Chemical Engineering Journal 162 (2010) 696–701

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

NO reduction and N_2 selectivity under various operating conditions for photo-SCR of NO

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ARTICLE INFO

Article history:
Received 9 February 2010
Received in revised form 14 June 2010
Accepted 23 June 2010

Keywords:
Photo-SCR
Photocatalysis
NO reduction
Titanium dioxide
Eley–Rideal mechanism

ABSTRACT

Photoassisted selective catalytic reduction (photo-SCR) of NO with ammonia under various operating conditions was investigated with a TiO_2-coated annular photoreactor at room temperature. Effects of UV irradiance, inlet concentrations of O_2, NO, NH_3 and H_2O, and retention time of inlet stream on the NO reduction efficiency and N_2 selectivity were discussed in this study. The experimental results indicated that more than 70% of NO molecules could be reduced by photo-SCR with the retention time more than 4 min. N_2 selectivity was found to be decreased due to the generation of NO_2 and N_2O molecules in the photo-SCR with specific operating conditions. Both NO reduction efficiency and N_2 selectivity were decreased for NO reduction by the photo-SCR with the presence of water molecules because of the competitive adsorption of water and NH_3 molecules on the active sites of TiO_2. The reaction behavior of the NO reduction by the photo-SCR was adequately described by Eley–Rideal kinetics.

1. Introduction

Nitrogen oxides (NO_x) such as nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O) exhausted from stationary emission source are considered as air contaminants due to the causative effects of town smog and acid rain. Selectively catalytic reduction (SCR) with ammonia has been widely applied to convert NO_x emission into nitrogen and water at the operating temperature higher than 300 °C [1,2]. Numerous researchers focused their study on developing new techniques for operating SCR at lower temperature in order to conserve energy. Metal oxides deposited on supporting materials have been considered as advanced catalysts capable to be activated at low temperature. Huang et al. [3] prepared carbon nanotube supported vanadium oxide (V_2O_5/CNT) by an incipient wetness method and indicated that V_2O_5/CNT showed good reaction activity in NO reduction by the SCR with a temperature range of 100–250 °C.

Photoassisted selective catalytic reduction (photo-SCR) of NO with ammonia using semiconductor catalyst under appropriate illumination was regarded as another potential alternative for NO reduction at lower temperature [4]. Tanaka et al. [5] reported that NO reduction by the photo-SCR with ammonia over TiO_2 in the presence of oxygen could be operated at 50 °C. Photoirradiation of UV light caused remarkable enhancement of NO reduction to form N_2. The authors also indicated that NO molecules were weakly adsorbed on the active sites of TiO_2 as compared to NH_3 molecules. The formation of N_2 in the photo-SCR was consisted of one N atom derived from NH_3 and another N atom derived from NO.

Teramura et al. [6] applied FT-IR to measure the adsorbed species and intermediates derived from NO, NH_3 and O_2 on the surface of TiO_2 for investigating the reaction mechanism of NO reduction by the photo-SCR. NH_3 was found to be firstly adsorbed on the active sites of TiO_2 (Ti^{4+}) and reacted with the light-induced holes to form NH_2 radicals. The formed NH_2 radicals reacted with NO in gas phase to form nitrosamide (NH_2NO). The formation of N_2 and H_2O was observed by the decomposition of NH_2NO intermediate. Finally, the reduced active sites of TiO_2 (Ti^{3+}) were re-oxidized to the original state (Ti^{4+}) by O_2. Teramura et al. [7] proposed the kinetic model of NO reduction in the photo-SCR according to Eley–Rideal mechanism and indicated that the rate-determining step was the decomposition of NH_2NO for cases containing excessive O_2 and the re-oxidation of Ti^{3+} for cases with insufficient O_2. Yamazoe et al. [8] studied the effect of TiO_2 characteristics on the performance of NO reduction by the photo-SCR. The experimental results revealed that the reaction activity of photo-SCR was correlated to the amount of Lewis acid sites on the surface of TiO_2, but was independent of specific surface area and crystal diameter of TiO_2.

