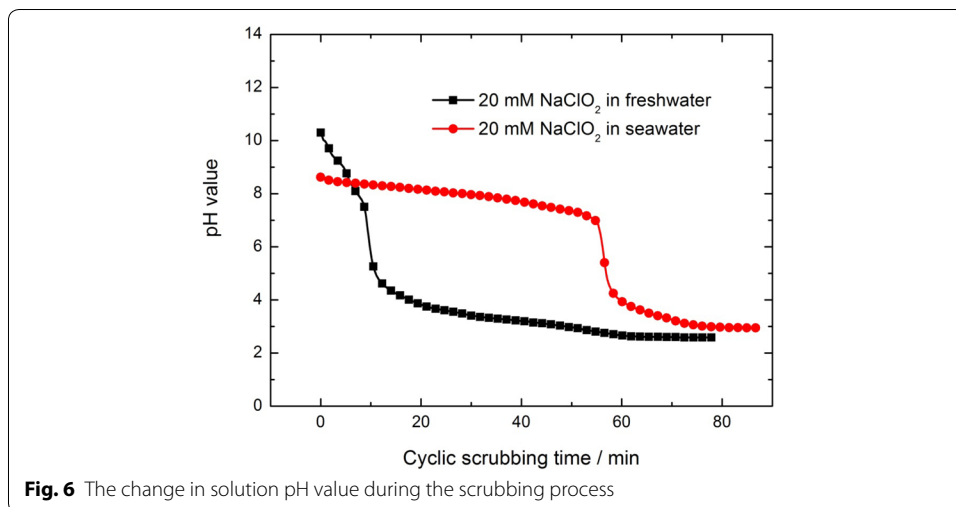
seawater. The neutral or slightly alkaline solution is beneficial to suppress the formation of ClO_2 effectively. In alkaline medium, NO is directly oxidized by ClO_2^- in Eq. (1) and NO_2 is absorbed in Eq. (10).

$$4NO_2 + ClO_2^- + 4OH^- \rightarrow 4NO_3^- + Cl^- + 2H_2O \tag{10}$$
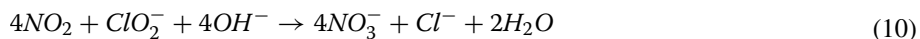
Thus, the reason for the extension of the breakthrough time for $NaClO_2$ seawater might be mainly ascribed to the improved utilization of $NaClO_2$. The acidic decomposition of $NaClO_2$ for $NaClO_2$ freshwater and further the escape of ClO_2 into atmosphere have lowered the utilization of $NaClO_2$ in freshwater scrubbing solution to some extent. The other factors (such as the transition metal ions, ion strength and solution pH etc.) may also influence the NO absorption by $NaClO_2$ seawater, which will be explored in the future in detail and the results will be reported in other forms.

To confirm the composition of reaction products, the anions in the spent liquor are determined using ion chromatography. Ion chromatographic analysis of spent scrubbing liquor and reagent blank is depicted in Fig. 7. Since the concentration of Cl^- in seawater is relatively too high, it results in that ion chromatography can not be used to analyze the spent liquor of $NaClO_2$ seawater scrubbing solution directly. Therefore, the spent liquor of $NaClO_2$ seawater scrubbing solution should be treated before doing ion chromatography analysis. Firstly, the spent liquor is diluted 100 times in order to reduce the consumption of Ag cartridge. Then, the diluted solution is filtered by Ag cartridge to remove excessive Cl^- ions from the seawater solution. Actually, the spent liquor of $NaClO_2$ freshwater scrubbing solution can be analyzed by ion chromatography directly. For comparison, the spent liquor of $NaClO_2$ freshwater is also treated by diluting 100 times, but it is not filtered by any Ag cartridge.

Figure 7 indicates that Cl^- and NO_3^- are the major anion products in the spent liquor. There is no ClO_2^- in the spent liquor because $NaClO_2$ in the solution has been consumed completely during the cyclic scrubbing process. For 20 mM $NaClO_2$ freshwater, there is certain amount of ClO_3^- in the spent solution, which may be formed by the acidic decomposition of ClO_2^- in Eq. (9).
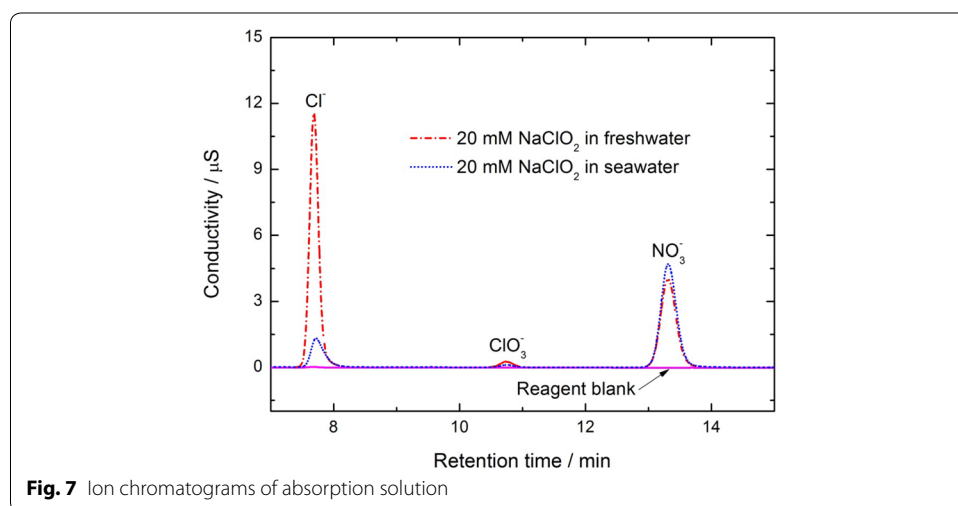

