



---

All Faculty Publications

---

2005-06-01

# The Effect of Reactor Configuration on NO Conversion and Energy Consumption in Non-thermal Plasma Parallel Tube Reactors

Morris D. Argyle  
mdargyle@byu.edu

Gui-Bing Zhao

*See next page for additional authors*

Follow this and additional works at: <https://scholarsarchive.byu.edu/facpub>

 Part of the [Chemical Engineering Commons](#)

## Original Publication Citation

G.B. Zhao, S.V.B.J. Garikipati, X. Hu, M.D. Argyle, M. Radosz, "The Effect of Reactor Configuration on NO Conversion and Energy Consumption in Non-thermal Plasma Parallel Tube Reactors." *AIChE Journal*, 51, 18-1812, 25.

---

## BYU ScholarsArchive Citation

Argyle, Morris D.; Zhao, Gui-Bing; Garikipati, S.V.B. Janardhan; Hu, Xudong; and Radosz, Maciej, "The Effect of Reactor Configuration on NO Conversion and Energy Consumption in Non-thermal Plasma Parallel Tube Reactors" (2005). *All Faculty Publications*. 378.

<https://scholarsarchive.byu.edu/facpub/378>

---

**Authors**

Morris D. Argyle, Gui-Bing Zhao, S.V.B. Janardhan Garikipati, Xudong Hu, and Maciej Radosz

# The Effect of Reactor Configuration on NO Conversion and Energy Consumption in Non-thermal Plasma Parallel Tube Reactors

Gui-Bing Zhao, S.V.B.Janardhan Garikipati, Xudong Hu, Morris D. Argyle, Maciej Radosz\*

*Department of Chemical & Petroleum Engineering, University of Wyoming, Laramie, WY  
82071-3295, USA*

## Abstract

This work shows that the configuration of a pulsed corona discharge reactor strongly affects the rate of electron collision reactions. Experiments involving the decomposition of NO in N<sub>2</sub> were performed in a reactor in which the number of parallel reactor tubes varied from 1 to 10 at a constant pressure of 147.6 kPa and ambient temperature. A previously developed lumped model of the reactions accurately predicted the effects of varying the initial concentrations of NO (from 240ppm to 593ppm) and gas residence time (from 1.93 to 7.42 s). With an increasing number of parallel reactor tubes, the rate of electron collision reactions decreases because the energy input per unit reactor volume at unit time decreases, while the energy consumption per molecule of NO converted to N<sub>2</sub> and O<sub>2</sub> decreases due to electrical and geometric effects associated with the decreasing peak width of the discharge voltage pulses and increasing reactor capacitance. Therefore, increasing the number of parallel reactor tubes provides a viable scale-up method for constructing more efficient pulsed corona discharge reactors.

Will be submitted to *AICHE J.*

---

\* Corresponding author. E-mail: [radosz@uwyo.edu](mailto:radosz@uwyo.edu), tel: 307-766-2500, fax: 307-766-6777

## Introduction

The conversion of nitrogen oxides ( $\text{NO}_x$ ) into elemental oxygen and nitrogen has become a central scientific concern because of the key role of  $\text{NO}_x$  in many global environmental problems, such as acid rain, photochemical smog formation and the greenhouse effect. These environmental concerns have resulted in considerable political pressure for the adoption of increasingly stringent  $\text{NO}_x$  emission standards. Among the emerging technologies for  $\text{NO}_x$  decomposition, non-thermal plasma is one of the most promising. A pulsed corona discharge reactor (PCDR) is a non-thermal plasma technology characterized by low gas temperature and high electron temperature achieved by producing high energy electrons in the gas while leaving the bulk temperature of the gas unchanged. A PCDR utilizes a high-voltage, short-duration ( $< 100$  ns) electrical discharge between non-uniform electrodes to produce streamers through the growth of electron avalanches formed by electron collision ionization events in the gas (Raether, 1964). A streamer is a region of highly ionized gas where a wide range of active radicals and chemical species are formed through electron collision reactions with the background gas. These active species, in turn, initiate bulk phase reactions that lead to  $\text{NO}_x$  conversion.

A critical issue in the use of plasma reactors for the treatment of  $\text{NO}_x$  is the energy consumption. The reported energy costs of using non-thermal plasmas for  $\text{NO}_x$  conversion vary considerably — for example, from 70 to 780 eV/molecule (Yamamoto et al., 2000). These conversions are characterized by low energy efficiency because N atoms, which are one of the main active species responsible for  $\text{NO}_x$  conversion, can be formed from  $\text{N}_2$  dissociation at a low dissociation energy of 9.8 eV. One of the primary factors affecting energy consumption of  $\text{NO}_x$  conversion in non-thermal plasma reactors is the reactor configuration. Although many investigators, including Tas et al. (1997), Puchkarev and Gundersen (1997) and Yan et al.

(2001), have recognized that reactor design is an important parameter for reducing energy cost in the conversion of NO using non-thermal plasma reactors, relatively few reports in the literature discuss reactor optimization. McLarnon and Penetrante (1998) investigated the effect of packing materials, voltage frequencies and electrode diameter on NO conversion in N<sub>2</sub> using a co-axial wire cylinder dielectric-barrier discharge reactor. They observed that reactor design had no substantial effect on energy consumption. Penetrante et al. (1995) investigated and compared the electrical energy consumption of three different kinds of non-thermal plasma reactors: pulsed corona, dielectric-barrier discharge and dielectric pellet bed reactors. They observed that the radical production efficiency in these reactors cannot be enhanced by varying the voltage pulse parameters, using a dielectric barrier, adding a dielectric packing or changing the electrode structure. The measured energy consumption was 240 eV per NO molecule in their experiments. Namihira et al. (2001) investigated the influence of reactor length on NO removal using a PCDR. They found that the energy efficiencies of both NO and NO<sub>x</sub> decomposition slightly increase with reactor length, but are not strongly dependent on it. Recently, Zhao et al. (2004b) investigated the effects of series and parallel operation of multiple PCDRs on energy consumption during N<sub>2</sub>O conversion. They found that series reactors are more energy efficient than a single reactor and parallel reactors.

For industrial applications of PCDRs, an important issue is scale-up in order to achieve maximum NO<sub>x</sub> conversion efficiency at minimum energy consumption. The scale-up of conventional reactors can generally be achieved by simply enlarging the reactor. For non-thermal plasma reactors, like the PCDR, the reactor would cease to operate if the reactor size were increased by increasing tube diameter because the electrical discharge would no longer occur unless the voltage was increased. The only practical way to scale up a PCDR is to increase the

number of parallel reactor tubes, which may change the rate of electron collision reactions and affect the energy efficiency of  $\text{NO}_x$  conversion. However, no detailed studies have been conducted to explore these issues. The goal of this work is to understand the effect of the number of parallel reactor tubes used in a PCDR on electrical discharge, the rate of electron collision reactions and energy consumption using the reaction system of NO in  $\text{N}_2$ .

## Experimental

The pulsed corona discharge reactor used in this work consisted of a high-voltage power supply with a control unit and the pulser/reactor assembly, as explained in detail by Hu et al. (2002). The high voltage controller contained the electronic and gas controls required to regulate the high voltage charging power supply as well as the pulsed power delivered to the reactor gas. The charging capacitance,  $C_P$ , is fixed at 800 pF. The pulser/reactor assembly contained the pulsed power generator and the pulsed corona discharge reaction chambers. The reactor had ten parallel reaction tubes, each 914 mm in length and 23 mm in diameter, with a stainless steel wire, 0.58 mm in diameter, passing axially through the center of each tube. The wire was positively charged, and the tube was grounded. The gas flowing through the reactor tube was converted to plasma by high voltage discharge from the reactor anodes. One tube was fitted with UV-grade quartz windows for diagnostics and plasma observation. The number of parallel-reactor tubes used in a given experiment was varied by installing a wire in the center of each active tube and sealing the unused tubes with Teflon corks with O-rings. The corona power per pulse was calculated from the product of the measured pulse voltage (V) and current (I). The energy delivered to the reactor per pulse is the time integral of power ( $\int VIdt$ ). The power consumed, W, was calculated as the product of the input energy per pulse and the pulse frequency. The system

design permitted variation and measurement of applied voltage and its frequency, reactor current and reactor voltage.

