

## **Improvement on Hybrid SNCR-SCR Process for NO Control: a Bench Scale Experiment**

**Li-Chiang Chen\***

*Department of Chemical Engineering, Ming Hsin University of Science and Technology  
1, Hsin-Hsing Road, Hsin-Fong, Hsin-Chu, Taiwan, R.O.C.*

### **Abstract**

The reducing agent [ammonia ( $\text{NH}_3$ )] injection procedure was improved for the hybrid process of selective non-catalytic reduction followed by selective catalytic reduction (hybrid SNCR-SCR) to remove nitric oxide (NO) through a bench-scale experiment. Instead of injecting all of the  $\text{NH}_3$  from the SNCR inlet, part of it was injected from the SNCR inlet and part from the SCR inlet, to react with NO in the flue gas. The experiment resulted in the significant reduction of NO. The effects of the operational conditions such as the SNCR reaction temperature, the SCR reaction temperature, and the initial concentration ratio of  $\text{NH}_3$  to NO were also investigated. Under the initial NO concentration of 300 ppm (dry, 6%  $\text{O}_2$ ), the space velocities of SNCR 5100-6300  $\text{hr}^{-1}$ , the space velocities of SCR 7100-10000  $\text{hr}^{-1}$ , and with the initial concentration ratios of  $\text{NH}_3$  to NO 1.0-1.5, the best operational temperatures were discovered to be SNCR reaction of 850°C and SCR reaction of 350°C for the improved hybrid SNCR-SCR process. In addition, a correlation equation has been developed of the maximum NO reduction under the above best-operational temperatures for the hybrid SNCR-SCR process, and closely fits with the experiment results.

**Keywords:** hybrid SNCR-SCR, NO reduction, ammonia injection, ammonia slip

---

\* Corresponding author. Tel: +886-3-5593142 ext. 3353 ; Fax: +886-3-6007577

E-mail address: [clc@must.edu.tw](mailto:clc@must.edu.tw)

## INTRODUCTION

Selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) are two major nitric oxide (NO) reduction technologies for post-combustion treatment of flue gas from industrial or utility boilers. The SNCR technology using ammonia ( $\text{NH}_3$ ) as reducing agent to react with NO selectively to yield  $\text{N}_2$  and  $\text{H}_2\text{O}$  in flue gas, is named the Thermal De- $\text{NO}_x$  Process (Lyon, 1975). The optimal reaction temperature range for Thermal De- $\text{NO}_x$  is around 900-950 °C (Muzio et al., 1977). Furthermore, to avoid ammonia slip in the exit flue gas, it was recommended that the reaction temperature higher than 930 °C and the resident time of reaction more than 0.25 s should be controlled (Pohl *et al.*, 1993). Miller and Bowman (1989) present a SNCR reaction mechanism, composed from several chain reactions, with the help of a self-generated active radical (OH,  $\text{NH}_2$ ) to reduce NO. Two important reactions were identified:



Because of possible toxicity and safety problems while handling  $\text{NH}_3$ , alternative SNCR processes were developed. These processes use agents, including urea (Arand *et al.*, 1980) and cyanuric acid (Perry and Siebers, 1986). These alternative agents decompose to form  $\text{NH}_3$  and HNCO under high temperatures and reduce NO to  $\text{N}_2$  or  $\text{N}_2\text{O}$ . The primary equations for HNCO to react with NO to form  $\text{N}_2\text{O}$  are:



$\text{N}_2\text{O}$  is an environmentally harmful gas. It contributes to ozone layer destruction and increased global warming. When the SNCR processes were applied to stationary industrial pollution sites, the NO reduction range was around 30-60% (Himes *et al.*, 1995).

Selective catalytic reduction (SCR) is a process that also uses  $\text{NH}_3$  as an agent, but with the help of a catalyst to reduce NO to  $\text{N}_2$  in the lower temperature range. A SCR catalyst is commonly fabricated into a monolith with the shape of honeycomb or flat-plate, when applied to an industrial site. It is usually made by  $\text{V}_2\text{O}_5$  active sites impregnated into porous  $\text{TiO}_2$  carriers ( $\text{V}_2\text{O}_5/\text{TiO}_2$ ), and then coated with the  $\text{V}_2\text{O}_5/\text{TiO}_2$  catalyst on the monolithic surface. The application of SCR in industrial or utility boilers can reach a higher NO reduction rate than the SNCR process. In applying the SCR process, European studies indicated that the lower the space velocity in catalyst bed the higher the NO reduction. The space velocity decreased from 3,400  $\text{hr}^{-1}$  to 1,000  $\text{hr}^{-1}$ , causing the resident time of the flue gas to increase

from 1.1 s to 3.6 s, and facilitating increased NO reduction from 70% to 90% (Cichanowicz, 1987). When the flue gas contained residual oxygen, the overall chemical reaction of SCR has the stoichiometry:



Equation (5) shows that  $\text{NH}_3$  and NO, with the same chemical stoichiometry, cooperate with the higher NO reduction of SCR. It shows why the  $\text{NH}_3$  slip of SCR is lower than that of SNCR.