Since the NO reduction by the photo-SCR is significantly affected by the operating conditions, the most important course in this process is how to enhance the NO reduction efficiency and the N_2 selectivity. In this study, gaseous NO was reduced by photo-SCR

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doi:10.1016/j.cej.2010.06.028

Nomenclature

C_{H_2O}	the concentration of water [ppmv]
C_{N_2}	the concentration of nitrogen [ppmv]
$C_{NO,0}$	the inlet concentration of nitric oxide [ppmv]
C_{NO}	the concentration of nitric oxide [ppmv]
C_{NO_2}	the concentration of nitric dioxide [ppmv]
C_{N_2O}	the concentration of nitrous oxide [ppmv]
$C_{NH_3,0}$	the inlet concentration of ammonia [ppmv]
C_{NH_0}	the concentration of ammonia [ppmv]
C_{O_2}	the inlet concentration of oxygen [vol.%]
E	the reduction efficiency of NO (defined as the ratio of reduced NO concentration to the original concentration of NO) [%]
I	the irradiance of light source [mW/cm^2]
k_a	the apparent reaction rate constant of NO reduction [(mW/cm^2)$^{-n}$/ppmv/min]
K	the adsorption constant of ammonia [1/ppmv]
K_s	the surface reaction equilibrium constant [1/ppmv]
K^*	the adsorption constant of water [1/ppmv]
n	the reaction order against UV irradiance
RH	the relative humidity of system [%]
r_{NO}	the photocatalytic reduction rate of NO in the photo-SCR [ppmv/min]
S	the N_2 selectivity (defined as the ratio of N_2 concentration to the sum concentration of N_2, NO_2, and N_2O at the outlet stream of photoreactor) [%]
U	the energy per mole photons at the wavelength of 365 nm [$U_{365} = 3.28 \times 10^5$ J/mol]
V	the effective volume of photoreactor [cm^3]
Greek letters	
τ	the retention time of inlet stream [min]
ϕ_{NO}	the apparent quantum yields of NO reduction
ω	the wavelength of light source [nm]

with NH_3 at room temperature in a TiO_2-coated annular photoreactor. NO reduction efficiency and N_2 selectivity were determined from gases composition at the outlet stream of photoreactor. Effects of operating conditions, such as UV irradiance, inlet concentrations of O_2, NO, NH_3 and H_2O, and retention time of inlet stream, on the reduction behavior of NO by photo-SCR were investigated. A simplified kinetic model was established to express NO reduction by the photo-SCR with ammonia over TiO_2 at room temperature based on Eley–Rideal mechanism.

2. Materials and methods

Titanium dioxide powder (P-25), a mixture of anatase and rutile, purchased from *Degussa* was used as the photocatalyst in this study. The suspension containing TiO_2 weight percentage of 10% was prepared by adding 50 g TiO_2 into 450 g of ethanol solution. The mixed solution was stirred with a mechanical stirrer for 2 h, and was then put in a sonicator for well mixing for more than 8 h. A quartz tube was dipped in the TiO_2 suspension for 1 min before it was taken out and then dried at the room temperature. This coating procedure was repeated several times to increase the amount of TiO_2 coated on the surface of quartz tube. The TiO_2-coated quartz tube was then put in the muffle furnace at 350 °C for 1 h.

The schematic diagram of the photo-SCR system used in this study is shown in Fig. 1. The photocatalytic reaction was carried out in an annular reactor composed of the Pyrex glass tube and a quartz tube coated with TiO_2 film for housing a *Sparkie* FL10W/BLB mercury lamp with wavelength of 365 nm and approximately 10 W maximum output. The irradiance of the UV lamp was controlled by adjusting the variable voltage transformer, and the irradiance on the surface of quartz tube was detected by a Radiometer/Photometer (*International Light Technologies* ILT 1400) equipped with the SEL005 radiation sensor. The composition of reaction gas in the inlet stream was mixed with NO, NH_3, O_2, and the balance gas, He. The humidity of the inlet stream was regulated by mixing the reactants-containing inlet stream with wet He of different flow rates. The temperature of inlet stream in the photoreactor was maintained at 25 °C. The pre-warmed light source in the reactor was turned on after the temperature, flow rate, pressure, and humidity of the mixed gas were considered to be steady. The gaseous concentrations of NO, and NO_2 were measured by the CLD62 NO/NO_x analyzer (*Eco Physics* CLD62). The gaseous N_2 and N_2O concentrations of inlet and outlet streams were determined by a gas chromatograph (*Agilent* 7895A) equipped with a HP-PLOT 5A and a thermal conductivity detector.