The experimental test matrix is shown in Table 1. The test gas mixture of NO in N<sub>2</sub> was introduced into the PCDR at ambient temperature, around 300K, and at constant pressure, 147.6 kPa. The gas samples were collected from a common header at the discharge end of the PCDR in small stainless steel cylinders and analyzed for stable species using a Spectrum 2000 Perkin-Elmer Fourier transform infrared spectrometer with a narrow-band mercury cadmium telluride detector.

The energy consumption analysis of the PCDR was one of the main tasks in this work. The voltage and current pulses were the source of energy for the gas. For these experiments, the energy per pulse was about 0.192 J. As found previously by Zhao et al. (2004a), NO<sub>2</sub> and N<sub>2</sub>O are formed as byproducts when NO is converted in N<sub>2</sub>. Therefore, total NO<sub>x</sub> conversion was calculated, rather than NO conversion, because total NO<sub>x</sub> conversion reflects the degree of direct decomposition of NO into N<sub>2</sub> and O<sub>2</sub>. The total NO<sub>x</sub> conversion was defined as the amount of NO converted to N<sub>2</sub>, as follows:



$$X_{N_2} = \frac{C_{i,\text{NO}} - C_{o,\text{NO}} - C_{o,\text{NO}_2} - 2 \times C_{o,\text{N}_2\text{O}}}{C_{i,\text{NO}}} \times 100\% \quad (2)$$

The corresponding energy consumption,  $En$ , in eV per NO molecule converted to benign gases (N<sub>2</sub> and O<sub>2</sub>) is expressed below in terms of total NO<sub>x</sub> conversion:

$$En = \frac{W}{C_{i,\text{NO}} \cdot X_{N_2} \cdot F} \times 1.0364 \times 10^{-5} \quad (3)$$

In these equations,  $C_i$  is the concentration at the reactor inlet ( $\text{mol/m}^3$ ),  $C_o$  is the concentration at the reactor outlet ( $\text{mol/m}^3$ ),  $X_{\text{N}_2}$  is the total conversion of NO to  $\text{N}_2$ ,  $W$  is power input ( $\text{J/s}$ ),  $F$  is flow rate ( $\text{m}^3/\text{s}$ ), and  $1.0364 \times 10^{-5}$  is the conversion factor for  $\text{J/mol}$  to  $\text{eV/molecule}$ .

## Mathematical Model

The pulsed corona discharge reactor described above was represented using a lumped kinetic model that describes the evolution of all species. The model details have been reported elsewhere (Zhao et al. 2004c), and only a brief introduction is presented here. This model includes three main assumptions. (1) Electron-impact reactions occur during the entire residence time, both the pulse-on period and the pulse-off period, and thus the model represents a time average of the reactions. (2) The distribution function for electron velocity is Maxwellian. The rate constant for the electron-impact reaction  $A + e \rightarrow B$  can then be expressed as:

$$k[e] = \beta \sqrt{\frac{1}{\alpha P}} W^{0.75} \exp\left(-\frac{\alpha P}{W}\right) \quad (4)$$

where  $P$  is the system pressure,  $W$  is the power input and  $\alpha$  and  $\beta$  are constants of proportionality. (3) Axial dispersion is negligible, and hence the gas flow can be considered as plug flow.

On the basis of these assumptions, a set of lumped model equations, including both electron-impact reactions and subsequent bulk reactions, were developed:



$$\left\{ \begin{array}{l} \frac{dC_1}{dt} = \sum_{j=1}^M \phi_{1j} \cdot r_j = g_1(C_1, C_2, \dots, C_m; \alpha_1, \beta_1, \dots, \alpha_n, \beta_n; W_k) \\ \frac{dC_2}{dt} = \sum_{j=1}^M \phi_{2j} \cdot r_j = g_2(C_1, C_2, \dots, C_m; \alpha_1, \beta_1, \dots, \alpha_n, \beta_n; W_k) \\ \dots \dots \dots \dots \dots \\ \frac{dC_m}{dt} = \sum_{j=1}^M \phi_{mj} \cdot r_j = g_m(C_1, C_2, \dots, C_m; \alpha_1, \beta_1, \dots, \alpha_n, \beta_n; W_k) \end{array} \right. \quad (k = 1, 2, \dots, L) \quad (5)$$

where  $C_i$  is the concentration of species  $i$  ( $i = 1, 2, \dots, m$ );  $t$  is time;  $M$  is the total number of reactions occurring in the PCDR including electron-impact reactions and subsequent bulk reactions;  $\phi_{ij}$  is the stoichiometric coefficient of the  $i$ -th species in the  $j$ -th reaction;  $r_j$  is the reaction rate of the  $j$ -th reaction ( $j = 1, 2, \dots, M$ );  $n$  is the number of electron-impact reactions;  $\alpha_j$  and  $\beta_j$  represent the model parameters for the  $j$ -th electron-impact reaction as shown in Equation (4); and  $W_k$  ( $k = 1, 2, \dots, L$ ) is the power input for the  $k$ -th experiment. Each experiment corresponds to a different concentration distribution in the reactor due to different power input. The model parameters  $\alpha$  and  $\beta$  for electron-impact reactions were determined from experimental data using an optimization method proposed by Zhao et al. (2004c). On the basis of the prior work (Zhao et al., 2004a; Zhao et al., 2004c), a total of 20 reactions with two electron collision reactions, shown in Table 2, were selected to simulate the system of NO in N<sub>2</sub>.

## Results and Discussion

### *The effect of the number of parallel reactor tubes on corona discharge*

The important initiating reactions in the corona discharge are due to the collisions of the energetic electrons produced by the electrical discharge with gas molecules in the reactor. Therefore, the rate of electron collision reactions directly determines the rate of NO<sub>x</sub> conversion.

The fingerprint of the electron collision reactions in the PCDR is the discharge voltage versus the time plot (waveform), which characterizes the properties of the streamers around the discharge wire. The main parameters that influence the properties of the streamers are the rise rate, pulse width and the peak value of the applied voltage (Hackam and Akiyama, 2000; van Veldhuizen et al., 1990; Creighton et al., 1991a; 1991b).

Figure 1 shows the discharge voltage waveforms for different numbers of parallel reactor tubes at 200Hz and 147.6kPa. The discharge voltage waveforms can be divided into two sections. The first section is the initial peak, where the discharge voltage increases from zero to a maximum and then decreases back to zero. Approximately 99% of the total energy to the PCDR is delivered in this first section, which corresponds to the energy dissipated for streamer propagation. The second section is the subsequent fluctuations of discharge voltage, which corresponds to the energy dissipated after streamer propagation. As discussed by Mok et al. (1998b), the second section of the energy input produces only slow electrons that do not contribute to the formation of active species because the energy delivered after streamer propagation is mainly used to sustain the low conductivity streamer channel and produce secondary streamers. Therefore, the important characteristics of the discharge streamer can be described by the first section of the discharge voltage. The important parameters of the first peak are the rise rate, pulse width and peak value of the applied voltage, which are shown in Table 3 for the different reactor configurations. These results show that pulse peak value and rise rate are not affected by the number of parallel reactor tubes. However, the pulse width decreases as the number of parallel reactor tubes increases. The pulse width is an important parameter that characterizes the energy efficiency of plasma chemical reactions. Generally, short pulses are

more economical in energy cost than longer pulses (Puchkarev and Gundersen, 1997; Hackam and Akiyama, 2000).

***The effect of initial NO concentration and gas residence time on model parameters***

Previous studies (Zhao et al., 2004c) using a four-tube reactor showed that the lumped model accurately predicts the effect of the inlet concentration of NO ranging from 593 ppm to 614 ppm and the effect of gas residence time ranging from 3.63 s to 7.06 s for the reaction system of NO in N<sub>2</sub>. In this work, we extended the range of experimental conditions. For example, the inlet concentration of NO varied from 593 ppm to 240 ppm and gas residence time varied from 1.93 s to 7.42 s to further verify the validity of the lumped model. If the lumped model accurately reflects the effect of the initial NO concentration and gas residence time, only one set of experimental data may be used to obtain the model parameters  $\alpha$  and  $\beta$  for electron collision reactions R1 and R2. These values of  $\alpha$  and  $\beta$  can then be used to model the energy consumption of NO decomposition at different initial NO concentrations and gas residence times for any number of parallel reactor tubes used.

