Available online at www.sciencedirect.com

SCIENCE DIRECT®

Catalysis Today 89 (2004) 127–133

CATALYSIS TODAY

www.elsevier.com/locate/cattod

NO_x removal from a flue gas in a corona discharge-catalyst hybrid system

Mirosław Dors*, Jerzy Mizeraczyk

Centre for Plasma and Laser Engineering, Institute of Fluid Flow Machinery, Polish Academy of Sciences, Fiszera 14, 80-231 Gdańsk, Poland

Abstract

The objective of this work was to investigate NO_x removal with a hybrid system consisting of a dc corona discharge and a catalyst at a room temperature (22 °C) in the presence of ammonia. The experimental procedure was as follows. A positive dc corona discharge was generated between a stainless steel hollow needle and a flat mesh made of brass. The needle was placed perpendicularly to the mesh maintaining the interelectrode distance of 40 mm. The outer and inner diameters of the hollow needle were 2 and 1.6 mm, respectively. The catalyst used in this investigation was a layer of V_2O_5 and TiO_2 deposited on Al_2O_3 globules of 5–6 mm in diameter. They were placed on the mesh so that the distance between the tube and the globules was 30 mm. The catalyst was either saturated with NH_3 or free of NH_3. A gas mixture of N_2 (80%):O_2 (5%):CO_2 (15%):NO (200 ppm) flowed through the tube with a flow rate of 1 l/min. Ammonia was added to the gas mixture through a hollow needle in a concentration of either 400 ppm when NH_3-free catalyst was used or 30 ppm when catalyst saturated with NH_3 was used. Results of the investigation showed that the hybrid system (with NH_3-saturated catalyst) removes up to 96% of NO_x with an energy efficiency of 3.4 g NO/kWh. Without the catalyst, NO_x removal in the “pure” corona discharge in the gas mixture with ammonia was lower (up to 66%). Also the energy efficiency was lower (about 1.8 g NO/kWh). The obtained results showed that the investigated corona discharge-catalyst hybrid system is attractive for NO_x removal because of relatively high efficiency both in NO_x decomposition and energy consumption.

Keywords: Hybrid; Catalyst; Corona discharge

1. Introduction

Investigations over the last 10 years carried out in laboratories and pilot plants showed that removal of NO_x from flue gases by corona discharges may be very efficient [1,2]. However, the energy consumption in this new technology is still not acceptable for commercial use and is to be improved. Therefore, many recent investigations have been focused on the performance improvement of the corona discharge processing by optimizing the power source [3], using various gaseous additives [4–10] or combining the corona discharge processing with other methods [11–13].

A technology competitive to the corona discharge processing is the selective catalytic reduction (SCR) which has proved its efficiency in NO_x removal [14]. In the SCR process, ammonia (NH_3) and a catalyst operating at a relatively high temperature range of 280–430 °C are used to reduce NO_x to N_2 and H_2O which are harmless products. Although, efficiency of NO_x removal using the SCR method is up to 90%, there are disadvantages of this method, such as high cost and short life-time of the catalyst due to its poisoning.

In the corona discharge processing, the dominant mechanism of NO_x removal is its oxidation to gaseous HNO_3 which then is converted to NH_4NO_3 solid particles by adding NH_3 [5,6,8,9,15]. Among many corona discharge types, the most efficient in NO_x removal is a corona radical shower (CRS) [8,9]. In the CRS reactor, NH_3 is introduced through a hollow needle electrode into the corona discharge zone where NH_3 molecules dissociate to NH_2 and NH radicals. These radicals react with NO_x molecules converting them into NH_4NO_3 solids. The record NO_x removal energy yield of the CRS method is 15 g/kWh at NO_x removal of 90% (Table 1, [9]) The disadvantage of the corona discharge is the fact that selective control of the plasma chemical reaction to reduce NO_x to N_2, like in the SCR, is difficult.

In recent years hybrid plasma-catalyst systems have been proposed because of their capability to reduce NO_x into N_2 [11–13,16–21]. A typical hybrid system consisted of a corona discharge and a catalyst operating at a temperature over 120 °C. So far researchers used a catalyst either as a layer coating the plane electrode in a point-to-plane dc corona discharge reactor [16], or as pellets or globules in a packed bed silent discharge reactors [17–21]. In some

---

[*] Corresponding author. Tel.: +48-58-341-12-71; fax: +48-58-341-61-44.
E-mail address: mdors@imp.gda.pl (M. Dors).