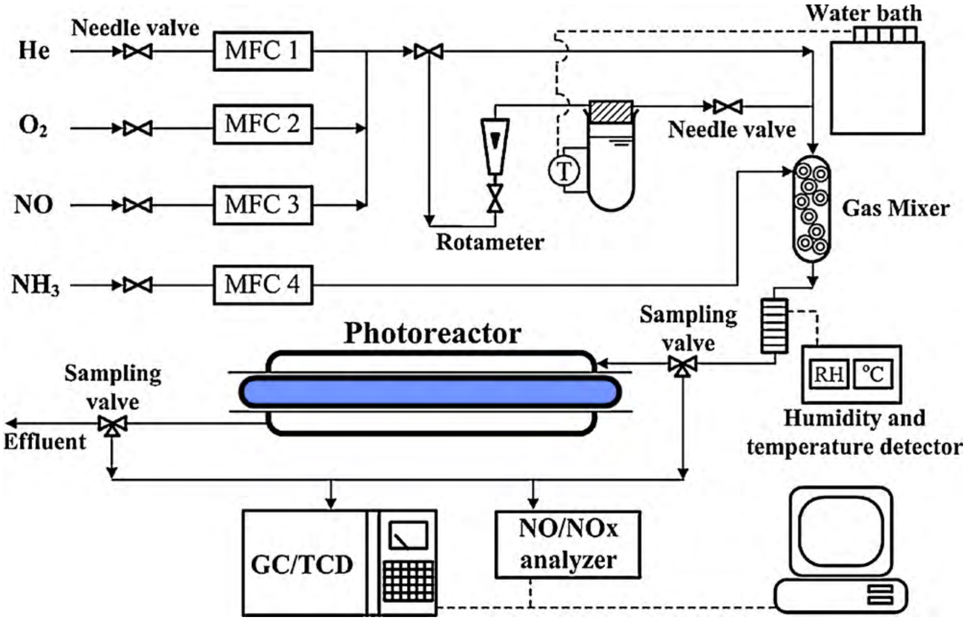

Fig. 1. Schematic diagram of the photo-SCR system.

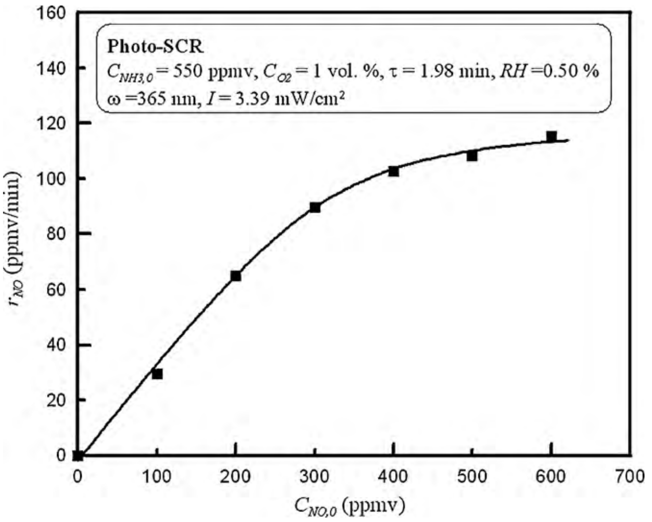

Fig. 2. Photocatalytic reduction rates of NO in the photo-SCR for experiments conducted with various inlet NO concentrations.

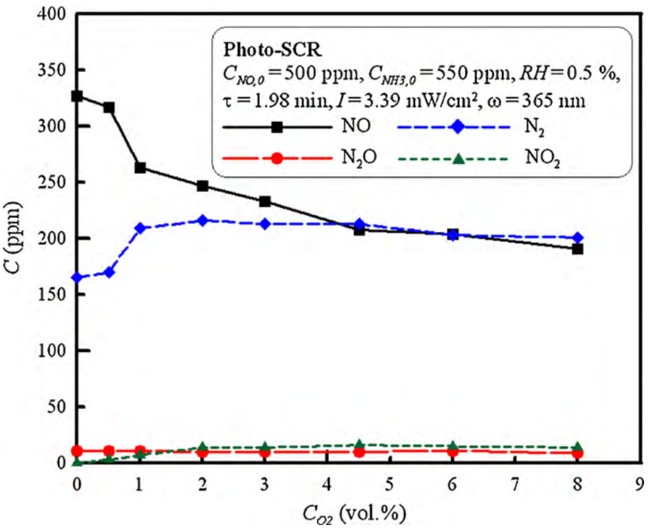

Fig. 3. Effect of inlet oxygen concentration on the gaseous composition of the outlet stream from the photoreactor.