Using the optimization method developed previously (Zhao et al., 2004c), the experimental data with an initial NO concentration of 595 ppm in N<sub>2</sub> in a one-tube reactor determined the model parameters  $\alpha$  and  $\beta$  for the electron collision reactions R1 and R2. The following model parameters were obtained:

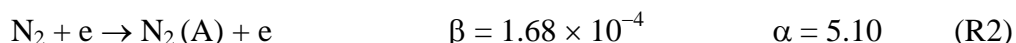
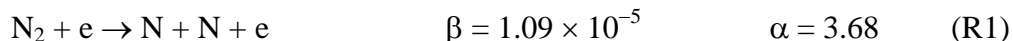


Figure 2(a) shows the experimental and correlated values of NO<sub>x</sub> at the reactor outlet. The calculated curves reasonably represent the experimental data. The same parameters were used to

predict the experimental concentrations of all species for the inlet concentration of 240 ppm NO in N<sub>2</sub>, as shown in Figure 2(b). Although the N<sub>2</sub>O fit is not precise due to the low concentration of N<sub>2</sub>O, the model accurately predicts the maximum. The prediction of the trends in NO<sub>x</sub> evolution for the experiment with 240 ppm NO in N<sub>2</sub> using the model parameters developed from the experiment with 595 ppm NO in N<sub>2</sub> shows that the lumped model captures the effect of varying the initial NO concentrations.

Using the optimization method developed previously (Zhao et al., 2004c), the experimental data at the gas flow rate of  $1.024 \times 10^{-4}$  m<sup>3</sup>/s in a two-tube reactor (corresponding to gas residence time of 7.42 s) are used to determine the model parameters  $\alpha$  and  $\beta$  of electron collision reactions R1 and R2. The following model parameters were obtained:

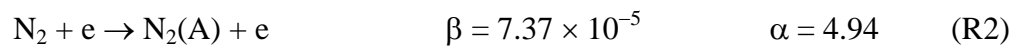
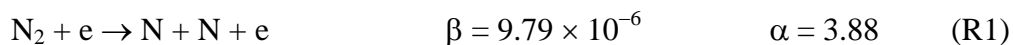


Figure 3(a) shows the experimental and correlated values of NO<sub>x</sub> at the reactor outlet. The calculated curves again reasonably represent the experimental data. The same parameters were used to predict the experimental results for two other flow rates,  $2.191 \times 10^{-4}$  m<sup>3</sup>/s and  $3.943 \times 10^{-4}$  m<sup>3</sup>/s, which correspond to gas residence times of 3.47 s and 1.93 s, respectively. Figures 3(b) and 3(c) show the experimental and predicted values for these two different flow rates. The reasonable prediction of NO<sub>x</sub> evolution for different gas residence times using one set of parameters shows that the lumped model captures the effect of varying gas residence times and proves that the assumption of plug flow in the lumped model is valid.

***The effect of the number of parallel reactor tubes on the rates of electron collision reactions***

Because the pulse widths decrease with an increasing number of parallel reactor tubes (Table 3), it appears that the number of parallel reactor tubes affects the rate of electron collision reactions. The important model parameters embodying the rate of electron collision reactions are  $\alpha$  and  $\beta$ , as shown in Eq.(4). The method used to determine the model parameters of electron collision reactions R1 and R2 for one- and two-tube reactors was discussed previously. The same method (Zhao et al., 2004c) was used to determine model parameters of the electron collision reactions R1 and R2 for four-, six-, eight- and ten-tube reactors. Figure 4 shows the experimental data and the correlated data for NO, NO<sub>2</sub> and N<sub>2</sub>O concentrations at the reactor outlet. The similarity of the experimental data and the correlated data indicates that model parameters  $\alpha$  and  $\beta$  of R1 and R2 characterize the kinetics of electron collision reactions.

Figures 2-4 show that there are always maximums in NO<sub>2</sub> and N<sub>2</sub>O concentrations for a range of different initial concentrations of NO, gas residence times and the number of parallel reactor tubes, as shown in Table 1. The evolution of NO concentration is the result of two processes: a reduction process (reaction R3 in Table 2) and an oxidation process (reaction R4). As corona power input increases, more NO<sub>2</sub> is generated by reaction R4, which then leads to an increase in the rate of the NO<sub>2</sub> conversion reactions R5-R9 and R12. As a result, NO<sub>2</sub> evolution reaches a maximum. N<sub>2</sub>O is formed from reaction R5. N<sub>2</sub>(A), which is the first excited electronic state of nitrogen, is the only active species responsible for N<sub>2</sub>O conversion, through reaction R11 (Zhao et al., 2004a). However, before NO is completely converted, N<sub>2</sub>(A) begins to be quenched by reaction R10 because its rate constant is 10 times higher than the rate constant of reaction R11. Therefore, the N<sub>2</sub>O concentration increases with an increasing power input before NO is completely converted. After NO is completely converted, N<sub>2</sub>O is converted by reacting with N<sub>2</sub>(A), which leads to the maximum N<sub>2</sub>O concentration. At a higher power input, as shown in

Figures 2(b), 3(a), 4(b) and 4(c), the  $\text{N}_2\text{O}$  concentration reaches a stable value and cannot be further converted because the  $\text{O}_2$ , N and O formed from the complete conversion of NO and  $\text{NO}_2$  strongly quench the active species  $\text{N}_2(\text{A})$  through reactions R13-R17, as shown in Table 2. However, an important finding is that the maximum  $\text{NO}_2$  concentration, the maximum  $\text{N}_2\text{O}$  concentration and the beginning of the constant value of  $\text{N}_2\text{O}$  concentration occurs at the same values of NO conversion ( $30.9\% \pm 2\%$ ,  $88.6\% \pm 3\%$  and  $98.5\% \pm 0.5\%$ , respectively) independent of the initial concentration of NO, gas residence time and the number of parallel reactor tubes used. This observation suggests that the reaction mechanism is unaffected by the varying experimental parameters and further confirms that the lumped model is capable of representing the NO/ $\text{N}_2$  system as described below.

Figure 5 shows the effect of the number of parallel reactor tubes on the model parameters for the two electron collision reactions R1 and R2. Previous work (Zhao et al., 2004c; Hu et al., 2003) has shown that the model parameter  $\beta$  includes the reactor and electrode geometry effects. For reaction R1,  $\beta$  decreases as the number of parallel reactor tubes increases. For reaction R2,  $\beta$  initially decreases but remains constant at higher tube numbers. This confirms the previous conjecture that  $\beta$  mainly depends on the reactor configuration. The model parameter  $\alpha$  depends on the threshold ionization potential of the reactant gases (Zhao et al., 2004c; Hu et al., 2003) and therefore, is almost independent of the number of parallel reactor tubes for the two electron collision reactions.

Figure 6 shows the variation of the rate constants of the electron collision reactions R1 and R2 as a function of the power input for different numbers of parallel reactor tubes. The rate constant of the electron collision reaction R1 decreases as the number of parallel reactor tubes increases at the same power input. The rate constant of the electron collision reaction R2 initially decreases

as the number of parallel reactor tubes increases from one to four, and then reaches a stable value when there are more than six reactor tubes for a given power input. This confirms the previous conjecture that rate of electron collision reactions is reactor configuration dependent (Hu et al., 2003; Zhao et al., 2004c). As shown in Eq.(4), the rate constant of electron collision reactions is governed by power input. The energy input to a unit reactor volume at unit time decreases with an increasing number of parallel reactor tubes, which explains why the rate of the electron collision reactions R1 and R2 decreases with the parallel reactor tube number at the same power input, as shown in Figure 6.

### ***The effect of gas residence time and power input on energy consumption***

The previous section shows that the lumped model captures the effect of the initial concentration of NO and gas residence time over the experimental range considered in this study. Also, the section on the rate of electron collision reactions shows that the model correlates well with the experimental results for the different reactor configurations achieved by changing model parameter  $\beta$ . Therefore, the lumped model can be used to investigate the conversion of NO and its energy consumption at different power inputs, initial NO concentrations and gas residence times. However, for convenience of comparison, a reaction system with the same initial concentration of ~600 ppm NO in N<sub>2</sub> was studied.