A hybrid technology combining SNCR with SCR (hybrid SNCR-SCR) was developed in order to achieve higher NO reduction or to reduce costs. Gullett *et al.* (1994), and Groff and Gullett (1997) used urea as reducing agent, injecting it through the SNCR inlet, partially reducing NO and forming  $\text{NH}_3$  from the decomposition of excessive urea. The process was then transferred to SCR for further NO reduction. This resulted in a space velocity of  $10,000 \text{ hr}^{-1}$  for SCR and a total 85% NO reduction for a 590 kw package boiler. Under the stoichiometric ratio of nitrogen from urea, initial NO was controlled by 2:1. Wendt *et al.* (2002) studied a pilot-scale SNCR-SCR hybrid process using  $\text{NH}_3$  as agent, where the total agent was also injected into the SNCR inlet. These results were used to develop a combined SNCR-SCR model, which was extended to operational coal-fired utility boilers to explore the economic benefits of the combined SNCR-SCR process under certain conditions.

While some high-efficiency SCR technologies are under development, minus SNCR, to achieve the same NO reduction (Zhu *et al.*, 1999; Hsu and Teng, 2001), this study attempted to improve the  $\text{NH}_3$  injection technique of a hybrid SNCR-SCR process. Through a bench-scale hybrid process,  $\text{NH}_3$  was injected separately, a part from the SNCR inlet and a part from the SCR inlet, to react with NO in the flue gas. NO reduction and  $\text{NH}_3$  slip of the different agent injection procedures were measured and compared. Moreover, the effects of operational conditions to the hybrid SNCR-SCR process such as the SNCR reaction temperature, the SCR reaction temperature, and the initial concentration ratio of  $\text{NH}_3$  to NO were also investigated. The optimal operational conditions to reach higher NO reduction and lower  $\text{NH}_3$  slip were also revealed by the experiment's results.

## EXPERIMENT

### APPARATUS

Figure 1 is a schematic diagram of the experimental apparatus. The apparatus is composed of high-pressure gases, flow rate controllers, SNCR furnace, SCR furnace, and the NO,  $\text{NH}_3$ ,  $\text{NH}_3$  measuring instruments. Dry flue gas composed of 81%  $\text{N}_2$ , 6%  $\text{O}_2$ , 13%  $\text{CO}_2$  was simulated by controlling the flow rates of the high-pressure gases. Furthermore, the initial concentrations of NO and  $\text{NH}_3$  in the flue gas

were controlled by adjusting the flow rates of the mixed gases of NO/N<sub>2</sub> and NH<sub>3</sub>/N<sub>2</sub>. The main feature of this experiment was that NH<sub>3</sub> was designed to be added into the simulated flue gas separately, part from the inlet of SNCR and a part from the inlet of SCR. The calibration data of all the flow meters were supplied by the manufacturer. The scale of the flow meter was tuned accordingly, with the flow rate of each flow meter calculated by volume balances of the gases contained in the flue gas. A hollow quartz tube with a 1.5 cm inner diameter and 23 cm long was put in the SNCR furnace. Another quartz tube the same diameter and length, but with a catalyst bed, was added to the SCR furnace. The V<sub>2</sub>O<sub>5</sub>/TiO<sub>2</sub> monolithic catalyst 1.0 cm in diameter supplied by a domestic SCR company, as shown in Fig. 2, was lined in SCR quartz tube with a total length of 11.5 cm. A total flue-gas flow rate was fixed at 1,500 ml/min (1atm, 300 K). Based on the fixed gas flow rate and the operation temperatures of SNCR and SCR, the space velocities of SNCR were calculated to be 5,100-6,300 hr<sup>-1</sup> (for SNCR temperature of 700-850 °C) and the space velocities of SCR were calculated to be 7,100-10,000 hr<sup>-1</sup> (for SCR temperature 200-450 °C).