0920-5861/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.cattod.2003.11.031

Table 1
Parameters of NO_x removal processing in selected systems using corona discharge (CD) and ammonia

System	Gas mixture	Gas temperature (°C)	Initial NO concentration (ppm)	Flow rate (l/min)	Specific energy (Wh/m^3)	NO_x removal efficiency (%)	Energy yield (g NO/kWh)	Ref.
CD (wire-to-cylinder)	N_2:O_2:CO_2 (balance:10%:10%)	22	400	2	333	90	0.6	[5]
CD (wire-to-plate)	Flue gas from coal-burning power station	100	300	10000	12	60	20	[6]
CD (needle-to-plate)	Combustion gas from city gas burner	70–200	200	60	230	90	0.2	[7]
CRS	N_2:O_2:CO_2:H_2O:SO_2 (89.4%: 2.6%:7.9%:<0.5%:800 ppm)	22	200	5	18	90	15	[9]
Hybrid CD-catalyst	N_2:O_2:CO_2 (85%:10%:5%)	150	430	2–6	8.3	75	21	[11]
Hybrid CD-catalyst	Diesel exhaust gas	94–189	198	1314	2.5	60	55	[13]
Hybrid CD-catalyst	N_2:O_2:CO_2 (80%:5%:15%)	22	200	1	80	96	3.4	This work

hybrid systems, first the corona discharges were used for oxidizing NO into NO_2, and then the SCR processing with NH_3 was used to convert NO_2 into N_2 and H_2O [11–13]. The efficiency of NO_x removal using hybrid plasma-catalyst systems was up to 98% at an energy yield up to 55 g/kWh (Table 1, [13]). In other hybrid systems, hydrocarbons were added to the flue gas polluted with NO_x to improve its removal [17–19].

This work was aimed at studying NO_x removal in a hybrid system consisted of a dc streamer corona discharge with a catalyst operating under low temperature (22 °C) in the presence of NH_3. In our reactor a catalyst typical of the SCR method, but operating at low temperature, interacted with a corona discharge. Gaseous NH_3 was introduced into the corona discharge zone through a hollow needle electrode similarly as in CRS reactors. We used a new way of introducing gaseous NH_3 into the corona discharge zone. In this new method, the gaseous NH_3 was introduced into the discharge zone after releasing it by the corona discharge from an NH_3 phase, which has been earlier adsorbed on the catalyst surface. The performance of our hybrid corona discharge-catalyst reactor is described below.

2. Experimental

The hybrid corona discharge-catalyst reactor used in this experiment is shown in Fig. 1. The positive dc corona discharge was generated between a stainless steel hollow needle electrode and grounded flat mesh electrode (1 mm × 1 mm) made of brass. The hollow needle electrode was placed perpendicularly to the mesh. The outer and inner diameters of the hollow needle were 2 and 1.6 mm, respectively. The hollow needle-mesh spacing was 40 mm.

The catalyst used in this investigation was a layer of V_2O_5 and TiO_2, as in the SCR processing, deposited on Al_2O_3 globules of 5–6 mm in diameter. The globules with deposited catalyst were delivered by the Katalizator Co., Krakow, Poland. The catalyst globules were placed on the mesh in the form of two layers. The hollow needle-catalyst spacing was about 30 mm.

The catalyst layer deposited on Al_2O_3 globules was used to play two roles. The first one, when a “pure” catalyst-covered globules were used, was the typical role of catalyst. The another role, consisting a novel in this investigation, resulted from using the catalyst-covered globules as an adsorber for NH_3 before placing the globules into the reactor. We expected that the NH_3-saturated globules could become a gaseous NH_3 source in the reactor, when subjected to the corona discharge. The releasing of gaseous NH_3 from the catalyst globules by the corona discharge was supposed to be an efficient way of NH_3 supply into the reactor.

In the following text, the case when the “pure” catalyst was used is called an NH_3-free catalyst case, while an NH_3-saturated catalyst case corresponds to the experiment in which the catalyst with NH_3 adsorbed on its surface was used.

The positive polarity dc high voltage was applied through a 10 MΩ resistor to the hollow needle electrode. The operating voltage was varied from 15 to 38 kV, sustaining a stable streamer corona discharge. The time-averaged discharge current varied in the range of 50–200 μA.