Figure 7 shows 3-dimensional plots of the conversion of NO (Figure 7(a)) and energy consumption (Figure 7(b)) as functions of power input and residence time for a four-tube reactor. Other reactor configurations generate similar plots. The model parameters  $\alpha$  and  $\beta$  (shown in Figure 5) for the electron collision reactions R1 and R2 were used in the calculation. The fraction of NO converted to benign N<sub>2</sub> and O<sub>2</sub> is used to define NO conversion and energy consumption,

as in Equations (2) and (3). Figure 7(a) shows that the conversion of NO reaches a constant value, around 98-99%, at higher power inputs and/or longer residence times because the byproduct N<sub>2</sub>O is not fully converted to benign N<sub>2</sub> and O<sub>2</sub> in the reactor, as discussed previously.

Before NO conversion reaches the constant value, the energy consumption weakly increases with gas residence time at the same power input, as shown in Figure 7(b). At a low power input, less than 5-10W, the energy consumption decreases quickly with an increasing power input at the same gas residence time. Before NO conversion reaches the plateau value at a high power input (> 5-10W), the energy consumption weakly increases with the power input at the same gas residence time, which is mainly due to the continuous formation of byproduct N<sub>2</sub>O through reaction R5. This indicates, as with N<sub>2</sub>O conversion (Zhao et al., 2004b), that an optimal power input corresponding to a minimal energy consumption exists for NO conversion at a given gas residence time. A similar conclusion can be drawn from the experimental data provided by Mizuno et al. (1995).

### ***The effect of reactor tube number on energy consumption***

The energy consumed depends on power input and residence time, both of which can be regulated to obtain optimum energy consumption for a particular reactor configuration. However, when the number of parallel reactor tubes changes, changing the reactor configuration, the energy efficiency also changes and hence, the energy consumption changes. Figure 8 shows the dependence of NO conversion (Figure 8(a)) and energy consumption (Figure 8(b)) on power input and the relation between energy consumption and NO conversion (Figure 8(c)) for different numbers of parallel reactor tubes at 147.6kPa pressure and 6 seconds of gas residence time (corresponding to a gas flow rate of  $6.33 \times 10^{-4} \text{ m}^3 \cdot \text{s}^{-1}$  for the one tube reactor) at the same



initial concentration of 600 ppm NO in N<sub>2</sub>. The model parameters  $\alpha$  and  $\beta$  (Figure 5) for electron collision reactions R1 and R2 were used in the calculation. NO conversion and the associated energy consumption were defined by Equations (2) and (3).

As shown in Figure 8(a), NO conversion increases with power and then reaches a stable value, consistent with Figure 7(a). However, with an increasing number of reactor tubes, NO conversion decreases for the same power input because the energy density decreases with the increase in reactor volume. With increasing power input, the energy consumption for NO conversion initially decreases quickly and then slowly increases, finally increasing linearly with power input, as shown in Figure 8(b). The final linear increase of energy consumption with power input is associated with the production of N<sub>2</sub>O, which cannot be converted into N<sub>2</sub> and O<sub>2</sub>, as explained previously. The results show that there is an optimal power input corresponding to a minimal energy consumption, which indicates that operating conditions of the PCDR can be optimized in order to decrease energy consumption. Figure 8(c) shows that energy consumption decreases with an increasing NO conversion at conversions below ~20%. At intermediate conversions, the energy consumption is constant or slightly increases with increasing conversion. The sharp increase in energy consumption at high NO conversion (98-99%) is caused by the difficulty of converting byproduct N<sub>2</sub>O. The minimum energy consumption per molecule of NO (~35 eV/molecule) for the ten-tube reactor is half of the lowest value reported previously (70 eV/molecule, (Yamamoto et al., 2000)). While this is still 3.6 times the theoretical minimum (9.8 eV/molecule for N<sub>2</sub> dissociation), ~35 eV/molecule is the most efficient value yet reported. Further, the minimum energy/molecule value is fairly insensitive to increasing conversion (e.g. ~50 eV/molecule at 98% NO conversion for the ten-tube reactor), which is again far superior to previous results.

Figures 8(b) and (c) show that at the same power input or the same NO conversion, the energy consumption of NO conversion decreases with an increasing number of parallel reactor tubes, which is shown explicitly in Figures 9(a) and (b). Figures 9(a) and (b) show the energy consumption during NO conversion as a function of the number of parallel reactor tubes for different gas residence times at a constant power input (15 W) and constant NO conversion (90%). The consistent conclusion is that the increase in parallel reactor tube number (reactor volume) decreases the energy consumption for NO conversion. This implies that the scale-up of a PCDR can be achieved by increasing the number of parallel reactor tubes. The energy efficiency is increased during the scale-up process as a result of two factors. First, as shown in Table 3, the pulse width of the initial discharge voltage peak decreases with an increasing number of parallel reactor tubes (Figure 1). Namihira et al. (2000) found that the energy required to convert NO decreased with a decreasing pulse width because the interaction time of energetic electrons and gas molecules and the acceleration time of ions during short pulses are less than that for long pulses. Therefore, less energy is dissipated as heat, which increases the energy efficiency of plasma chemical reactions for shorter pulse widths.

In addition, Uhm and Lee (1997) reported that the reactor capacitor plays a pivotal role for energy efficiency during NO conversion. Mok et al. (1998a) further found that when the pulse-forming capacitance (the capacitance of the charging capacitor, 800 pF for the reactors in our study) is five times larger than the geometric capacitance of the reactor, the energy utilization efficiency was maximized. Chung et al. (2000) observed the maximum NO conversion efficiency when the pulse-forming capacitance is 3.4 times larger than the reactor capacitance. This indicates that NO conversion efficiency can be achieved by applying a low ratio of the pulse-

forming capacitance to reactor capacitance, typically 3-5. The capacitance of a co-axial cylinder is defined as (Shin et al., 2000):

$$C = \frac{2\pi\epsilon_0 L}{\ln(R/r)} \quad (6)$$

where  $\epsilon_0$  is the permittivity of  $N_2$ ,  $l$  is the length of the reactor,  $R$  is the inner radius of the cathode (reactor tube) and  $r$  is the outer radius of the anode (central wire). Thus, one tube of the present reactor has a capacitance of 13.9 pF. The capacitance of multiple parallel co-axial cylinder capacitors ( $C_N$ ) is:

$$C_N = NC \quad (7)$$

where  $N$  is the number of parallel reactor tubes. Therefore, with an increasing number of parallel reactor tubes, the reactor capacitance increases, allowing the external circuit to deliver energy to the reactor more efficiently, which is another reason for the observed decrease in energy consumption with an increasing number of parallel reactor tubes. The ratio of the pulse-forming capacitance ( $C_P$ ) to reactor capacitance for our reactor configuration is:

$$\frac{C_P}{C_N} = \frac{800}{13.9N} = \frac{57.8}{N} \quad (8)$$

Therefore, by increasing the parallel reactor tube number from one to ten, the ratio of the pulse-forming capacitance to the reactor capacitance decreases from 57.8 to 5.78, which is close to the optimal ratio of the pulse-forming capacitance to reactor capacitance as presented by Mok et al. (1998a) and Chung et al. (2000).

## Conclusions

In this work, carefully designed experiments were conducted to investigate how the number of parallel reactor tubes affects the rate of electron collision reactions and energy efficiency for

NO conversion in N<sub>2</sub>. The pulse width of the initial discharge voltage peak decreases with an increasing number of parallel reactor tubes. The lumped model developed previously accurately models the effect of the initial concentration of NO and gas residence time, but it does not capture the effect of reactor configuration. Therefore, different model parameters are required for different reactor configurations. The rate of electron collision reaction decreases with an increasing number of parallel reactor tubes. The energy consumption of NO conversion weakly depends on gas residence time at a given power input. However, there is an optimal power input corresponding to a minimal energy consumption at a given gas residence time. The energy consumption during NO conversion decreases with increasing numbers of parallel reactor tubes at the same power input or at the same NO conversion. This indicates that the scale-up of PCDR can be achieved by increasing the number of parallel reactor tubes.