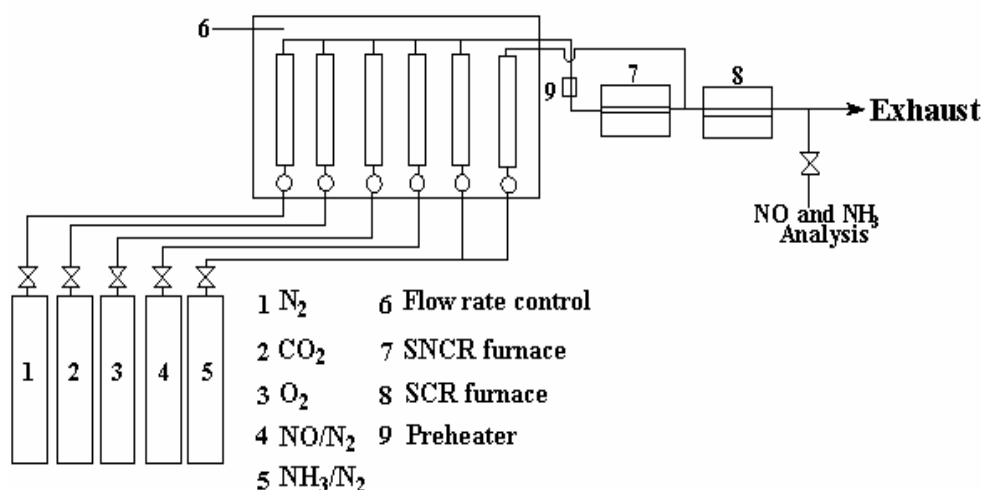
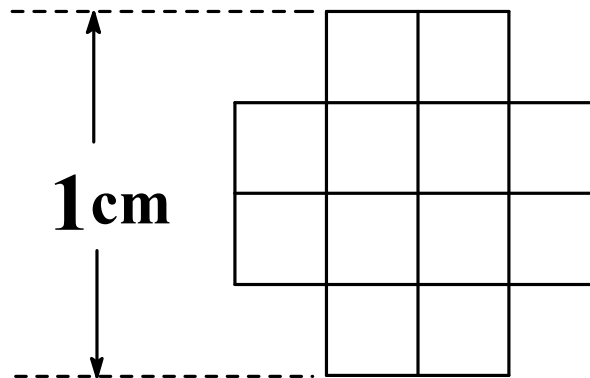


Figure 1. Schematic diagram of the experimental apparatus.

## MEASUREMENT OF NO AND NH<sub>3</sub>

The measuring point for NO and NH<sub>3</sub> was located at the SCR exhaust (Fig. 1). A Bacharach NONOXOR portable NO<sub>x</sub> analyzer with the NO<sub>x</sub> display range of 0-1,999 ppm, a resolution of 1 ppm, and the accuracy of ± 3 ppm was adopted for the NO measurement. The effects of NH<sub>3</sub> contamination in the simulated flue gas on the NO measured by the NO<sub>x</sub> analyzer are shown in Fig. 3. It shows that the existence of NH<sub>3</sub> will not interfere with the NO measurement.



**Figure 2.** Cross section diagram of the SCR catalyst.

To measure the  $\text{NH}_3$  in the flue gas, an electrical conductivity method was used. A sampling pump was employed to extract a fixed amount of flue gas (0.7 l/min), which was bubbling out and in contact with a fixed volume of distilled water (120 ml) in a sampling bottle for 10 min. After sampling, the water solution was taken from the sampling bottle and conductivity was measured. The concentration of  $\text{NH}_3$  was then calculated by the following calibration equation:

$$C_{\text{NH}_3} = 4.20 \times (E_{\text{NH}_3} - E_{\text{H}_2\text{O}}) - 78.9 \quad (6)$$

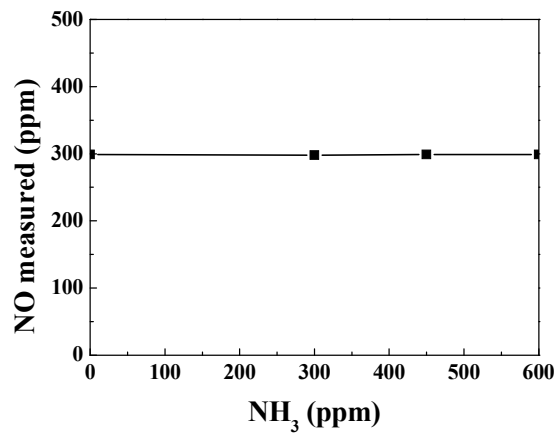
$$C_{\text{NH}_3} = \text{NH}_3 \text{ concentration in the flue gas (ppm)}$$

$E_{\text{NH}_3} - E_{\text{H}_2\text{O}}$ : the solution electric conductivity differences after sampling and before sampling ( $\mu\text{s}/\text{cm}$ )