3. Results and discussion

According to the proposed mechanisms reported by previous researchers [6], the reduction of NO in the photo-SCR is the reaction between the adsorbed ammonia molecules and NO molecules in gas phase. The photocatalytic reaction rate of NO reduction by the photo-SCR with various inlet concentrations of NO in the range of 100–600 ppmv is illustrated in Fig. 2. The reduction rate of NO was significantly increased with the increase of the inlet NO concentration for experiments conducted at NO concentrations lower than 500 ppmv; therefore, the reduction of NO was limited by the NO molar flux from bulk stream onto the ammonia molecules adsorbed on the active sites of TiO_2. However, reduction rate of NO tended to be less influenced by the inlet concentration of NO for experiments conducted at NO concentration higher than 500 ppmv. This phenomenon indicated that the NO molecules transfer onto TiO_2 surface was excessive for the adsorbed ammonia molecules and was no longer the limiting factor for the reduction of NO by photo-SCR. In order to minimize the mass transfer effect of NO, the inlet stream containing 500 ppmv NO was chosen to investigate the NO reduction by the photo-SCR for further investigation.

Fig. 3 illustrates the gaseous compositions of the outlet stream from UV-illuminated photoreactor carrying out photo-SCR with NH_3 under various inlet oxygen concentrations. Most of the reduced NO was converted to N_2; NO_2 and N_2O were generated only in trace amounts. N_2O molecules were generated when the reduced active sites (Ti^{3+}) reacted with NO molecules. No NO_2 molecules were found to be generated for NO reduction by the photo-SCR in the absence of oxygen molecules; however, NO_2 concentration was increased with increasing oxygen concentration due to the photocatalytic oxidation of NO molecules. The generation of NO_2 was found to be kept relatively constant for experiments conducted with the presence of oxygen higher than 2 vol.%. Fig. 4 shows the effect of inlet concentration of O_2 on the NO reduction efficiency and N_2 selectivity in the photo-SCR with NH_3 over TiO_2. N_2 selectivity is defined as the ratio of N_2 concentration to the sum of N_2, NO_2, and N_2O concentrations in the outlet stream. N_2 selectivity for experiments conducted with various inlet O_2 concentrations was found to be higher than 90%. The N_2 selectivity was slight decreased with the introduction of less than 2 vol.% O_2 because of the generation of NO_2 in the presence of oxygen. Reduction efficiency of NO was increased with increasing inlet concentration of O_2 from 0 to 1 vol.%, and then approached to a constant value for inlet O_2 concentration higher than 1 vol.%. As the reaction mechanism of NO reduction in the photo-SCR proposed by Teramura et al. [6], O_2 was assumed to play important role for the re-generation of the reduced active sites of TiO_2 (Ti^{3+}) during NO reduction by the photo-SCR. The re-generation reaction of Ti^{3+} with oxygen molecules was found to be rate-determining step for cases with insufficient O_2. In this study, 1 vol.% oxygen was introduced into the reaction system to sufficiently regenerate active sites of TiO_2 for the following study.

Table 1 illustrates the composition of the outlet stream, the NO reduction efficiency, the N_2 selectivity, and the apparent quantum yields (ϕ_{NO}) for NO reduction by the photo-SCR with NH_3 under various irradiances. The concentration of NO in the outlet stream was decreased from 290 to 225 ppmv with increasing irradiance from 2.37 to 3.73 mW/cm^2, while the concentration of N_2 was increased from 166 to 230 ppmv. The formations of N_2, NO_2 and N_2O were found to be increased with the increase of irradiance. Experimental results shown in Table 1 also revealed that the reduction efficiency of NO was increased with the increase of UV irradiance, and almost 50% of NO reduction efficiency was achieved at the UV irradiance of 3.73 mW/cm^2. The increased NO reduction efficiency was because

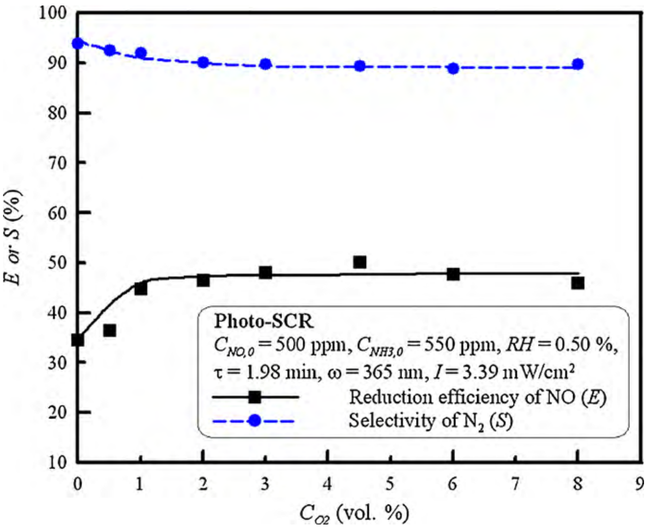

Fig. 4. Effect of inlet O_2 concentration on NO reduction efficiency and N_2 selectivity in the photo-SCR.