### **Acknowledgments**

This work was funded by the National Science Foundation (CTS – 9810040; CTS – 0078700) and the Department of Defense (ARO-DAAD19-01-1-0488). The matching support was provided by the Research Office, University of Wyoming. The authors also gratefully acknowledge experimental assistance provided by Dr. S. Legowski and Mr. R. Borgialli.

## References

- Raether H. Electron avalanches and breakdown in gases. Washington: Butterworths, 1964.
- Yamamoto T, Yang CL, Beltran MR, Kravets Z. Plasma-assisted chemical process for NO<sub>x</sub> control. *IEEE Transactions on Industry Applications*, **36**, 923, (2000).
- Tas MA, van Hardeveld R, van Veldhuizen EM. Reactions of NO in a positive streamer corona plasma. *Plasma Chemistry and Plasma Processing*. 1997; 17: 371.
- Puchkarev V, Gundersen M. Energy efficient plasma processing of gaseous emission using a short pulse discharge. *Applied Physics Letters*. 1997; 71: 3364.
- Yan K, Van Heesch EJM, Pemen AJM, Huijbrechts PAHJ. From chemical kinetics to streamer corona reactor and voltage pulse generator. *Plasma Chemistry and Plasma Processing*. 2001; 21: 107.
- McLarnon CR, Penetrante BM. Effect of reactor design on the plasma treatment of NO<sub>x</sub>. SAE Technical Paper Series 982434. 1998.
- Penetrante BM, Hsiao MC, Merritt BT, Vogtlin GE, Wallman PH. Comparison of electrical discharge techniques for nonthermal plasma processing of NO in N<sub>2</sub>. *IEEE Transactions on Plasma Science* 1995; 23: 679.
- Namihira T, Tsukamoto S, Wang D, Hori H, Katsuki S, Hackam R, Akiyama H, Shimizu M, Yokoyama K. Influence of gas flow rate and reactor length on NO removal using pulsed power. *IEEE Transactions on Plasma Science*, 2001; 29: 592.
- Zhao GB, Hu X, Plumb OA, Radosz M. Energy consumption and optimal reactor configuration for nonthermal plasma conversion of N<sub>2</sub>O in nitrogen and N<sub>2</sub>O in Argon. *Energy & Fuels* (submitted). 2004b.
- Hu X, Nicholas J, Zhang JJ, Linjewile TM, de Filippis P, Agarwal PK. The destruction of N<sub>2</sub>O in a pulsed corona discharge reactor. *Fuel*.2002: 81: 1259.
- Zhao GB, Hu X, Argyle MD, Radosz M. N atom and N<sub>2</sub>(A<sup>3</sup>Σ<sub>u</sub><sup>+</sup>) found to be responsible for nitrogen oxides conversion in non-thermal nitrogen plasma. *Ind. Eng. Chem. Res.* (submitted). 2004a.
- Zhao GB, Hu X, Yeung MC, Plumb OA, Radosz M. Nonthermal-plasma reactions of dilute nitrogen oxide mixtures: NO<sub>x</sub>-in-nitrogen. *Ind. Eng. Chem. Res.* (in press). 2004c.
- Hackam R, Akiyama H. Air pollution control by electrical discharges. *IEEE Transactions on Dielectrics and Electrical Insulation*. 2000; 7: 654.

van Veldhuizen EM, Creyghton YLM, Rutgers WR. High resolution schlieren study of pulsed corona. Proceedings of 4th International Conference on ESP, Beijing, China 1990.

Creyghton YLM, van Bladel FMAM, van Veldhuizen EM. Electrical and spectroscopic investigation of pulsed positive streamer corona in O<sub>2</sub>-N<sub>2</sub> and CO<sub>2</sub>-O<sub>2</sub> mixtures. 3rd International Symposium on High Pressure, Low Temperature Plasma Chemistry, Strasbourg, France. 1991a.

Creyghton YM, van Veldhuizen EM, Rutgers WR. Streamer characteristics of positive pulsed corona. In: 10th International Symposium on Plasma Chemistry, Bochum, Germany. 1991b.

Mok YS, Ham SW, Nam IS. Mathematical analysis of positive pulsed corona discharge process employed for removal of nitrogen oxides. IEEE Transactions on Plasma Science. 1998b; 26: 1566.

Hu X, Zhang JJ, Mukhnahallipatna S, Hamann J, Biggs MJ, Agarwal P. Transformations and destruction of nitrogen oxides-NO, NO<sub>2</sub> and N<sub>2</sub>O-in a pulsed corona discharge reactor. Fuel. 2003; 82: 1675.

Mizuno A, Shimizu K, Chakrabarti A, Dascalescu L, Furuta S. NO<sub>x</sub> removal process using pulsed discharge plasma. IEEE Transactions on Industry Applications. 1995; 31: 957.

Namihira T, Tsukamoto S, Wang D, Katsuki S, Hackam R, Akiyama H, Uchida Y, Koike M. Improvement of NO<sub>x</sub> removal efficiency using short-width pulsed power. IEEE Transactions on Plasma Science. 2000; 28: 434.

Uhm HS, Lee WM. An analytical theory of corona discharge plasmas. Phys. Plasmas. 1997; 4: 3117.

Mok YS, Ham SW, Nam IS. Evaluation of energy utilization efficiencies for SO<sub>2</sub> and NO removal by pulsed corona discharge process. Plasma Chemistry and Plasma Processing. 1998a; 18: 535.

ChungJW, Cho MH, Son BH, Mok YS, Namkung W. Study on reduction of energy consumption in pulsed corona discharge process for NO<sub>x</sub> removal. Plasma Chemistry and Plasma Processing. 2000; 20: 495.

Shin DN, Park CW, Hahn JW. Detection of OH(A<sup>2</sup>Σ<sup>+</sup>) and O(<sup>1</sup>D) emission spectrum generated in a pulsed corona plasma. Bulletin of the Korean Chemical Society. 2000; 21: 228.

Atkinson R, Baulch DL, Cox RA, Hampson JRF, Kerr JA, Rossi MJ, Troe J. Evaluated kinetic and photochemical data for atmospheric chemistry: supplement VI. J. Phys. Chem. Ref. Data. 1997; 26: 1329.

Atkinson R, Baulch D L, Cox RA, Hampson JRF, Kerr JA, Troe J. Evaluated Kinetic and photochemical data for atmospheric chemistry: supplement III. J. Phys. Chem. Ref. Data. 1989; 18: 881.

Kossyi IA, Kostinsky AY, Matveyev AA, Silakov VP. Kinetic scheme of the non-equilibrium discharge in nitrogen-oxygen mixtures. *Plasma Sources Sci. Technol.* 1992; 1: 207.

Herron JT, Green DS. Chemical kinetics database and predictive schemes for nonthermal humid air plasma chemistry: part II, Neutral species reactions. *Plasma Chemistry and Plasma Processing.* 2001; 21: 459.

## Table Captions

**Table 1.** Experimental matrix

**Table 2.** List of all possible chemical reactions for modeling the system NO in N<sub>2</sub>

**Table 3.** Influence of parallel reactor tube number on discharge parameters at 200 Hz



**Table 1. Experimental matrix**

Reactor tube number	System	Flow rate (m <sup>3</sup> /s)	Gas residence time (s)
1	595 ppm NO + N <sub>2</sub>	$2.01 \times 10^{-4}$	1.89
	240 ppm NO + N <sub>2</sub>	$1.11 \times 10^{-4}$	3.42
2	595 ppm NO + N <sub>2</sub>	$1.02 \times 10^{-4}$	7.45
	595 ppm NO + N <sub>2</sub>	$2.19 \times 10^{-4}$	3.47
	595 ppm NO + N <sub>2</sub>	$3.94 \times 10^{-4}$	1.93
4	593 ppm NO + N <sub>2</sub>	$2.10 \times 10^{-4}$	7.23
6	593 ppm NO + N <sub>2</sub>	$2.55 \times 10^{-4}$	8.93
8	593 ppm NO + N <sub>2</sub>	$2.60 \times 10^{-4}$	11.7
10	593 ppm NO + N <sub>2</sub>	$3.70 \times 10^{-4}$	10.3