Fig. 7 Ion chromatograms of absorption solution

As shown in Fig. 7, the concentration of Cl^- in freshwater represents the actual value of Cl^- which exist in the spent liquor and comes from the $NaClO_2$ oxidant. While the concentration of Cl^- in seawater represents the value of Cl^- left in the sample solution after being filtered by Ag cartridge.

Note that the treatment of the spent liquor does not affect the concentrations of other ions, such as NO_3^- and ClO_3^-. As shown in Fig. 7, the concentration of NO_3^- in spent liquor of $NaClO_2$ seawater is a little higher than that in freshwater. It means that, with the same concentration of $NaClO_2$, the seawater solution has absorbed more NO during the cyclic scrubbing process than freshwater solution. It also demonstrates that, seawater is helpful to improve the utilization of $NaClO_2$ compared with freshwater.

According to the measurement results of ion chromatography, the $NaClO_2$ utilization for the scrubbing solution may be calculated approximately as follows. For 20 mM $NaClO_2$ seawater, NO_3^- ion concentration in the spent solution is about 2.72 mmol that can be calculated from the measurement result of ion chromatograms. As NO_3^- derives from the absorption of NO by $NaClO_2$ through the Eq. (11), so one can deduce that, the molar quantity of NO_3^- ions correspond to equal molar of NO, which has consumed 2.04 mmol $NaClO_2$ during this process.

$$4NO + 3NaClO_2 + 4NaOH \rightarrow 4NaNO_3 + 3NaCl + 2H_2O \tag{11}$$
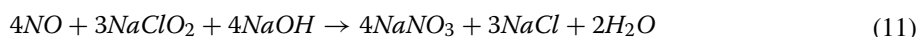
Because NO is absorbed completely during the breakthrough time, the amount of NO can be calculated approximately as the product of the flow rate of flue gas, NO concentration and the breakthrough time, which is about 4.02 mmol. From Eq. (1), we can see that, NO_2 in the exit flue gas derives from NO oxidation by $NaClO_2$, which can be calculated by substracting the molar quantity of 2.72 mmol from the molar quantity of 4.02 mmol. From Eq. (1), it can be seen that 1.3 mmol NO_2 has consumed 0.65 mmol $NaClO_2$. Therefore, the sum of $NaClO_2$ that has made contribution to the absorption of NO_x during the scrubbing process is 2.69 mmol. Since the addition of $NaClO_2$ in the initial seawater solution is 4 mmol, the utilization of $NaClO_2$ in seawater solution can be calculated as 67.25 %.

Similarly, for 20 mM $NaClO_2$ freshwater, NO_3^- ion concentration in the spent liquor is about 2.34 mmol, which has consumed 1.76 mmol $NaClO_2$ according to Eq. (12). NO that has been absorbed by $NaClO_2$ freshwater during the whole breakthrough time is about 3.29 mmol. NO_2 in the exit gas is 0.95 mmol, which has consumed 0.48 mmol $NaClO_2$ accordingly. Thus the sum of $NaClO_2$ that has made contribution to the absorption of NO_x during the whole scrubbing process is 2.24 mmol. Since the addition of $NaClO_2$ in the initial freshwater solution is also 4 mmol, the utilization of $NaClO_2$ in freshwater solution can be calculated as 56 %.

$$4NO + 3NaClO_2 + 2H_2O \rightarrow 4HNO_3 + 3NaCl \tag{12}$$
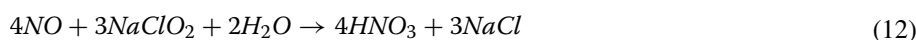
After in all, the utilization of $NaClO_2$ in seawater is enhanced by about 20.1 % compared with that of $NaClO_2$ in freshwater solution, which agrees well with the comparison result of the breakthrough times in Fig. 3.

Conclusion

In this work, the effect of seawater on NO removal of $NaClO_2$ solution has been investigated in a cyclic scrubbing mode. Compared with $NaClO_2$ freshwater solution, $NaClO_2$ seawater solution exhibits much longer breakthrough time for NO absorption. The result of blank experiment and acidic titration demonstrates that the extension of breakthrough time for $NaClO_2$ seawater might be ascribed to the buffering ability of seawater, which could suppress the acidic decomposition of $NaClO_2$ into ClO_2. The reduction of ClO_2 escape may be the main reason for the enhancement of NO removal for $NaClO_2$ seawater during the cyclic scrubbing process. The analysis of liquid reaction products indicated that $NaClO_2$ has been consumed completely during the cyclic scrubbing process and turned into Cl^- in the spent liquor. The calculation result from the ion chromatography demonstrates the enhancement of $NaClO_2$ utilization in seawater, which agrees well with the breakthrough times for NO removal. This work suggests that $NaClO_2$ seawater solution is a promising choice for NOx removal, especially for the applications in onshore power plants and ocean-going ships.

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