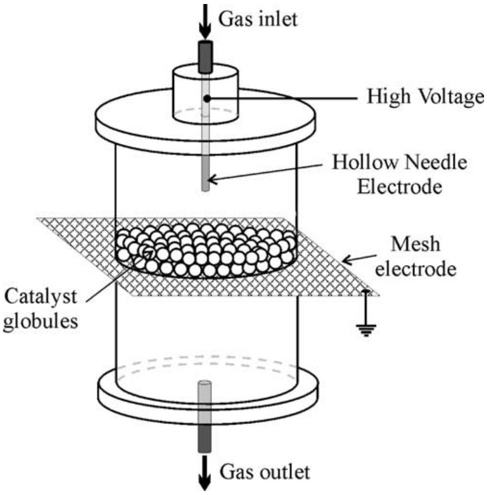

Fig. 1. The hybrid corona discharge-catalyst reactor.

A gas mixture of N_2 (80%):O_2 (5%):CO_2 (15%):NO (200 ppm), simulating a flue gas (without water and hydrocarbons), was supplied through the hollow needle and then flowed through the reactor with a flow rate of 1 l/min.

When the performance of the reactor with the “pure” catalyst was investigated, gaseous NH_3 was first mixed with the N_2:O_2:CO_2:NO mixture, forming the working gas. Then the working gas was introduced through the hollow needle electrode into the reactor. The NH_3 concentration in the working gas was 400 ppm, which corresponds to a molar ratio of NH_3 to NO equal to 2:1. As it was found by Park et al. [9], the removal efficiency of NO_x by the corona discharge is highest when the molar ratio NH_3:NO = 2:1.

When the performance of the reactor with NH_3-saturated catalyst globules was tested, gaseous NH_3 (30 ppm) was introduced into the reactor, after mixing with the N_2:O_2:CO_2:NO mixture. This additional gaseous NH_3 was supposed to make up a loss of NH_3 released from the globules and sustain steady concentration of NH_3 in the reactor with a minimum slip in the outlet gas (1 ppm). As the concentration of NH_3 adsorbed on the globules layer was expected to decrease with elapsing time of the discharge operation, this part of the investigation had a time-dependent character. Also, time-dependent deterioration of the catalyst layer when employing NH_3 was expected (a kind of catalyst poisoning by products of the plasma-chemistry reactions in the reactor).

Concentrations of NO, NO_2 and NH_3 in the working gas at the reactor inlet and outlet were measured by absorption spectroscopy method using a Perkin-Elmer 16 PC FTIR spectrophotometer operating in the infrared range 4400–1000 cm^{-1}.

3. Results

The experimental results showed that three factors influence strongly the efficiency of NO_x removal from the working gas. They are: the plasma (parametrically represented here by the energy density), catalyst and NH_3 including the way of its supplying into the reactor. The details are described below.

3.1. Corona discharge processing without catalyst and gaseous NH_3 supply

The removal efficiency of NO from the working gas by processing it with the corona discharge without catalyst and NH_3 was no higher than 25% (at energy density of 400 J/l, Fig. 2). The processing was accompanied with production of NO_2 up to 50 ppm. As a result, NO_x removal was not higher than 8% (Fig. 3). In this case, NO is believed to be removed mainly in reactions with N and O atoms and O_3 molecules, produced in the corona discharge [22]:

$$NO + N \rightarrow N_2 + O, \quad (1)$$

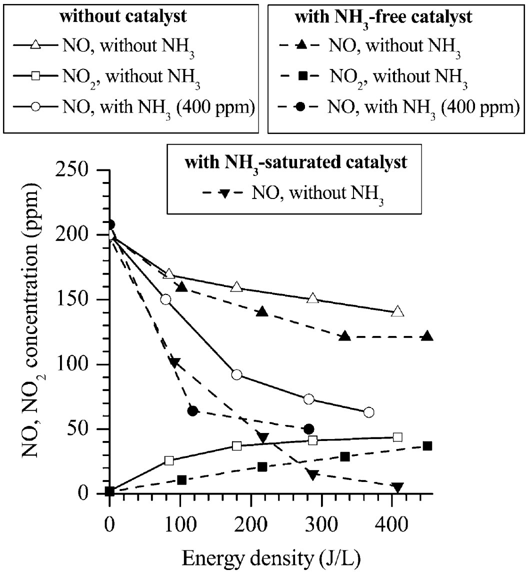

Fig. 2. Concentrations of NO and NO_2 in the working gas at the reactor outlet as a function of energy density. Cases: (a) processing without catalyst [without or with gaseous NH_3 (400 ppm) supply]; (b) processing with NH_3-free catalyst [without or with gaseous NH_3 (400 ppm) supply]; and (c) processing with NH_3-saturated catalyst [without gaseous NH_3 (30 ppm) supply].