**Table 2. List of all possible chemical reactions for modeling the system NO in N<sub>2</sub>**

Chemical reaction	Rate constant (cm <sup>3</sup> ·mol <sup>-1</sup> ·s <sup>-1</sup> )	Source	No.
$N_2 + e \rightarrow N + N + e$	$\alpha_1$ and $\beta_1$	This work	R1
$N_2 + e \rightarrow N_2(A) + e$	$\alpha_2$ and $\beta_2$	This work	R2
$N + NO \rightarrow N_2 + O$	$1.87 \times 10^{13}$	(Atkinson et al., 1989)	R3
$O + NO + N_2 \rightarrow NO_2 + N_2$	$k_0 = 3.62 \times 10^{16} [N_2]$ $k_\infty = 1.81 \times 10^{13}$ $Fc = 0.85$	(Atkinson et al., 1997)	R4
$NO_2 + N \rightarrow N_2O + O$	$1.81 \times 10^{12}$	(Atkinson et al., 1989)	R5
$NO_2 + N \rightarrow N_2 + O_2$	$4.21 \times 10^{11}$	(Kossyi et al., 1992)	R6
$NO_2 + N \rightarrow N_2 + 2O$	$5.48 \times 10^{11}$	(Kossyi et al., 1992)	R7
$NO_2 + N \rightarrow 2NO$	$1.38 \times 10^{12}$	(Kossyi et al., 1992)	R8
$NO_2 + O \rightarrow NO + O_2$	$5.85 \times 10^{12}$	(Atkinson et al., 1997)	R9
$N_2(A) + NO \rightarrow N_2 + NO$	$3.31 \times 10^{13}$	(Herron and Green, 2001)	R10
$N_2(A) + N_2O \rightarrow 2N_2 + O$	$3.73 \times 10^{12}$	(Herron and Green, 2001)	R11
$N_2(A) + NO_2 \rightarrow N_2 + NO + O$	$7.83 \times 10^{12}$	(Herron and Green, 2001)	R12
$N_2(A) + O_2 \rightarrow N_2 + 2O$	$1.51 \times 10^{12}$	(Herron and Green, 2001)	R13
$N_2(A) + O_2 \rightarrow N_2O + O$	$4.70 \times 10^{10}$	(Kossyi et al., 1992)	R14
$N_2(A) + O_2 \rightarrow N_2 + O_2$	$7.77 \times 10^{11}$	(Kossyi et al., 1992)	R15
$N_2(A) + O \rightarrow N_2 + O$	$1.81 \times 10^{13}$	(Herron and Green, 2001)	R16
$N_2(A) + N \rightarrow N_2 + N$	$2.71 \times 10^{13}$	(Herron and Green, 2001)	R17
$N + N + N_2 \rightarrow N_2 + N_2$	$1.59 \times 10^{15} [N_2]$	(Kossyi et al., 1992)	R18
$O + O + N_2 \rightarrow O_2 + N_2$	$1.10 \times 10^{15} [N_2]$	(Kossyi et al., 1992)	R19
$N + O + N_2 \rightarrow NO + N_2$	$3.68 \times 10^{15} [N_2]$	(Kossyi et al., 1992)	R20

**Table 3. Influence of parallel reactor tube number on discharge parameters at 200 Hz**

Reactor tube number	Pulse peak (kV)	Pulse width (ns)	Rising rate (kV/ns)
1	19.3	51	1.32
2	18.3	47	1.33
4	19.6	43	1.35
6	19.5	31	1.39
8	20.0	29	1.37
10	18.2	29	1.36

## Figure Captions

**Figure 1.** The effect of the number of parallel reactor tubes on the discharge voltage waveform at 200Hz.

**Figure 2** Lumped Model performance at different initial concentrations of NO in a one-tube reactor.

(a) 595 ppmNO + N<sub>2</sub>; (b) 240 ppmNO + N<sub>2</sub>.

Experimental data: ■ (NO), ● (NO<sub>2</sub>), ▲ (N<sub>2</sub>O); calculated data: —

**Figure 3** Lumped Model performance at different gas flowrates in two-tube reactor.

(a)  $1.024 \times 10^{-4}$  m<sup>3</sup>/s, (b)  $2.191 \times 10^{-4}$  m<sup>3</sup>/s, (c)  $3.943 \times 10^{-4}$  m<sup>3</sup>/s

Experimental data: ■ (NO), ● (NO<sub>2</sub>), ▲ (N<sub>2</sub>O); Model calculated data: —

**Figure 4** Experimental data and correlated data for varying numbers of parallel reactor tubes.

(a) four-tube reactor, (b) six-tube reactor, (c) eight-tube reactor, (d) ten-tube reactor

Experimental data: ■ (NO), ● (NO<sub>2</sub>), ▲ (N<sub>2</sub>O); calculated data: —

**Figure 5** The effect of the number of parallel reactor tubes on model parameters  $\alpha$  and  $\beta$  for two electron collision reactions. (a) Electron collision reaction R1, (b) Electron collision reaction R2. Data: ■ ( $\beta$ ), ▲ ( $\alpha$ )

**Figure 6** The rate constant of electron collision reaction as a function of power input for different number of parallel reactor tubes. (a) Electron collision reaction R1, (b) Electron collision reaction R2. (— one-tube reactor; --- two-tube reactor; ..... four-tube reactor; - - - - six-tube reactor; - · - · - eight-tube reactor; - - - ten-tube reactor)

**Figure 7** An example of the effect of gas residence time and power input on energy consumption of NO conversion to N<sub>2</sub> and O<sub>2</sub> (four-tube reactor).

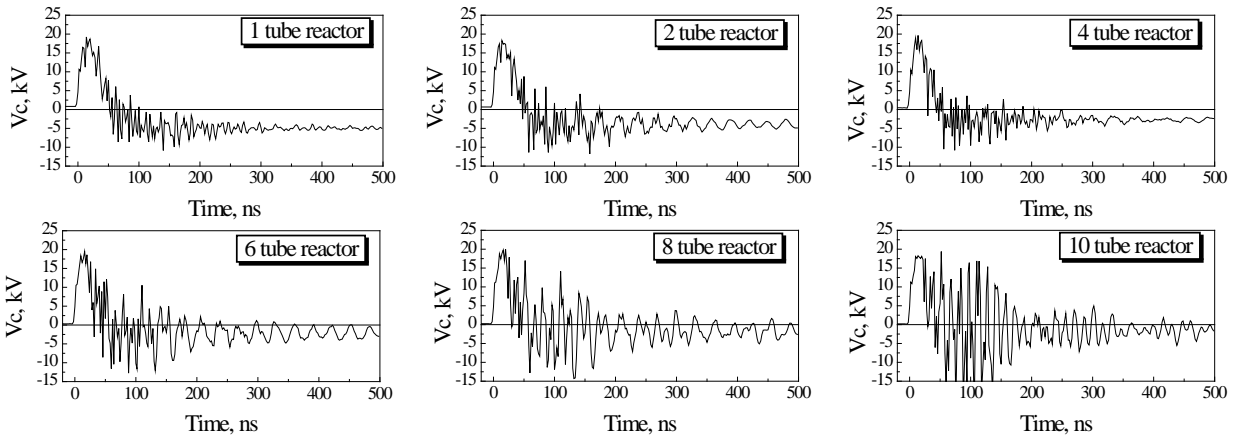
**Figure 8** The effect of the number of parallel reactor tubes on energy consumption at a gas residence time of 6 s.