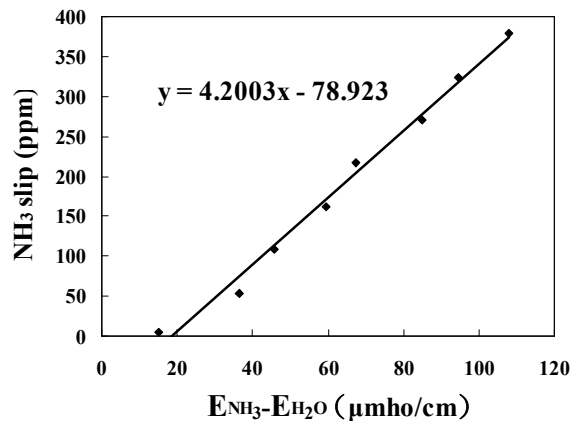
This equation was prepared by sampling flue gas with a known  $\text{NH}_3$  concentration, following the same steps to measure the conductivity difference of the solution after and before sampling. The calibration diagram is shown in Fig. 4. It is suggested that the suitable application range of the  $\text{NH}_3$  measurement is 0-400 ppm.

## EXPERIMENTAL SCOPE

During the hybrid SNCR-SCR experiment, some of the reducing agent  $\text{NH}_3$  was injected through the inlet for SNCR and some through the inlet for SCR. The  $\text{NH}_3$  ratio was defined as the ratio of the percentages of ammonia injected from the inlet of SNCR to that injected from the inlet of SCR. The ratio values were controlled at 100:0, 66.6:33.4, or 50:50 for each set of experimental conditions. During the experiment, the initial NO concentration (*i.e.*,  $\text{NO}_i$ ) was fixed at a value of 300 ppm in the simulated dry flue gas with 6%  $\text{O}_2$  content, which is similar to the NO emissions of an industrial heavy oil-fired or



**Figure 3.** Effects of NH<sub>3</sub> contaminations in the simulated flue gas on NO measured value.



**Figure 4.** Calibrated relation between electric conductivity difference and NH<sub>3</sub> slip.

coal-fired boiler. Also, the total flow rate of the dry flue gas (*i.e.*,  $Q$ ) was fixed at 1,500 ml/min (1 atm, 300K) and was preheated to 500°C before input into the SNCR furnace. Other experimental conditions include reaction temperature of SNCR (*i.e.*, SNCR temperature), reaction temperature of SCR (*i.e.*, SCR temperature), and stoichiometry ratio of initial total NH<sub>3</sub> to NO<sub>x</sub> (*i.e.*, NH<sub>3</sub>:NO). The ranges of all experimental conditions are summarized in Table 1.

## RESULTS AND DISCUSSION

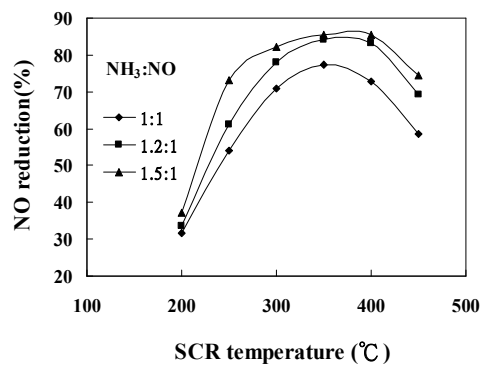
### SCR REACTION ALONE

An SNCR reaction does not occur when set at a low temperature of 550°C. Figure 5 shows the effects of SCR temperature and a NH<sub>3</sub>:NO ratio on NO reduction (*i.e.*, the percentage of NO reduced from NO<sub>x</sub>)

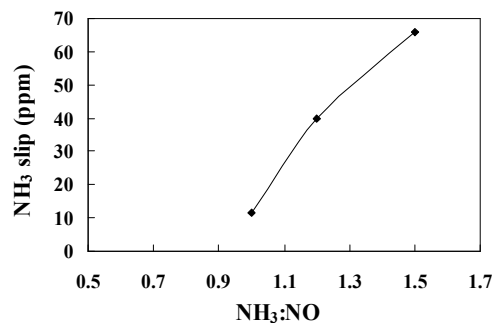
of SCR reaction alone. NO reduction is increased as SCR temperature increases until an optimal temperature of 350°C is reached. Above 350°C, some NH<sub>3</sub> will decompose and cause the NO reduction to be lessened. In addition, optimal NO reduction occurs when NH<sub>3</sub>:NO is at a 1:1 ratio. Furthermore, reduction improved from 77.5% at 1:1 to 85% 1.5:1. However, increasing NH<sub>3</sub>:NO increases the unreacted NH<sub>3</sub> contained in the ventilated flue gas (*i.e.*, NH<sub>3</sub> slip) (Fig. 6). NH<sub>3</sub> slip increases from 11 ppm to 67 ppm when NH<sub>3</sub>:NO increases from 1:1 to 1.5:1.