$$NO + O \rightarrow NO_2, \quad (2)$$

$$NO + O_3 \rightarrow NO_2 + O_2. \quad (3)$$

The resulting balance between the production and decomposition of NO and NO_2 molecules is influenced by the reverse reaction:

$$NO_2 + O \rightarrow NO + O_2. \quad (4)$$

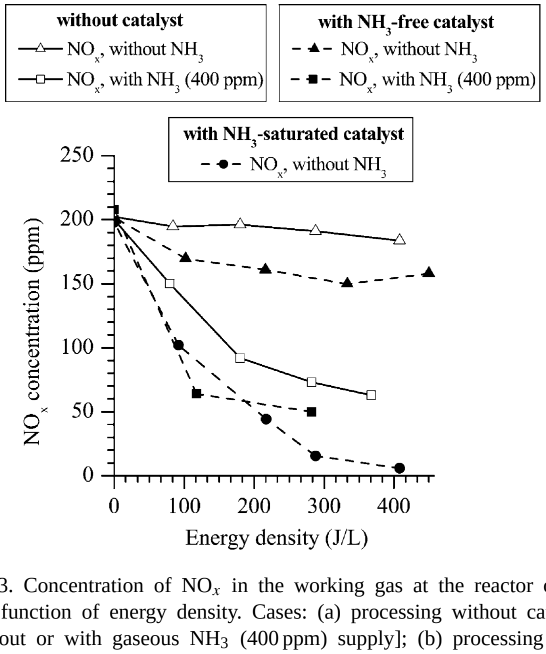

Fig. 3. Concentration of NO_x in the working gas at the reactor outlet as a function of energy density. Cases: (a) processing without catalyst [without or with gaseous NH_3 (400 ppm) supply]; (b) processing with NH_3-free catalyst [without or with gaseous NH_3 (400 ppm) supply]; and (c) processing with NH_3-saturated catalyst [without gaseous NH_3 (30 ppm) supply].

Reactions (2) and (3) are responsible for NO_2 production which causes NO_x removal low.

3.2. *Corona discharge processing without catalyst and with gaseous NH_3 (400 ppm) supply*

NH_3 (400 ppm) added to the working gas increased NO removal to 66% (at energy density of 400 J/l) and resulted in the absence of NO_2 molecules in the outlet gas (Fig. 2), which are consumed in reactions (5) and (6). As a result, NO_x removal (Fig. 3) is equal to NO removal.

When the working gas is processed by the corona discharge in the presence of NH_3, NO is believed to be removed in two pathways. The first pathway is oxidation to NO_2 in reactions (2) and (3). Then NO_2 reacts with OH and HO_2 radicals, produced from NH_3 and O_2 molecules in the corona discharge [9]:

$$NO_2 + OH \rightarrow HNO_3, \tag{5}$$

$$NO_2 + HO_2 \rightarrow HNO_3 + O. \tag{6}$$

Afterwards, HNO_3 reacts with NH_3 forming NH_4NO_3 solid particles:

$$HNO_3 + NH_3 \rightarrow NH_4NO_3. \tag{7}$$

In this experiment we could find deposits of white NH_4NO_3 solids on the reactor wall and mesh electrode produced during the corona processing. The second pathway is reduction of NO by NH_2 and NH radicals, produced in the corona discharge from NH_3 molecules [9]:

$$NO + NH \rightarrow N_2 + OH, \tag{8}$$

$$NO + NH_2 \rightarrow N_2 + H_2O. \tag{9}$$

At this moment we are not able to determine the relative importance of both pathways.

Although, NH_3 was involved in both pathways of NO removal, only a small fraction, i.e. about 15%, of the introduced NH_3 is consumed during the corona discharge processing (Fig. 4). This resulted in a high slip of NH_3. It seems that the initial concentration of NH_3 used in this experiment after [9] was too high. However, we did not investigate this problem further.

3.3. *Corona discharge processing with NH_3-free catalyst and without gaseous NH_3 supply*

In the presence of the NH_3-free catalyst in the reactor, NO removal from the working gas without NH_3 was higher (about 40% at 340–450 J/l) than that without catalyst and NH_3 (Fig. 2). The NO removal was accompanied with NO_2 production, which is, however, lower than that without catalyst and NH_3. As a result, NO_x removal increased up to 25% (Fig. 3).