(— one-tube reactor; --- two-tube reactor; ..... four-tube reactor; - - - - six-tube reactor; - · - · - eight-tube reactor; - - - ten-tube reactor)

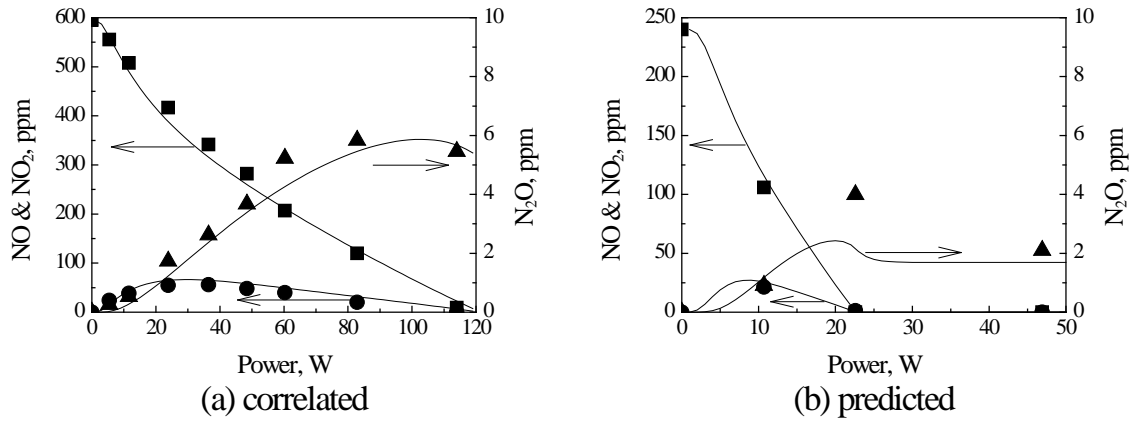
**Figure 9** Energy consumption of NO conversion as a function of the number of reactor tubes.

(a) At power input of 15W, (b) At 90% conversion of NO  
gas residence time

□ 6s, ○ 9s, △ 12s, ▽ 15s.



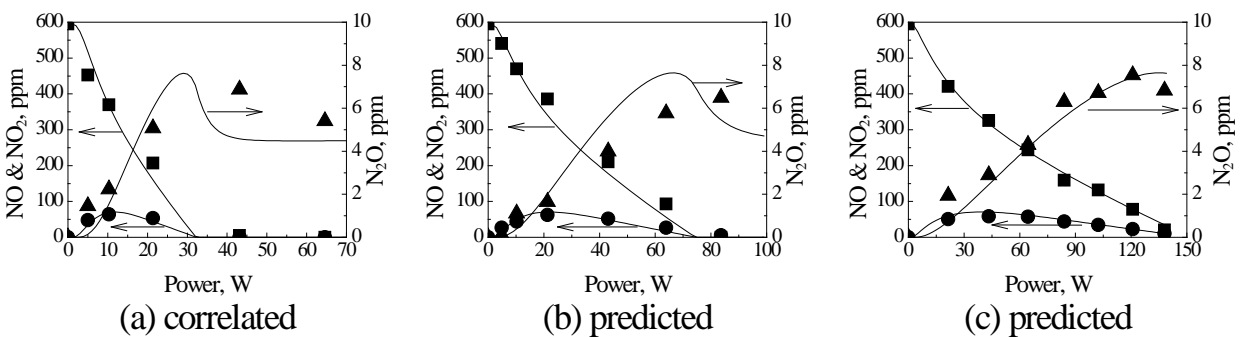
**Figure 1.** The effect of the number of parallel reactor tubes on the discharge voltage waveform at 200Hz.



**Figure 2.** Lumped Model performance at different initial concentrations of NO in a one-tube reactor.

(a) 595 ppmNO + N<sub>2</sub>; (b) 240 ppmNO + N<sub>2</sub>

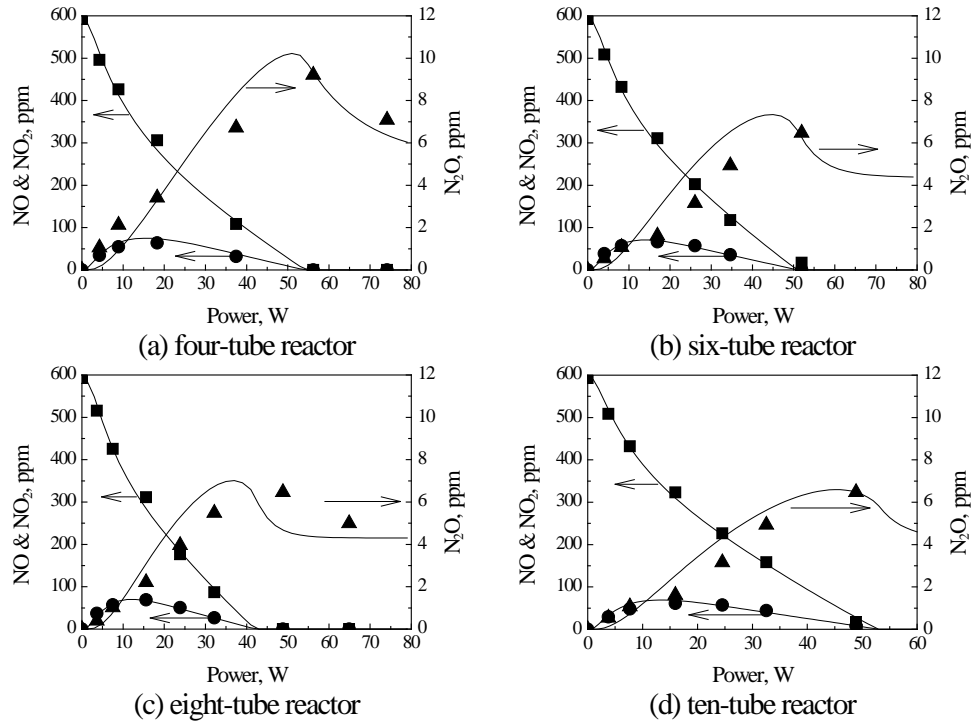
Experimental data: ■ (NO), ● (NO<sub>2</sub>), ▲ (N<sub>2</sub>O); Calculated data: —



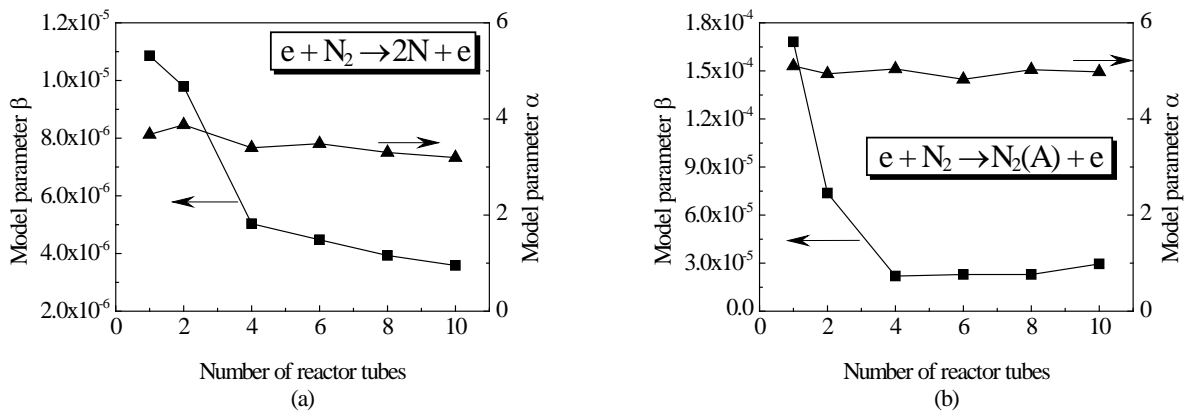
**Figure 3.** Lumped Model performance at different gas flowrates in two-tube reactor.