Table 1
Effects of irradiance on the performance of NO reduction by the photo-SCR.

I [mW/cm^2]	C_{NO} [ppmv]	C_{NO_2} [ppmv]	C_{N_2} [ppmv]	C_{N_2O} [ppmv]	E [%]	S [%]	$\phi_{NO} \times 10^2$
2.37	290	3	166	15	35	90	3.11
2.71	269	4	192	20	40	89	3.03
3.05	250	4	209	22	44	89	3.01
3.39	233	6	224	23	48	89	2.91
3.73	225	7	230	25	50	88	2.79

$C_{NO,0}$ = 500 ppmv, $C_{NH_3,0}$ = 550 ppmv, C_{O_2} = 1 vol.%, τ = 1.98 min, RH = 0.50%.

that more electrons-hole pairs were generated with the increase of UV irradiance. N_2 selectivity for experiments conducted at the irradiance of 2.37 mW/cm^2 was about 90%. The N_2 selectivity was found to be slightly decreased by increasing UV irradiance. This result is ascribed to the increased concentrations of NO_2 and N_2O at higher irradiance.

In this study, the apparent quantum yields were calculated with incident photons of UV light, assuming all incident photons encountered the photocatalyst as absorbed photons and neglecting the occurrence of reflection, scattering, transmission and absorption of photons [14]. The apparent quantum yields for NO reduction (ϕ_{NO}) were defined as the ratio of the reaction rate to the photons absorption rate, that is,

$$\phi_{NO} = \frac{\text{moles of NO reduction}}{\text{moles of photons absorbed}} \cong \frac{\Delta C_{NO} \cdot V}{I_{abs}/U \cdot \tau} \qquad (1)$$

where the U is the energy per mole photons at the wavelength of 365 nm ($U = 3.28 \times 10^5$ J/mol); V and τ are the effective volume (cm^3) and the retention time (min) of photoreactor. As the experimental results shown in Table 1, the apparent quantum yields for NO reduction were found to be decreased with the increase of UV irradiance possibly ascribed to the limited surface area of TiO_2 to absorb excessive light energy.

The composition of out stream, the NO reduction efficiency, the N_2 selectivity, and the apparent quantum yields (ϕ_{NO}) for NO reduction by the photo-SCR with various inlet ammonia concentrations are shown in Table 2. Generation of NO_2 was found to be less influenced by the inlet concentration of NH_3 because NO_2 was generated mainly by the photocatalytic oxidation of NO. N_2O concentrations were increased with increasing inlet NH_3 concentration because more reduced active sites (Ti^{3+}) were generated at higher NH_3 concentration. Experimental results shown in Table 2 also indicated that both the NO reduction efficiency and the apparent quantum yields for NO reduction were increased with the increase of NH_3 concentration because more NH_2 radicals generated photocatalytically from adsorbed NH_3 molecules. Approximately 90% of N_2 selectivity was also observed in the photo-SCR with various inlet NH_3 concentrations.

The influence of water content of inlet stream on the NO reduction by the photo-SCR is presented in Table 3. The relative humidity of inlet stream, used in this experiment, was in the range of 0.5–50%. The NO reduction efficiency and the apparent quantum yields for NO reduction decreased rapidly with the relative humidity, while only 6% of NO molecules were photocatalytically reduced by photo-SCR with the relative humidity of 50%. The selectivity of N_2 was also found to be decreased from 89% to 54% with increasing relative humidity from 0.5% to 50%. The decreased NO reduction efficiency with increasing water content is contributed to the competitive adsorption of water and NH_3 molecules for the active sites on TiO_2 by previous researchers [9].

As the composition data of the outlet stream shown in Table 3, the concentration of NO_2 was found to be increased with increasing relative humidity of inlet stream because water molecules might improve the photocatalytic oxidation of NO molecules. From the experimental results, it is concluded that water molecules play a vital role in the reduction reaction of NO by photo-SCR. The increase of water content in the inlet stream promoted the photocatalytic oxidation of NO to generate NO_2 molecules, while the generation of N_2O molecules was restricted due to the favorable adsorption of water molecules for the reduced active sites (Ti^{3+}). In addition, water molecules may compete with NH_3 molecules on the active site (Ti^{4+}) of TiO_2. The competitive adsorption of water and NH_3 molecules on the active sites of TiO_2 caused the decrease of NO reduction efficiency.