The presence of NO_2 in the post-processing gas proves that NO_2 was produced in reactions (2) and (3), causing NO removal. However, the resulting NO_2 concentration, which was lower than that without catalyst, may result from:

(a) lower operating voltage (32.5 kV against 34 kV due to the shorter discharge gap with the catalyst at the same discharge current equal to 200 μA); it may cause lower production of radicals involved in NO_2 production [reactions (2) and (3)];

(b) losses of NO_2 molecules due to their adsorption on the catalyst surface, resulting in the lower NO_2 concentration in the outlet gas.

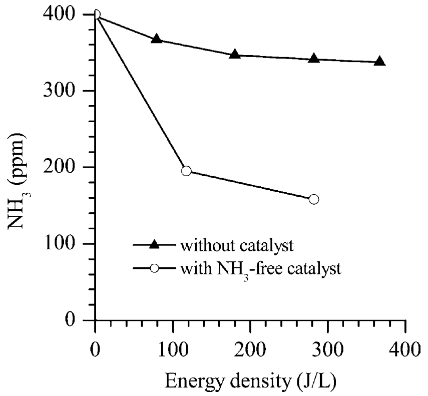

Fig. 4. Concentration of NH_3 in the working gas at the reactor outlet as a function of energy density. Inlet NH_3 concentration 400 ppm. Cases: (a) processing without catalyst [with gaseous NH_3 (400 ppm) supply]; and (b) processing with NH_3-free catalyst [with gaseous NH_3 (400 ppm) supply].

The higher efficiency of NO removal in the presence of the catalyst seems to be caused by the lower concentration of NO_2 molecules, which easily reduce to NO.

3.4. *Corona discharge processing with NH_3-free catalyst and gaseous NH_3 (400 ppm) supply*

When 400 ppm of NH_3 was introduced into the reactor with NH_3-free catalyst globules, removal of NO and NO_x increased up to 75% at energy density of 450 J/l (Figs. 2 and 3). Like in the case without catalyst, NH_3 in the working gas caused absence of NO_2 in the outlet gas due to reactions (5) and (6). Consumption of NH_3 in the processing increased with increasing energy density and reached 60% at 290 J/l (Fig. 4).

We believe that the dominant mechanisms of NO, NO_2 and NH_3 removal remain those described by reactions (5)–(9). However, the observed increase of removal efficiency of NO, NO_2 and NH_3 may be attributed to the cumulative effect of plasma enhanced reactions in gas volume, adsorption of certain gaseous compounds on the catalyst surface and reactions with these adsorbed compounds.

The importance of reactions (5) and (6) in the plasma-chemistry kinetics in the reactor with NH_3-free catalyst in the presence of NH_3 was confirmed by production of NH_4NO_3 particles [according to reaction (7)], which deposited in the form of solids on the catalyst globules and