(a)  $1.024 \times 10^{-4} \text{ m}^3/\text{s}$ , (b)  $2.191 \times 10^{-4} \text{ m}^3/\text{s}$ , (c)  $3.943 \times 10^{-4} \text{ m}^3/\text{s}$

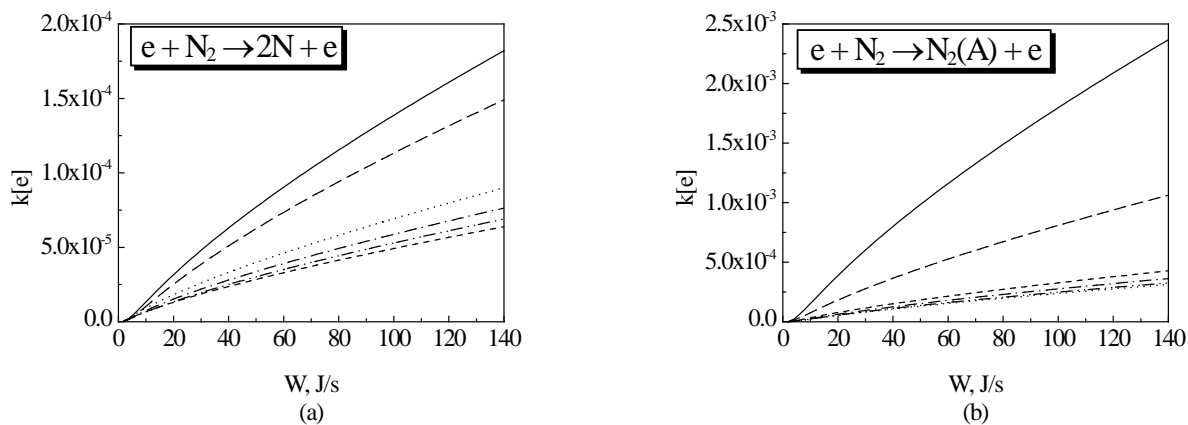
Experimental data: ■ (NO), ● (NO<sub>2</sub>), ▲ (N<sub>2</sub>O); Calculated data: —



**Figure 4.** Experimental data and correlated data for varying numbers of parallel reactor tubes. (a) four-tube reactor, (b) six-tube reactor, (c) eight-tube reactor, (d) ten-tube reactor  
 Experimental data: ■ (NO), ● (NO<sub>2</sub>), ▲ (N<sub>2</sub>O); Calculated data: —



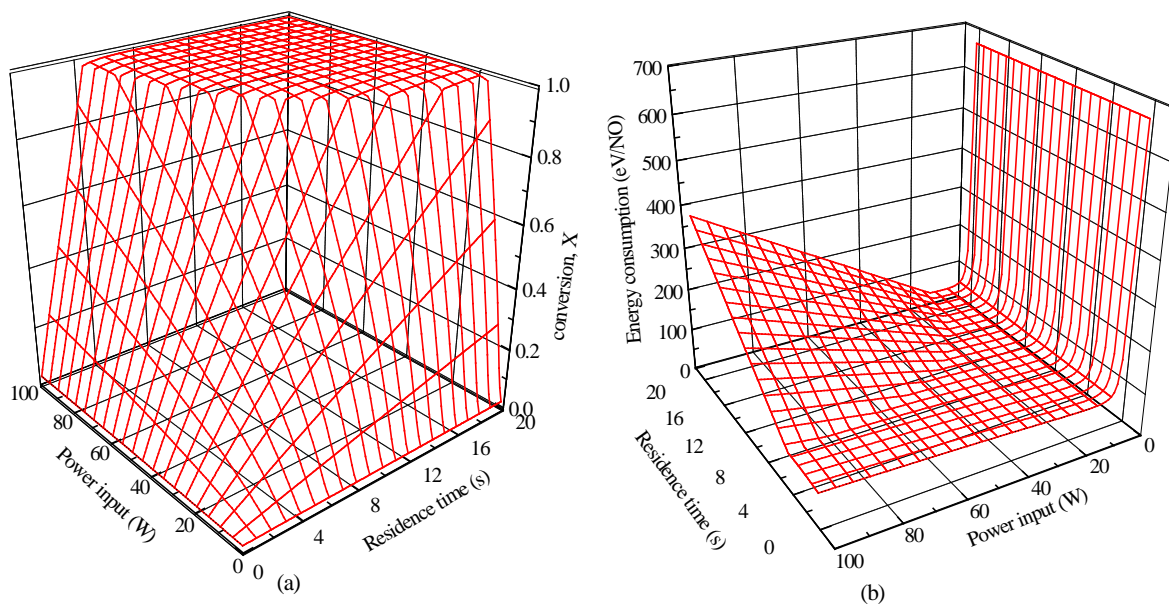
**Figure 5.** The effect of the number of parallel reactor tubes on model parameters  $\alpha$  and  $\beta$  for two electron collision reactions. (a) Electron collision reaction R1, (b) Electron collision reaction R2. ■ ( $\beta$ ), ▲ ( $\alpha$ )



**Figure 6.** The rate constant of electron collision reaction as a function of power input for different number of parallel reactor tubes.

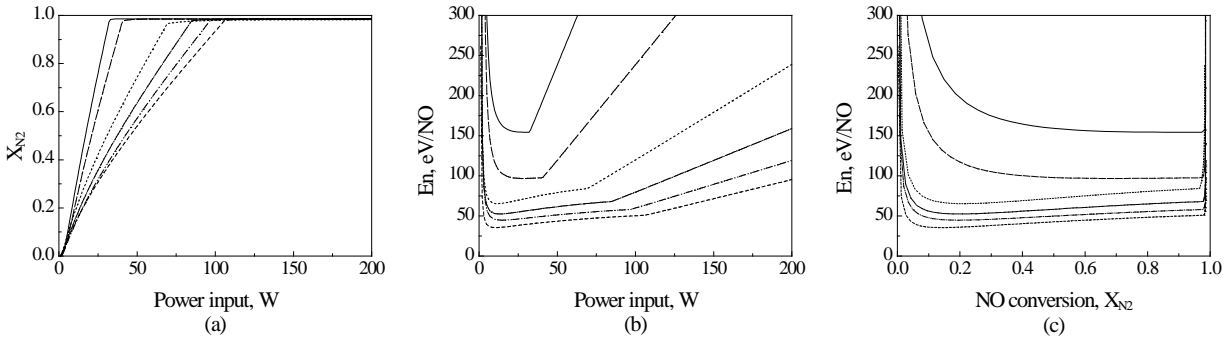
(a) Electron collision reaction R1, (b) Electron collision reaction R2

(—, one-tube reactor; ———, two-tube reactor; ·····, four-tube reactor; - - - - -, six-tube reactor; - - - - -, eight-tube reactor; ---, ten-tube reactor)



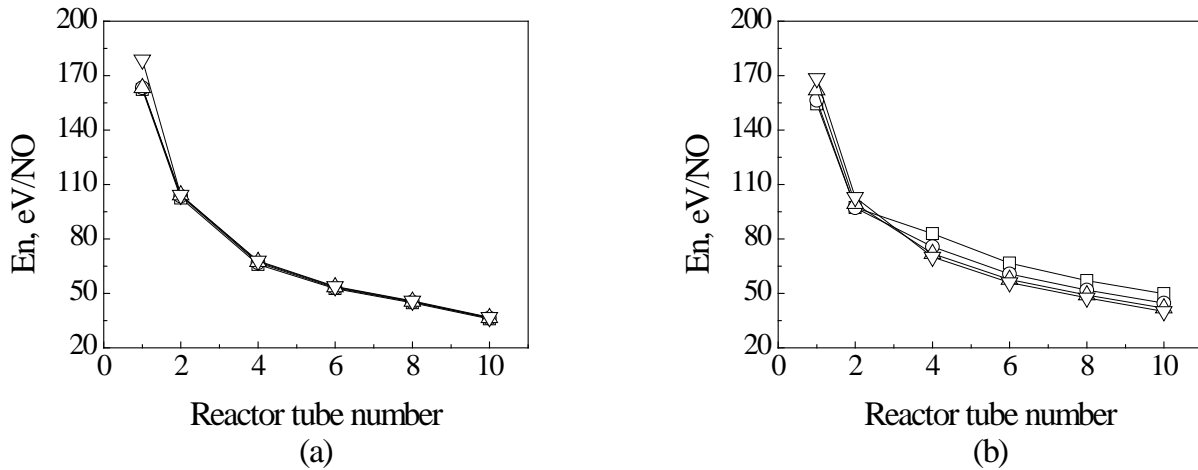
**Figure 7.** An example of the effect of gas residence time and power input on energy consumption of NO conversion to  $N_2$  and  $O_2$  (four-tube reactor).





**Figure 8.** The effect of the number of parallel reactor tubes on energy consumption at a gas residence time of 6 s.

(—, one-tube reactor; ---, two-tube reactor; ·····, four-tube reactor; -·-·-, six-tube reactor; - - - -, eight-tube reactor; ---, ten-tube reactor)



**Figure 9.** Energy consumption of NO conversion as a function of the number of reactor tubes.

(a) At power input of 15W, (b) At 90% conversion of NO gas residence time

□ 6s, ○ 9s, △ 12s, ▽ 15s