According to previous studies [10,11], the dependence of photocatalytic NO reduction rate on irradiance could be expressed by a power function. Taking the natural logarithm of both sides of the power function, the reaction order against UV irradiance, n, for photo-SCR reaction can be obtained from the plotted curve using $\ln(r_{NO})$ versus $\ln(I)$. The kinetic regression results are shown in Fig. 5, that is,

$$\ln(r_{NO}) = 0.78\ \ln(I) + 3.71 \qquad (2)$$

The reaction order of UV irradiance against the reduction rate of NO by photo-SCR was found to be 0.78. The reaction order against UV irradiance lower than unity for photo-SCR is possibly because that the promotion of electron-hole pairs recombination can be found for experiments conducted at excessive UV irradiance [12], therefore decreasing the dependence of NO conversion on the irradiance. Several previous studies indicated that the reaction order with respect to the UV irradiance was ranging between 0.5 and 1.0 for most photocatalytic reactions [11,12].

Based on the proposed mechanisms reported by previous researchers as presented in the Introduction Section, the reduction mechanism of NO in the photo-SCR was assumed to be described by Eley–Rideal model, and the rate-determining step was determined as the decomposition of NH_2NO. NH_3 molecules are assumed to be adsorbed on the active sites, and then react with NO molecules to carry further reaction. Experimental results implied that water

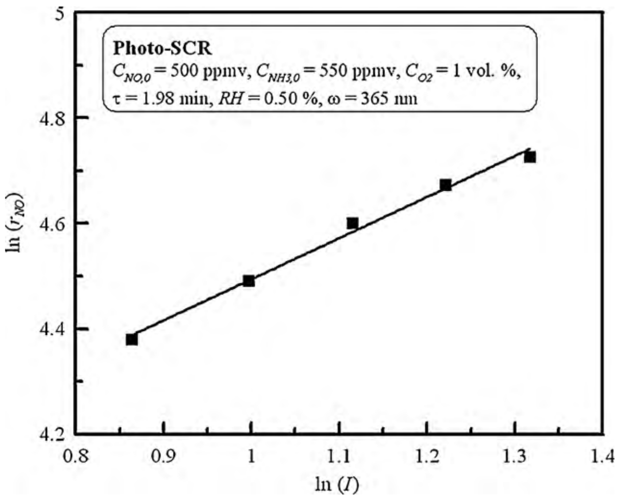

Fig. 5. Kinetic regressions for the photoassisted selective catalytic reduction of NO under various irradiances.

Table 2
Effects of initial ammonia concentration on the performance of NO reduction by the photo-SCR.

$C_{NH_3,0}$ [ppmv]	C_{NO} [ppmv]	C_{NO_2} [ppmv]	C_{N_2} [ppmv]	C_{N_2O} [ppmv]	E [%]	S [%]	$\phi_{NO} \times 10^2$
100	331	7	128	12	27	87	1.69
200	280	8	175	14	38	89	2.32
300	263	9	189	16	41	88	2.54
400	251	9	199	18	44	88	2.68
500	240	8	206	19	46	89	2.79
550	231	6	224	23	48	89	2.89
600	232	8	213	21	47	88	2.86

$C_{NO,0}$ = 500 ppmv, C_{O_2} = 1 vol.%, I = 3.39 mW/cm^2, τ = 1.98 min, RH = 0.50%.

Table 3
Effects of inlet relative humidity on the performance of NO reduction by the photo-SCR.

Relative humidity [%]	C_{NO} [ppmv]	C_{NO_2} [ppmv]	C_{N_2} [ppmv]	C_{N_2O} [ppmv]	E [%]	S [%]	$\phi_{NO} \times 10^2$
0.5	238	6	224	23	48	89	2.97
1	258	10	216	20	43	88	2.70
5	309	13	146	18	32	82	2.01
10	339	13	116	17	25	79	1.59
15	361	14	94	16	20	76	1.27
20	380	14	82	16	17	73	1.03
25	406	16	64	14	11	68	0.70
30	417	18	61	13	8	66	0.51
40	427	18	43	12	7	59	0.39
50	426	21	40	13	6	54	0.40