**Table 1.** The ranges of all experimental conditions.

Experimental Condition	Range
NO <sub>i</sub>	300ppm (dry, 6% O <sub>2</sub> )
Q	1500 ml/min
NH <sub>3</sub> Ratio	100:0, 66.6:33.4, or 50:50%
SNCR Temperature	550-900°C
SCR Temperature	200-450°C
NH <sub>3</sub> : NO	1:1, 1.5:1, or 2:1



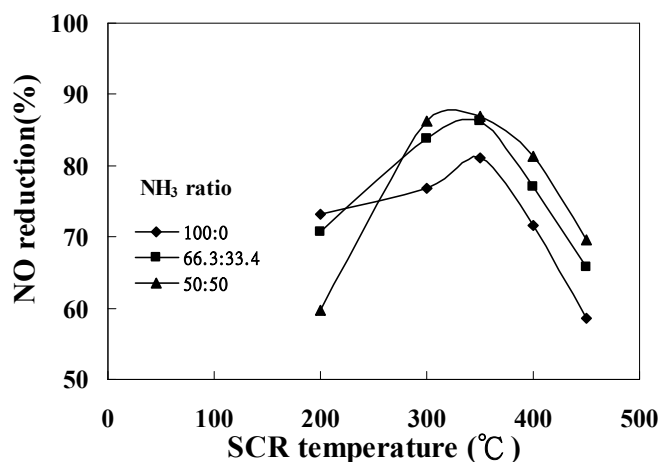
**Figure 5.** Effects of SCR temperature and NH<sub>3</sub>:NO on NO reduction, SCR reaction alone.



**Figure 6.** Effect of NH<sub>3</sub>:NO on NH<sub>3</sub> slip, SCR reaction alone.

## EFFECT OF SCR TEMPERATURE ON HYBRID SNCR-SCR

The effects of SCR temperature and  $\text{NH}_3$  ratio on the hybrid SNCR-SCR process, at the SNCR temperature of  $850^\circ\text{C}$  and  $\text{NH}_3:\text{NO}$  of 1:1 is shown in Fig. 7. This figure depicts the optimal operating temperature (with the maximum NO reduction) of SCR in the hybrid SNCR-SCR is the same as the SCR reaction alone; *i.e.*,  $350^\circ\text{C}$ . Figure 7 also shows that by reducing the  $\text{NH}_3$  ratio (within range of  $\text{NH}_3$  ratio shown in Table 1), part of the agent will input directly to SCR, avoiding the over consumption of  $\text{NH}_3$  in SNCR, thus maximizing NO reduction. Comparing Fig. 7 with Fig. 5, the maximum NO reductions at the optimal SCR temperature of  $350^\circ\text{C}$  increases from 77.5% of the SCR reaction alone to 87% of the hybrid SNCR-SCR when the  $\text{NH}_3$  ratio is 50:50. In addition,  $\text{NH}_3$  slip is 11 ppm of SCR reaction alone comparing to 0 ppm of the hybrid SNCR-SCR, as indicated in Fig. 6 and Table 2.



**Figure 7.** Effects of SCR temperature and  $\text{NH}_3$  ratio on NO reduction: hybrid SNCR-SCR,  $\text{NH}_3:\text{NO}=1:1$ , SNCR =  $850^\circ\text{C}$ .

**Table 2.** The maximum NO reduction and  $\text{NH}_3$  slip for the optimal SNCR temperature  $850^\circ\text{C}$  and SCR temperature  $350^\circ\text{C}$ .

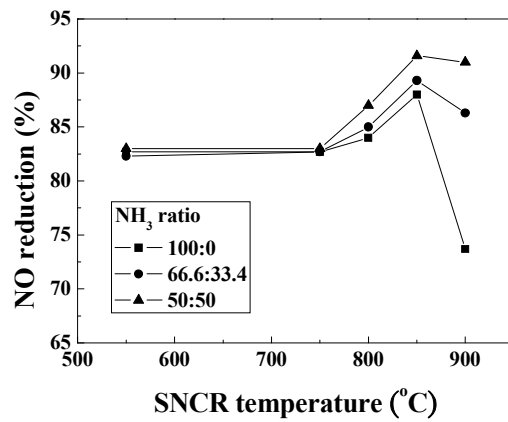
Maximum NO Reduction (%) And $\text{NH}_3$ Slip (ppm)	Hybrid SNCR-SCR ( $\text{NH}_3$ Ratio, %)			SCR Reaction Alone
	100:0	66.6:33.4	50:50	
$\text{NH}_3 : \text{NO}=1:1$	81% 0ppm	85% 0ppm	87% 0ppm	77.5% 11ppm
$\text{NH}_3 : \text{NO}=1.5:1$	88% 0ppm	89.5% 5ppm	91.5% 27ppm	85% 67ppm