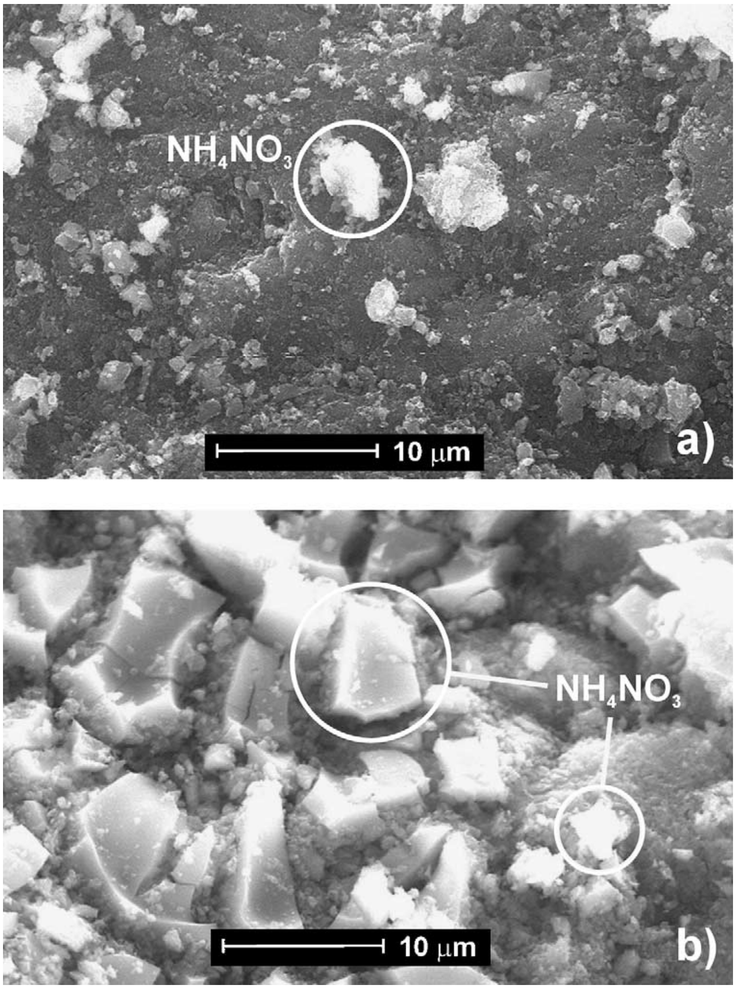

Fig. 5. SEM images of the catalyst surface, (a) after short-time (5 min) processing with NH_3-free catalyst and gaseous NH_3 (400 ppm) supply; and (b) after long-time processing (67 h) with NH_3-saturated catalyst and NH_3 (30 ppm) supply. Magnification: 2000×. Irregular and crystal forms of NH_4NO_3 are clearly present on the catalyst surface.

the reactor wall. An image of the catalyst surface taken using scanning electron microscopy (SEM) after short-time corona processing (5 min) is presented in Fig. 5a. As it can be seen, the number of NH_4NO_3 solid deposits on the catalyst surface was relatively low. The NH_4NO_3 solids had the form of irregular conglomerates (like incipient crystals), the size of which is approximately 5 μm. However, after longer time of the processing the catalyst surface became considerably deteriorated with NH_4NO_3 deposits, which resulted in a progressive decrease of NO removal. Eventually, the deteriorated catalyst surface stopped acting as a catalyst.

3.5. Corona discharge processing with NH_3-saturated catalyst without gaseous NH_3 supply

When the catalyst saturated with NH_3 without any additional supply of gaseous NH_3 was used, removal of NO and NO_x increased to 96% (Figs. 2 and 3). NO_2 molecules were not present in the outlet gas, which, however, contained 2 ppm of NH_3. This NH_3 slip was formed by those NH_3 molecules, which released from the catalyst surface and were not consumed in reactions (7)–(9).

The very high efficiency of NO (and NO_x) removal recorded in this case suggests that the surface reactions with adsorbed compounds are very efficient when the interaction of the corona discharge with the NH_3-saturated catalyst takes place.

The high NO (and NO_x) removal and relatively low discharge power resulted in a high energy yield of the NO removal process. At NO removal efficiency of 96% and discharge power of 4.8 W the energy yield was 3.4 g NO/kWh (Table 2). This is superior to the other cases tested in this experiment (Table 1). However, better results were obtained in other hybrid plasma-catalyst [13] and CRS systems [9].

The number and shape of NH_4NO_3 solids deposited on the catalyst surface are similar to those in Fig. 5a, which corresponds to the case of NH_3-free catalyst and gaseous NH_3 supply.

After some time, the NH_3-saturated catalyst started to loose its properties due to either NH_3 depletion on the

Table 2
Parameters of NO_x removal processing in the hybrid corona discharge-catalyst reactor

Processing	Discharge voltage (kV)	Discharge power (W)	Removal efficiency (%)	Energy yield (g NO/kWh)
Without catalyst and gaseous NH_3 supply	34	6.8	25	0.7
Without catalyst, with gaseous NH_3 (400 ppm) supply	31	6.2	66	1.8
With NH_3-free catalyst, without gaseous NH_3 supply	32.5	6.5	40	1.0
With NH_3-free catalyst and gaseous NH_3 (400 ppm) supply	29	5.8	75	2.2
With NH_3-saturated catalyst, without gaseous NH_3 supply	24	4.8	96	3.4

Flow rate: 1 l/min; corona discharge current: 200 μA.

catalyst surface or deterioration of the catalyst surface by NH_4NO_3 solids. This was investigated in the following experiment.

3.6. Temporal performance of the hybrid reactor

Fig. 6 illustrates temporal performance of the hybrid reactor for the following cases:

(a) processing without catalyst [without or with gaseous NH_3 (400 ppm) supply];
(b) processing with NH_3-free catalyst [without gaseous NH_3 (400 ppm) supply];
(c) processing with NH_3-saturated catalyst [without or with gaseous NH_3 (30 ppm) supply].

In all the cases the discharge current was fixed at 100 μA.

As expected, NO concentration at the reactor outlet remained constant when the working gas processing was carried out either without catalyst or with NH_3-free catalyst without gaseous NH_3 supply.