$C_{NO,0}$ = 500 ppmv, $C_{NH_3,0}$ = 550 ppmv, C_{O_2} = 1 vol.%, I = 3.39 mW/cm^2, τ = 1.98 min.

molecules may compete with NH_3 molecules for same active sites to inhibit the reduction efficiency of NO. Illuminated UV light was emitted from a hypothetical line source located at the center of the reactor in this study. The reflection or refraction of light at all interfaces was assumed to be negligible [13,14]. Combining the effect of UV irradiance, the reduction rate of NO in the photo-SCR with ammonia in the presence of oxygen over TiO_2 can be expressed as follow:

$$r_{NO} = k_a I^{0.78} \frac{C_{NO} C_{NH_3}}{1 + K C_{NH_3} + K K_s C_{NO} C_{NH_3} + K^* C_{H_2O}} \tag{3}$$

where r_{NO} is the reduction rate of NO in the photo-SCR (ppmv/min); C_{NO}, C_{NH_3}, and C_{H_2O} are the concentrations (in ppmv) of NO, NH_3 and water molecule, respectively; and I is the irradiance of UV lamp (mW/cm^2). In addition, k_a, K_s, K and K^* are the apparent reaction rate constant, the surface reaction equilibrium constant and the adsorption constants of ammonia and water molecule, respectively.

The rate law parameters, k_a, K_s, K and K^*, are determined and listed in Table 4 by regressing experimental data for reduction of NO by photo-SCR conducted with the irradiance of 3.39 mW/cm^2 under various concentrations of NO, NH_3 and H_2O. By inserting these coefficients into Eq. (3), the reduction rate of NO in the photo-SCR under various operating conditions can be correlated by the Eley–Rideal type kinetic model.

As the results shown in Figs. 6 and 7, fairly good agreements were found between the experimental results and the calculated values for the reduction rate of NO in the photo-SCR conducted under various NH_3 concentrations and relative humidities. These facts infer that the kinetic equation proposed in this study is applicable for NO reduction by the photo-SCR in the presence of oxygen. As the results shown in Fig. 6, reduction rate of NO increased rapidly with NH_3 concentration because more ammonia molecules were adsorbed on active sites of TiO_2. Almost no enhancement of NO reduction rate was observed for experiments conducted with NH_3 concentration higher than 400 ppmv because of the limited active sites on the surface of TiO_2. Teramura et al. [7] investigated the kinetic study of the photo-SCR and depicted that the NH_3 concentration ranged from 500 to 1250 ppmv was independent of the NO conversion in the photo-SCR. Fig. 7 reveals that the NO reduction rate was found to be decreased with increasing relative humidity due to the competitive adsorption of water and NH_3 molecules on the active sites of TiO_2.

The calculated results of NO reduction by the photo-SCR operated at various retention times agreed fairly well with the available experimental data as depicted in Fig. 8. Reduction efficiency of NO was elevated with the increase of retention time. Greater than 70% of NO reduction efficiency can be achieved for experiments conducted at room temperature at retention time more than 4 min. For current applications, SCR using V_2O_5/TiO_2 catalyst could attain NO reduction efficiency of 70–90% at operating temperatures higher than 300 °C at retention time less than 1 s [15]. Even though the application of photo-SCR can be processed at room temperature, the retention times required are much longer than those for SCR to achieve satisfactory NO reduction efficiency. Therefore, the modification of photocatalyst to effectively utilize the incident photons under practical operational conditions is vital for applications of photo-SCR in the real processes.

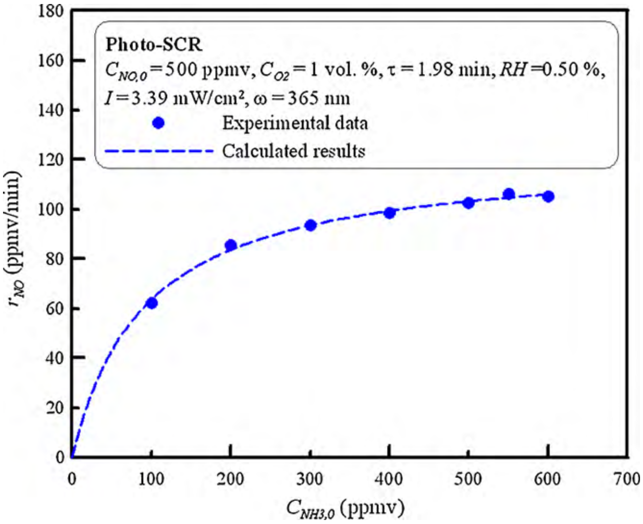

Fig. 6. Calculated and experimental results of NO reduction rate for NO reduction by photo-SCR with various inlet ammonia concentrations.