## **EFFECT OF SNCR TEMPERATURE ON HYBRID SNCR-SCR**

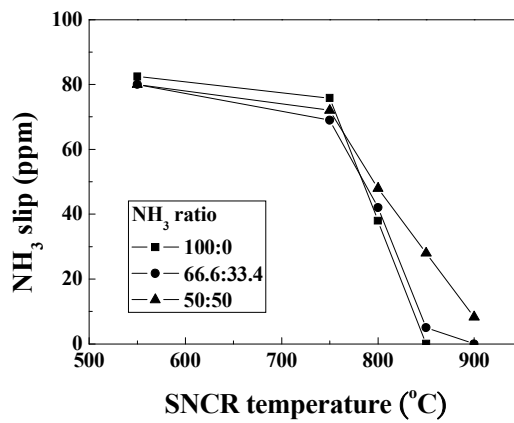
Figures 8-9 show the effects of SNCR temperature on NO reduction and NH<sub>3</sub> slip of hybrid SNCR-SCR process at the optimal SCR temperature 350 °C and NH<sub>3</sub>:NO = 1.5:1.0. NO reduction begins to rise from the SNCR temperature of 750 °C to the maximum value when the SNCR temperature reaches 850 °C (Fig. 8). When the SNCR temperature is higher than 850 °C, the over consumption of NH<sub>3</sub> in the SNCR will happen. Without enough NH<sub>3</sub> in SCR the NO reduction decreases. The harmful effect of over consumption of NH<sub>3</sub> in SNCR on NO reduction can be improved by adjusting the NH<sub>3</sub> ratio. When the experimental range of NH<sub>3</sub> ratio is within 100:0 to 50:50, the maximum NO reduction increases from 88 to 92% when the NH<sub>3</sub> ratio reduces from 100:0 to 50:50 (Fig. 8). It is believed that an optimal NH<sub>3</sub> ratio exists for the hybrid SNCR-SCR, because when reducing NH<sub>3</sub> ratio to 0:100, the NO reductions of the hybrid SNCR-SCR will be the same as SCR reaction alone. The SNCR is unnecessary in such a condition. Figure 9 shows the effect of SNCR temperature on NH<sub>3</sub> slip of the hybrid SNCR-SCR. At a SCR temperature of 350 °C, NH<sub>3</sub>:NO = 1.5:1.0, and SNCR temperature above 850 °C, NH<sub>3</sub> slip of hybrid SNCR-SCR is obviously lower than the SCR reaction alone (see Fig. 6).

## **EFFECT OF NH<sub>3</sub>:NO ON HYBRID SNCR-SCR**

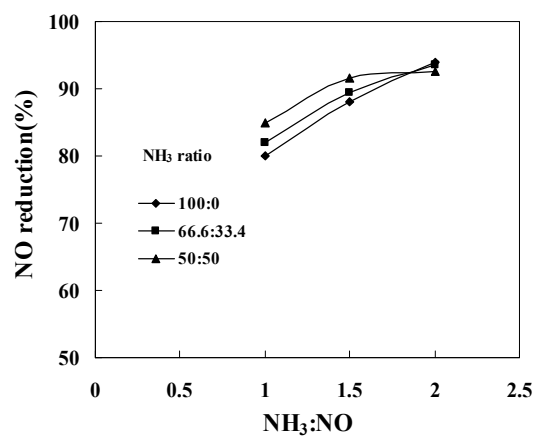
The optimal SNCR temperature of 850 °C and SCR temperature of 350 °C, the effects of NH<sub>3</sub>:NO on NO reduction, and NH<sub>3</sub> slip of the hybrid SNCR-SCR process are shown in Figs. 10-11. Figure 10 shows that NO reduction increases as the stoichiometry ratio NH<sub>3</sub>:NO increases. This figure also demonstrates that when the ratio of NH<sub>3</sub>:NO is higher than 1.5, the effect on NO reduction is insignificant. In Fig. 11 it can be seen that the NH<sub>3</sub> slip becomes serious when NH<sub>3</sub>:NO is higher than 1.5. Therefore, it is not recommended to operate NH<sub>3</sub>:NO any higher than 1.5 for the improved hybrid SNCR-SCR process.