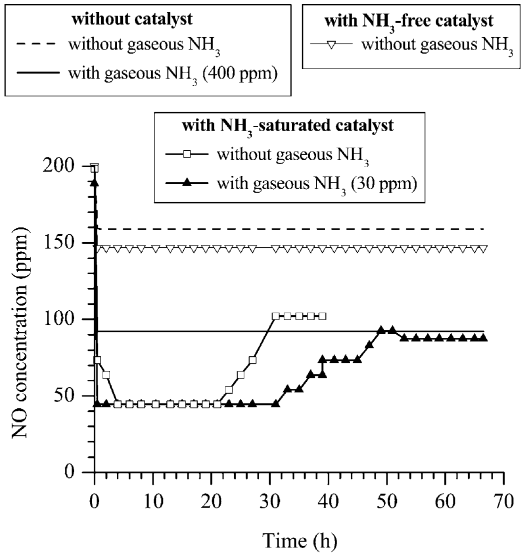

Fig. 6. Time dependence of NO concentration in the working gas at the reactor outlet. Corona discharge current 100 μA. Cases: (a) processing without catalyst [without or with gaseous NH_3 (400 ppm) supply]; (b) processing with NH_3-free catalyst [without gaseous NH_3 (400 ppm) supply]; and (c) processing with NH_3-saturated catalyst [without or with gaseous NH_3 (30 ppm) supply].

When the NH_3-saturated catalyst without gaseous NH_3 supply was used, NO (and NO_x) removal efficiency was relatively high (78% at a discharge current of 100 μA) and remained constant over the first 20 h. After that time, the NH_3-saturated catalyst started to loose its activity and NO removal efficiency decreased. After the next 10 h, the NO removal efficiency remained steady at a level corresponding to the corona discharge processing without catalyst but with gaseous NH_3 (400 ppm) supply.

When the corona discharge processing was performed in the presence of NH_3-saturated catalyst with gaseous NH_3 (30 ppm) supply, NO removal efficiency was equal to that without gaseous NH_3 supply (78%) but it remained constant longer (during about 30 h). After that time the catalyst lost its activity. As a result, NO removal efficiency started to decrease and NO concentration increased during the next 20 h until it leveled at a concentration typical of the processing without catalyst but with gaseous NH_3 (400 ppm) supply. After leveling at a time of 50 h, the performance of the hybrid reactor became unchanged over the next 20 h.

Without additional gaseous NH_3 supply catalyst lost its activity 10 h earlier then in the case with gaseous NH_3 (30 ppm) supply (Fig. 6). It proves that during corona discharge processing NH_3 molecules are released from the NH_3-saturated catalyst surface.

The significant changes of the catalyst surface due to NH_4NO_3 deposits after 67 h corona discharge processing were revealed by scanning electron microscopy (SEM) imaging (Fig. 5b). The catalyst surface exposed to the corona discharge was almost completely covered with NH_4NO_3 solids, which formed relatively large crystals.

Taking the above into consideration, we conclude that the NH_3-saturated catalyst (without or with gaseous NH_3 supply) lost its activity not due to releasing NH_3 from its surface but due to NH_4NO_3 deposits. The surface-deteriorated catalyst still was able to release NH_3 molecules enough to remove NO molecules on a level typical of processing with gaseous NH_3 (400 ppm) supply.

From the weight balance analysis of the NH_3 and NH_4NO_3 carried out after long-time processing [NH_3-saturated catalyst with gaseous NH_3 (30 ppm) supply], we found that only a small fraction of NO and NO_2 was transformed into NH_4NO_3, according to reaction (7). This resulted from a small quantity of NH_4NO_3 solids weighted after the processing, compared to that predicted by Eqs. (7)–(9), if they were the only pathway of NO and NO_2 removal. This may mean that part of NO and NO_2 are reduced into molecular nitrogen via other reactions related to the presence of ammonia.

4. Summary and conclusions

In this paper results of investigation of the performance of a hybrid corona discharge-catalyst reactor to be used for NO_x removal from the flue gases are presented. The catalyst was a layer of V_2O_5 and TiO_2 deposited on Al_2O_3 globules. The gas mixture, which simulated a flue gas, was N_2 (80%):O_2 (5%):CO_2 (15%):NO (200 ppm). The corona discharge processing of the gas mixture was carried out: without catalyst, with NH_3-free catalyst, and with NH_3-saturated catalyst, all either without or with gaseous NH_3 supply.