Table 4
Reaction coefficients in Eq. (3) for the photo-SCR of NO.

n	k_a [(mW/cm^2)$^{-0.78}$ ppmv^{-1} min^{-1}]	K [ppmv^{-1}]	K_s [ppmv^{-1}]	K^* [ppmv^{-1}]
0.78	1.8×10^{-3}	6.2×10^{-3}	4.2×10^{-3}	5.2×10^{-3}

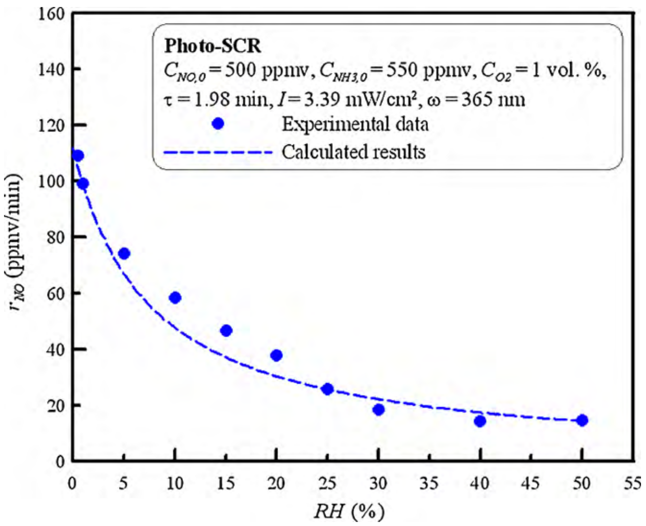

Fig. 7. Calculated and experimental results of NO reduction rate for NO reduction by photo-SCR with various inlet relative humidities.

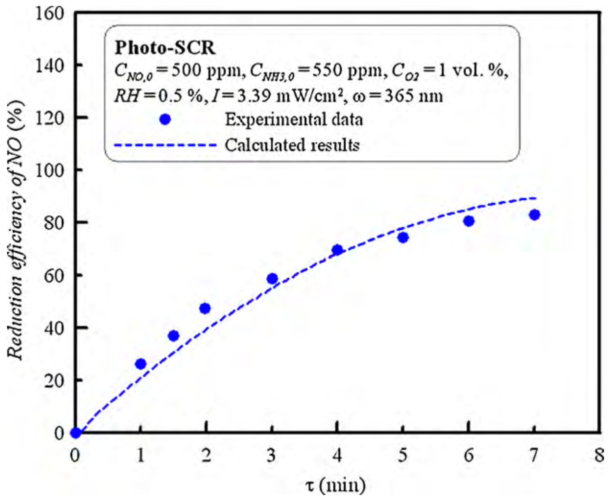

Fig. 8. Calculated and experimental results of NO reduction by photo-SCR at various retention times.

4. Conclusions

The performance of NO reduction by the photo-SCR under various irradiances, inlet concentrations of O_2, NO, NH_3 and H_2O, and retention time of inlet stream at room temperature was presented. Reduction rate of NO was less influenced by the inlet concentration of NO for experiments conducted with NO concentration higher than 500 ppmv. In this study, introduction of 1 vol.% oxygen into the reaction system was sufficiently to regenerate the active sites on TiO_2. More than 70% of NO was reduced by photo-SCR with the retention time more than 4 min. Most NO molecules consumed were photocatalytically reduced to form N_2; however, N_2O molecules were generated when certain NO molecules were reduced by the reduced active sites (Ti^{3+}) in the presence of oxygen. N_2 selectivity and NO reduction efficiency were decreased with the introduction of water molecules in the inlet stream mainly because of the competitive adsorption of water and NH_3 molecules for the active sites on TiO_2 surface. Reduction of NO was found to be increased with the increase of UV irradiance and NH_3 concentration. The reaction order against UV irradiance was lower than unity for the photo-SCR of NO because excessive irradiance possibly promoted the recombination of electron-hole pairs. For experiments conducted with NH_3 concentration higher than 400 ppmv, NO reduction rate approached to a constant value because of the limited active sites on the surface of TiO_2. The reaction behavior of the NO reduction by the photo-SCR was satisfactorily illustrated by Eley–Rideal kinetics.

Acknowledgements

This research was supported by Grant NSC-96-2628-E-011-001-MY3 from the National Science Council, Taiwan, Republic of China.

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