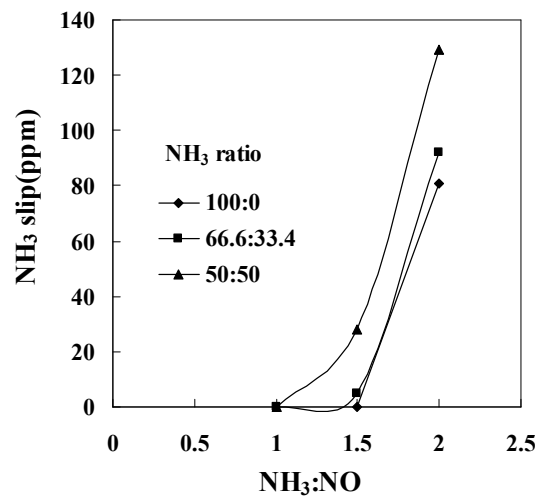
**Figure 8.** Effects of SNCR temperature and  $\text{NH}_3$  ratio on NO reduction: hybrid SNCR-SCR,  $\text{NH}_3$  : NO = 1.5:1, SCR = 350 °C.



**Figure 9.** Effects of SNCR temperature and  $\text{NH}_3$  ratio on  $\text{NH}_3$  slip: hybrid SNCR-SCR,  $\text{NH}_3$  : NO = 1.5:1, SCR = 350 °C.



**Figure 10.** Effects of  $\text{NH}_3$ :NO and  $\text{NH}_3$  ratio on NO reduction: hybrid SNCR-SCR, SNCR = 850 °C, SCR = 350 °C.



**Figure 11.** Effects of NH<sub>3</sub>:NO and NH<sub>3</sub> ratio on NH<sub>3</sub> slip: hybrid SNCR-SCR, SNCR = 850 °C, SCR = 350 °C.

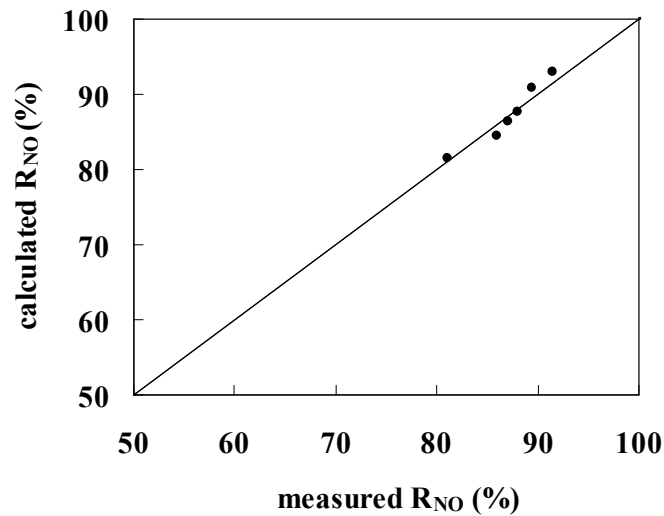
## COMPARING NO REDUCTION AND NH<sub>3</sub> SLIP UNDER OPTIMAL TEMPERATURES

Maximum NO reductions are reached under the optimal SNCR and SCR temperatures with NH<sub>3</sub> slips for comparing the performance of hybrid SNCR-SCR and SCR reaction alone. Table 2 shows that the performance of hybrid SNCR-SCR is superior to that of the SCR reaction alone and NO reduction can be further improved for hybrid SNCR-SCR if NH<sub>3</sub> is injected partly from the inlet of SNCR and partly from the inlet of SCR.

A correlation equation of maximum NO reduction for hybrid SNCR-SCR from the experimental results of Table 2 is shown as:

$$R_{NO} = 81.5(R_{NH_3:NO})^{0.182}(R_{SNCR})^{-0.085} \quad (7)$$

where  $R_{NO}$  is maximum NO reduction (%),  $R_{NH_3:NO}$  is NH<sub>3</sub>:NO and  $R_{SNCR}$  is the ratio of NH<sub>3</sub> injected from the inlet of SNCR to the total NH<sub>3</sub> added to the hybrid SNCR-SCR. The comparison of the calculated  $R_{NO}$  from equation (7) and the measured  $R_{NO}$  from Table 2 for hybrid SNCR-SCR process is shown in Fig. 12. Figure 12 indicates that the calculated values from the correlation equation are qualitatively confirmed with the experimental results. The correlation equation identifies the conditions of SNCR temperature (850 °C), SCR temperature (350 °C), NH<sub>3</sub>:NO = 1:1-1.5:1, and  $R_{SNCR}$  = 0.5-1.0. It is suggested to apply equation (7) within the identified conditions to avoid the misguided error for  $R_{NO}$  calculations.