The investigation showed that:

- The catalyst increased significantly NO_x removal efficiency. The highest NO_x removal (96% at energy density of 400 J/l) was observed when the catalyst was saturated with NH_3 [case without gaseous NH_3 (30 ppm) supply].
- In the presence of NH_3, the corona discharge produced solid particles of NH_4NO_3 which depositing on the catalyst surface shortened the active life of the catalyst (poisoning of the catalyst). The life-time of the catalyst due to its poisoning was about 30 h.
- NO_x removal energy yield in the presented reactor with NH_3-saturated catalyst without additional gaseous NH_3 supply is up to 3.4 g/kWh (at 96% of NO_x removal) compared to 1.8 g/kWh in the “pure” corona discharge processing with gaseous NH_3 (400 ppm) supply.
- The hybrid reactor with NH_3-saturated catalyst operated efficiently over 30 h without additional gaseous NH_3 supply.

The obtained results showed that the proposed hybrid reactor consisted of the corona discharge and NH_3-saturated catalyst is attractive for NO_x removal and may be alternative to other non-thermal plasma methods used for NO_x removal. The processes which occur when the corona discharge interacts with NH_3-saturated catalyst are not known and need further investigation the results of which may improve performance of the presented reactor.

References

[1] J.S. Chang, in: B.M. Penetrante, S.E. Schultheis (Eds.), Non-thermal Plasma Techniques for Pollution Control, vol. G 34 (A), Springer-Verlag, Heidelberg, Berlin, NATO ASI Series, 1993, pp. 1–32.
[2] E.M. Van Veldhuizen, Electrical Discharges for Environmental Purposes, Nova Science Publishers, New York, 2000.
[3] K. Yan, E. van Heesch, A. Pemen, P. Huijbrechts, F. van Gompel, H. van Leuken, Z. Matyas, IEEE Trans. Ind. Appl. 38 (2002) 866–872.
[4] Y.H. Song, W.H. Shin, Y.S. Choi, S.J. Kim, G.H. Chang, in: Proceedings of the Second International Symposium on Non-thermal Plasma Technology for Gaseous Pollution Control, Salvador, Brazil, 1997, pp. 9–12.
[5] A. Mizuno, K. Shimizu, T. Matsuoka, S. Furuta, IEEE Trans. Ind. Appl. 31 (1995) 1463–1467.
[6] G. Dinelli, L. Civitano, M. Rea, IEEE Trans. Ind. Appl. 26 (1990) 535–541.
[7] K. Onda, K. Kato, Y. Kasuga, JSME Int. J. Ser. B 39 (1996) 202–210.
[8] T. Ohkubo, S. Kanazawa, Y. Nomoto, J.S. Chang, T. Adachi, IEEE Trans. Ind. Appl. 30 (1994) 856–860.
[9] J.Y. Park, I. Tomicic, G.F. Round, J.S. Chang, J. Phys. D: Appl. Phys. 32 (1999) 1006–1011.
[10] K. Onda, K. Kato, Y. Kasuga, JSME Int. J. Ser. B 39 (1996) 202–210.
[11] H.H. Kim, K. Takashima, S. Katsura, A. Mizuno, J. Phys. D: Appl. Phys. 34 (2001) 604–613.
[12] T. Hammer, S. Broer, Plasma enhanced selective catalytic reduction of NO_x for diesel cars, Society of Automotive Engineers Technical Paper Series No. 982428, 1998.
[13] T. Hammer, S. Broer, Plasma enhanced selective catalytic reduction of NO_x in diesel exhaust: test bench measurements, Society of Automotive Engineers Technical Paper Series No. 1999-01-3633.
[14] A.K. Hjalmarsson, Int. J. Ener. Res. 14 (1990) 813–820.
[15] J.S. Chang, J. Aerosol. Sci. 20 (1989) 1087–1090.
[16] H. Suhr, G. Weddigen, Combust. Sci. Technol. 72 (1990) 101–115.
[17] K. Shimizu, T. Oda, IEEE Trans. Ind. Appl. 35 (1999) 1311–1318.
[18] T. Oda, T. Kato, T. Takahashi, K. Shimizu, J. Electrostat. 42 (1997) 151–157.
[19] T. Yamamoto, C.-L. Yang, M.R. Beltran, Z. Kravets, IEEE Industrial Application Society Annual Meeting, New Orleans, USA, 1997, pp. 1956–1960.
[20] T. Kawasaki, S. Kanazawa, T. Ohkubo, J. Mizeraczyk, Y. Nomoto, Thin Solid Films 386 (2001) 177–182.
[21] B.S. Rajanikanth, S. Rout, Fuel Process. Technol. 74 (2001) 177–195.
[22] J. Mizeraczyk, M. Dors, G.V. Nichipor, J. Adv. Oxid. Technol. 4 (1999) 380–385.