**Figure 12.** Comparison of the calculated and the measured maximum NO reductions for hybrid SNCR-SCR, SNCR = 850°C, SCR = 350°C.

## CONCLUSIONS

The performance of the hybrid SNCR-SCR process has been improved by adding a controlled-parameter NH<sub>3</sub> ratio; *i.e.*, instead of injecting the total NH<sub>3</sub> through the SNCR inlet, NH<sub>3</sub> was injected partly during SNCR and partly during SCR. The experiment on the improved hybrid SNCR-SCR process was carried out using a bench-scale apparatus. The experimental results indicate that in order to reach the maximum NO reduction the optimal temperatures for SNCR is 850°C and for SCR it is 350°C. It is recommended that the values of NH<sub>3</sub>:NO in the range of 1-1.5 for the improved hybrid process to avoid any serious NH<sub>3</sub> slip. The performances of the maximum NO reduction increase with reducing the NH<sub>3</sub> ratio, and the NH<sub>3</sub> slip is still superior to SCR reaction alone, as shown in Table 2. Also, the correlation equation of the maximum NO reduction for the hybrid SNCR-SCR process is developed and well-fitted with the experiment results.

## ACKNOWLEDGMENT

The author would like to thank the Ming Hsin University of Science and Technology for financially supporting this research under Contract No. MUST-91-CHE-004.

## REFERENCES

Arand, J.K., Muzio, L.J. and Sotter, J.G. (1980), Urea Reduction of NO<sub>x</sub> in Combustion Effluents. U. S.

Patent No. 4,208,386.

- Cichanowicz, J.E. and Offen, G.R. (1987), Applicability of European SCR Experience to U.S. Utility Operation. EPRI Symposium on Stationary Combustion NO Control, 28-1.
- Groff, P.W. and Gullett, B.K. (1997), Industrial Boiler Retrofit for NO<sub>x</sub> Control: Combined Selective Non-catalytic Reduction and Selective Catalytic Reduction. *Environment Progress*. 16: 116 -120.
- Gullett, B.K., Groff, P.W., Lin, M.L. and Chen, J.M. (1994), NO Removal with Combustion Selective Catalytic Reduction and Selective Non-catalytic Reduction: Pilot-Scale Test Results. *J. Air & Waste Manage. Assoc.* 44: 1188-1194.
- Himes, R., Hubbard, D., West, Z. and Stallings, J. (1995), A Summary of SNCR Applications to Two Coal-Fired Wet Bottom Boilers. EPRI/EPA Joint Symposium on Stationary Combustion NO Control, Kansas City, KS.
- Hsu, L.Y. and Teng, H. (2001), Catalytic NO Reduction with NH<sub>3</sub> over Carbons Modified by Acid Oxidation and by Metal Impregnation and its Kinetic Studies. *Applied Catalysis B: Environmental*. 35: 21-30.
- Lyon, R.K. (1975), Method for the Reduction of the Concentration of NO in Combustion Effluent using Ammonia. U. S. Patent No. 3, 900, 544.
- Miller, J.A. and Bowman, C.T. (1989), Mechanism and Modeling of Nitrogen Chemistry in Combustion. *Prog. Energy Combustion Science*. 15: 287-298.
- Muzio, L.J., Arand, J.K. and Teixeira, D.P. (1977), Gas Phase Decomposition of Nitric Oxide in Combustion Products. The 16<sup>th</sup> Symposium of Combustion, pp.199-208.
- Perry, R.A. and Siebers, D.L. (1986), Rapid Reduction of Nitrogen Oxides in Exhaust Gas Streams. *Nature*. 324: 657-664.
- Pohl, J.H., Yang, S.C., Sowa, W.A. and Dill, J.W. (1993), Limits to NO<sub>x</sub> Reduction by NH<sub>3</sub> Injection. Meeting of the American Chemical Society Division of Fuel Chemistry, Denver, CO.
- Wendt, J.O.L., Linak, W.P., Groff, P.W. and Srivastava, R.K. (2001), Hybrid SNCR-SCR Technologies for NO<sub>x</sub> Control. *AIChE Journal*. 47(11): 2603-2617.
- Zhu, Z., Liu, Z., Liu, S. and Niu, H. (1999), A Novel Carbon-Supported Vanadium Oxide Catalyst for NO Reduction with NH<sub>3</sub> at Low Temperature. *Applied Catalysis B: Environmental*. 23: L229-L233.

*Received for review, October 8, 2005*

*Accepted, November 25, 2005*